Evaluation of Protective Filter Erosion Boundaries

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Table of Contents

Tables

Table of Contents (continued)

Figures

Objective

The objectives of the experiments described in this paper are to provide insight into the self-healing capabilities of protective filters used in embankment dams and to verify the results and reproducibility of previous research. Existing dams may have filters that do not meet Sherard's No Erosion Filter (NEF) criteria; however, the filters may still perform adequately after "some" erosion of the base material into the filter. The research documented in this paper will focus on the soil retention aspect of protective filters.

Introduction

Protective filters placed within embankment dams need to be permeable enough to collect seepage entering the filter, while preventing the migration of finer materials into coarser zones within the embankment and foundation. If a concentrated leak were to develop within the core of an embankment dam, a properly designed filter should be able to control and seal that leak. This report focuses on reproducing previous soil retention criteria recommended by earlier research. Previous criteria are based on the ability of a protective filter to control and seal a concentrated leak that is simulated in a laboratory test.

The soil retention guidelines provided in the Bureau of Reclamation's protective filter design standards for embankment dams [1] are based on the NEF criteria developed by Sherard and Dunnigan [2]. Their criteria are based on the results obtained from extensive testing of cohesive and cohesionless materials in the NEF test. The NEF test simulates a pressurized, concentrated leak through the core of an embankment with only a protective filter as defense against erosion of that material. The NEF criteria are broken up into four categories, depending on the percentage of fines within the embankment core (also referred to as the base material). The criteria shown in table 1 are taken from Reclamation's design standards [1]. Table 1 is provided to show how the maximum D15F (soil particle diameter for 15 percent of the filter sample) is determined. This table does not provide all the details stated in the design standard. The reader should follow Reclamation's design standard when designing the required filter gradation.

The University of New South Wales (UNSW) [3] has developed new supplemental criteria to evaluate filters within existing dams. Building upon Sherard and Dunnigan's [2] work in 1989, the UNSW [3] has extended the NEF test to include a Continuing Erosion Filter (CEF) test. The CEF test examines partial to continuous erosion for filters that do not meet current design standards. Their results show that filters may perform adequately after some erosion of the core materials has taken place. The results obtained from the CEF test may be instructive when considering older structures that do not meet current filter design criteria.

Table 1.—NEF criteria

Base soil category	Percentage of fines	Base soil description	Filter criteria
1	> 85	Fine silts and clays	[1] D15F ≤ 9 x D85B
2	40 - 85	Sands, silts, clays, and silty and clayey sands	D15F ≤ 0.7 mm
3	15 - 39	Silty and clayey sands and gravels	[2, 3] D15F ≤ 0.7 mm + $\frac{[(40 - A) (4 \times D85B - 0.7 \text{ mm})]}{25}$
4	< 15	Sands and gravels	D15F ≤ 4 x D85B

[1] When 9 x D85B is less than 0.2 millimeter (mm), use 0.2 mm.
[2] A = percent passing the No. 200 sieve after any regrading
[3/] When 4 x D85B is less than 0.7 mm, use 0.7 mm.

The experiments performed for this project build upon Sherard's and UNSW's data that establish the NEF criteria and upon UNSW's data that establish the CEF criteria. The experiments also attempt to verify the reliability and reproducibility of the UNSW test procedure.

Reclamation has performed the NEF test and CEF test on five different base soils. These base soils consist of glacial till, loess, nondispersive clay, and two dispersive clay samples. Data that are generated from these experiments could be used to aid in verifying and defining the gradation limits for protective filters for different types of base materials.

The results obtained from the NEF and CEF tests are no erosion, some erosion, and continuous erosion. Each of these test results is defined as:

> **No Erosion** (NE) – Filter seals concentrated leak with no erosion of base soil.
>
> **Some Erosion** (SE) – Filter seals concentrated leak after some base soil is eroded. The volume of eroded materials varies from minor to excessive.
>
> **Continuing Erosion** (CE) – Filter does not seal concentrated leak through the base soil.

Figure 1 (at back),[1] which is taken from Foster and Fell [3], plots the filter size (represented as D15F) versus the D85B. This figure is provided to illustrate the erosion boundaries (no erosion and continuous erosion) as the filter size becomes progressively coarser.

No Erosion Filter Test

Sherard and Dunnigan developed the NEF test as a means to determine the coarsest filter gradation that will seal a concentrated leak with no erosion of the core material. The details of the NEF test are illustrated in figure 2. The procedure for performing the NEF test is detailed in Foster and Fell's report [3].

[1] All figures are located at the back of this report.

During the NEF test, a concentrated leak through the base soil is intentionally made before starting the flow of water. Water enters through the top of the cylinder, flows through the preformed hole (concentrated leak) in the base soil, then through the filter, and exits at the base of the cylinder. During the test, soil particles erode from the walls of the preformed hole and deposit onto the filter. When the filter is sized correctly, eroded base materials will be captured within the voids of the filter material at the filter/base material interface. If the filter size (D15F) is too large, eroded base materials will pass through the voids within the filter material. To meet the NEF requirements, the filter must seal the leak with practically no erosion of the base soil.

After performing an extensive probabilistic review on available research and reviewing their test results, the UNSW recommended the following changes to Sherard's NEF criteria.

1. For dispersive soils, the NEF filter test should be carried out to confirm the D15F for no erosion.

2. The range in the percentage of fines should be changed for Reclamation base soil categories 2 and 3. The recommended changes are shown in table 2.

Table 2.—Proposed change to NEF criteria by UNSW

Base soil category	Existing criteria (% fines)	Proposed criteria (% fines)
1	> 85	> 85 (no change)
2	40 – 85	35 - 85
3	15 – 40	15 - 35
4	< 15	< 15 (no change)

Reclamation has not yet adopted UNSW's recommendations for modifying the NEF criteria into the design standards.

Continuing Erosion Filter Test

Since many existing dams do not satisfy the NEF criteria, the UNSW expanded the NEF test to a CEF test. Once the NEF size is established by the NEF test, the filter size is gradually increased until the filter can no longer seal the concentrated leak through the base soil. Figure 3 illustrates the details of the CEF test. The test procedure for the CEF test is the same as the NEF test, except the base soil is four times thicker.

The results of the CEF test are either "some erosion" or "continuous erosion." Some erosion means the filter did eventually seal the concentrated leak after enough of the base material had been captured within the filter. Continuous erosion means that the filter is not capable of sealing the concentrated leak no matter how much of the base material passes through the filter.

The UNSW found that, for base soils with a D95B < 2 mm (gradations are not adjusted to the No. 4 sieve), the continuing erosion filter size (D15F) is approximately equal to 9 x D95B. This means that if the filter can prevent the coarsest 5 percent of base materials from eroding, the filter will eventually seal the concentrated leak. No recommendation for the continuing erosion boundary was provided for base soils with a D95B > 2 mm. UNSW's results varied significantly for these soils.

Base Materials

The NEF and CEF tests were performed by Reclamation on base soils ranging from 17 to 94 percent fines (percent passing the No. 200 sieve). The base soils tested by Reclamation consist of several problematic soils, ranging from glacial till to loess. Soils were picked for direct comparison to the UNSW study, as well as "new" soils, which would add to the database of tested materials. The gradations for these soils are shown in figure 4.

Foster and Fell used materials that were finer than the No. 4 sieve for the NEF test and materials finer than the 3/4-inch sieve for the CEF test. The test cylinder used by Foster and Fell was either 5 or 8 inches in diameter, depending on the gradation of the base material. The cylinder being used by Reclamation is 11.25 inches in diameter. Because a larger diameter cylinder was used in this study, no adjustment was made for soil maximum size aggregate or test type.

The first sample tested was obtained from Horsetooth Dam in Colorado. This material contained 68 percent fines and 32 percent sand. The Horsetooth material is a Reclamation Base Category 2 material and is classified as a well-graded, nondispersive clay of low plasticity (CL). The Horsetooth Dam material was used for a baseline comparison with the Doletoric Clay soil from the UNSW study [3]. The gradations for these materials are similar.

The second base sample was obtained from Keechelus Dam. This sample is a broadly graded flow-till and is internally unstable. This material is a mixture of boulders, cobbles, gravel, sand, and fines. This material (minus 1.5 inches) is generally classified as silty sand with gravel $(SM)_g$. The Keechelus material is a Reclamation Base Category 2 material that contains 17 percent fines, 47 percent sand, and 36 percent gravel.

The third sample was obtained from Teton Dam borrow area. This material is a poorly graded aeolian silt of low plasticity (ML) that is very erodible. The Teton material is a Reclamation Base Category 1 material that contains 90 percent fines and 10 percent sand.

The fourth sample was obtained from the Tracey Fish Screen Project. This material is a dispersive clay of high plasticity (CH). The Tracey material is a Reclamation Base Category 1 material that contains 94 percent fines and 6 percent sand. The results of the crumb test for this material indicate that it is nondispersive, but the results of the pinhole test indicate it is a dispersive material. Reclamation's *Earth Manual* [4] states the results of the crumb test are less effective than the pinhole test for identifying dispersive clays. The *Earth Manual* also states that the crumb test may show nondispersive reactions for soils that contain kaolinite. A petrographic examination was performed on the Tracy material to determine its mineralogical composition. One of the primary minerals in the Tracey material is kaolinite. Therefore, the Tracey material is believed to be dispersive.

The last sample was obtained from Many Farms Dam. This material is dispersive clay of low plasticity (CL). The Many Farms material is a Reclamation Base Category 2 material that contains 75 percent fines and 25 percent gravel. The results of the pinhole and the crumb test indicate that this is a dispersive material. Because both the pinhole and crumb test indicated that this is a dispersive material, a petrographic examination was not performed.

Table 3 summarizes the properties of each material.

Table 3.—Material properties

Soil	% fines	Reclamation category	USCS classification	LL	PI	Dispersive or erosive	Sand (%)	Gravel (%)
Keechelus	17	2	SM_g	NP	NP	Erosive	47	36
Horsetooth	68	2	CL	29	12	Neither	32	0
Teton	90	1	ML	29	4	Erosive	10	0
Many Farms	75	2	CL	47	34	Dispersive	25	0
Tracy Fish Screen	94	1	CH	55	40	Dispersive	6	0

USCS = Unified Soil Classification System, LL = Liquid Limit, PI = Plasticity Index, NP = Nonplastic

Filter Materials

Filter materials were composed of sand and gravel available in Reclamation's laboratory. These materials are typically used as aggregate for concrete mixes. The necessary filter gradations for the experiments can be made from these materials. Large quantities of these materials were screened into various sizes and are available for use. Eleven filter materials were used for this project. Before the materials were blended together, the prescreened material was thoroughly washed and dried to remove dust that accumulated during the screening process. The filter material was thoroughly washed again after the material was compacted within the test cylinder. If fines within the filter were to wash out during testing and the color of the base soil and filter materials were similar, the fines could be misinterpreted as fines from the base soil.

The gradations for the filters that were used in the experiments are shown in figure 5 and table 4. The finest to coarsest filters were labeled filter No. 1 through filter No. 11, with filter No. 1 representing the finest filter. The coefficient of uniformity (3.33) was the same for each filter, with the exception of filter No.1. Filter No. 1 represents the finest possible gradation that could be specified using Reclamation's design standards [1].

Table 4.—Gradations for filters No. 1 – No. 11

		Percent finer (by weight)										
		Filter No.										
Sieve No.	Particle size (mm)	1	2	3	4	5	6	7	8	9	10	11
	75	100	100	100	100	100	100	100	100	100	100	100
	37.5	100	100	100	100	100	100	100	100	100	100	100
	19	100	100	100	100	100	100	98	94	87	61	45
	9.5	100	100	100	100	100	95	86	75	55	26	5
4	4.75	100	100	97	93	85	73	56	35	15	3	0
8	2.36	98	90	80	65	53	40	20	7	2	0	0
16	1.18	86	70	55	36	20	8	4	0	0	0	0
30	0.6	61	45	22	10	4	0	0	0	0	0	0
50	0.3	33	15	5	3	0	0	0	0	0	0	0
100	0.15	10	2	0	0	0	0	0	0	0	0	0
200	0.075	4	0	0	0	0	0	0	0	0	0	0
D15F (mm)		0.18	0.3	0.5	0.7	1.0	1.4	2.0	3.0	4.75	8.1	12

A ring of finer material was placed along the outside of the top inch of the filter material (see figures 2 and 3). The purpose of this "side material" was to eliminate larger voids along the contact between the filter material and the test cylinder and reduce the potential for the migration of particles along the outside of the cylinder. The particle size of the "side material" for each filter is shown in table 5. Beneath the filter, an additional 2-inch layer of material was placed between the filter material and the bottom gravel layer. The purpose of this material was to eliminate the migration of filter materials into the lower gravel layer. The particle sizes of this "lower filter" are also shown in table 5.

Table 5.—Side material and lower filter material sizes

Filter No.	D15F (mm)	Side material size (No.)	Lower filter size
1	0.18	100	No. 4 to No. 16
2	0.30	100	No. 4 to No. 16
3	0.49	50	No. 4 to No. 8
4	0.70	30	No. 4 to No. 8
5	1.00	30	No. 3/8 inch to No. 8
6	1.40	16	No. 3/8 inch to No. 4
7	2.00	8	No. 3/8 inch to No. 4
8	3.00	8	3/4 inch to 3/8 inch
9	4.80	8	3/4 inch to 3/8 inch
10	8.10	4	3/4 inch
11	12.00	4	3/4 inch

Test Equipment

Acrylic cylinders were fabricated for the test apparatus. Using acrylic provides the advantage of visual observation of soil movement during the test. The fragile nature of acrylic materials did cause several problems. The main problem was with the connections between the cylinders and the bottom and top caps. A total of four test apparatuses were fabricated over the duration of the test program. During each new fabrication, the thickness of the welds was increased for the connections or the thickness of the acrylic cylinder walls was increased. The pertinent dimensions for the test (cylinder height and inside diameter) remained constant throughout testing.

A regulated water pressure of 40 pounds per square inch (lb/in^2) was used for these tests. This pressure is consistent with previous UNSW testing programs. A pressure regulator was placed at the connection between the water supply and the inflow pipe to eliminate pressure surges and to maintain a consistent value for each test.

The inflow pipe used for the Horsetooth and Teton materials was 1 inch in diameter. The inflow pipe for the Tracey, Many Farms, and Keechelus material was 1.5 inches in diameter. The advantage of using a larger inflow pipe was that a second hose from another water supply line could be attached to the inflow pipe for additional flows needed for the larger filter sizes. In addition, the diameter of the inflow pipe appeared to have an effect on the volume of eroded materials. This will be discussed later in this paper.

The procedures for the NEF and CEF tests are documented in Foster and Fell's research report [3].

Test Results

Documentation Recorded for Each Test

The final result of each test is either no erosion, some erosion, or continuous erosion. Several factors were used to determine the degree of erosion during each test. Before the test began, the initial preformed hole size in the base soil was documented and photographed. During the test, the following information was recorded: water pressure above the base soil, outflow from the acrylic cylinder, and the quality of the water exiting the cylinder. Water pressures were recorded in pounds per square inch. Outflows were recorded in milliliters per second (ml/s). The quality of the water was based on visual descriptions. The visual descriptions used throughout testing were dirty, cloudy, slightly cloudy, and clear. The frequency of readings typically decreased as the elapsed time of the test increased. Each test was stopped after the water pressures and outflows stabilized, and the verbal description of the outflow was clear. Once the test was completed, the final hole size was documented and photographed. In general, a test took 15 to 45 minutes to run.

Typical Observations of a NEF Test

The following observations were typically recorded for a filter that satisfied the NEF criteria:

- At the start of the test, water pressures reached 40 lb/in^2 immediately. Since the size of the inflow pipe is much larger than the 2-mm preformed hole, this pressure was easily reached with available house pressures. This pressure was maintained for the entire test.
- Outflows from the cylinder generally reached a maximum value at the start of the test. As eroded materials from the base soil began to fill in voids on the base/filter material interface, outflows gradually decreased over time to a constant value.
- The quality of outflow remained clear for the entire test.
- There was no increase in the preformed hole size at the completion of the test.

Typical Observations for a Test That Allowed for Some (Minor) Erosion

- At the start of the test, water pressures typically are between 30 to 40 lb/in^2. The water pressure would typically remain at or increase to 40 lb/in^2 within several minutes after the test began and remain at 40 lb/in^2 until the test was completed.
- Outflows from the cylinder generally reached a maximum value at the start of the test. As eroded materials from the base soil began to fill in voids on the base/filter material interface, outflows gradually decreased over time to a constant value.
- The quality of the water was cloudy at the start of the test. The water eventually cleared as the water pressures and outflows leveled off to a consistent value.
- At the end of the test, there was a slight increase in the hole size.

Typical Observations for a Test That Allowed for Some (Excessive) Erosion

- At the start of the test, water pressures were less than 40 lb/in^2. The water pressure either remained at the initial value or decreased after several minutes. After a large amount of erosion had taken place, the water pressure slowly began to increase until the maximum value of 40 lb/in^2 was reached.
- Outflows from the cylinder were high (compared to tests that allowed minor erosion) at the start of the test. When water pressures decreased, the outflow increased. When water pressures increased, the outflow decreased. After large amounts of erosion had taken place, outflows gradually decreased to a consistent value.
- The quality of the outflow was dirty at the start of the test. Flows gradually cleared up over time.

- The size of the preformed hole increased at the end of the test. Eroded paths along the side of the test cylinder were often visible.

Typical Observations for a CEF Test

- At the start of the test, water pressures were less than 40 lb/in^2. For the most part, pressures decreased rapidly to a value less than 10 lb/in^2. The filter was not able to seal the preformed hole; thus, pressures typically remained well below 40 lb/in^2 for the duration of the test.

- Outflows from the cylinder were high at the start of the test. As the pressure decreased, the outflow increased. Once the water pressure leveled off, the outflow remained at a consistent value.

- The quality of the outflow was dirty at the start of the test. The outflow remained cloudy for most of the test. For some base soils, the water did eventually clear up, but the leak never sealed.

- The size of the preformed hole increased significantly by the time the test was completed. Eroded paths along the side of the test cylinder were often visible. The final hole size was limited by the size of the inflow pipe. This is discussed later in this paper.

Results Obtained for Each Base Soil

Horsetooth Dam Material Results

The Horsetooth material is a Reclamation Base Category 2 material. For this material, Reclamation's filter design criteria require a filter with a D15F less than or equal to 0.7 mm. The NEF test was performed, in order, on filters No. 3, 4, and 5. The NEF tests on filters No. 3 and 4 resulted in no erosion. The result for filter No. 5 was some erosion.

The Horsetooth material was selected because of its availability, and the gradation is similar to Foster and Fell's [3] Doletoric Clay sample. The Horsetooth sample was tested first to provide an initial comparison with the results obtained by Foster and Fell. Table 6 shows the results obtained from the NEF test for the Doletoric Clay and Horsetooth samples. The NEF size (D15F) for the Horsetooth material is between 0.7 mm to 1.0 mm. A similar result was found by Foster and Fell [3] for their Doletoric Clay sample. The NEF size found for the Horsetooth material meets Reclamation's soil retention criteria for filter design.

Table 6.—Comparison between Horsetooth and Doletoric clay samples

Soil	Base category	Gradation		Dispersivity	NEF size (D15F) determined by NEF test
		% Fines	D85B		
Horsetooth	2	68	0.31 mm	Nondispersive	0.7 to 1.0 mm
Doletoric Clay	2	70	0.2 mm	Nondispersive	0.5 to 0.7 mm

Once the NEF size (D15F) was determined, progressively coarser filters were used to determine the CEF size. Filters No. 6 through 9 were used for the CEF tests on the Horsetooth material. Testing stopped at filter No. 9. Filter No. 9 was unable to seal the concentrated leak, and large amounts of erosion took place. The overall thickness of the base material used for filter No. 9 decreased by 1/4 inch.

Once the CEF size (D15F) was established, a second CEF test was performed on filter No. 9. In this second test, the filter material thickness increased to 12 inches. This filter is labeled as filter No. 9b. The purpose of this test was to verify that the CEF size did not depend on the overall thickness of the filter. The same result was obtained for this test. Thus, a 6-inch-thick filter was determined to be adequate for the remainder of the tests.

The gradations for the Horsetooth material and filters No. 3 through 9 are plotted in figure 6 to illustrate the range in filter sizes between the NEF size and the CEF size. The gradation of the Doletoric Clay soil from the UNSW [3] study is also shown on figure 6. The filter sizes (D15F) varied from 0.49 mm for the NEF to 4.8 mm for the CEF. Appendix 1 contains the final photos of each test. Table 7 presents a brief summary of each test. A more detailed summary is provided in Appendix 1.

Table 7.—Summary of test results for Horsetooth material

Base soil	Filter No.	Test type	D15F (mm)	Time (min)	Initial hole diameter (mm)	Final hole diameter (mm)	Test result
Horsetooth	3	NEF	0.49	30.0	2.0	2.0	NE
	4	NEF	0.70	20.0	2.0	2.0	NE
	5	NEF	1.00	60.0	2.0	2.0	SE
	6	CEF	1.40	20.0	4.75	4.75	SE
	7	CEF	2.00	55.0	4.75	7.00	SE
	8	CEF	3.00	42.0	4.75	11.00	SE
	9	CEF	4.80	85	4.75	see photo in Appendix 1	CE
	9b	CEF	4.80	40.0	4.75	see photo in Appendix 1	CE

Figures 7 and 8 illustrate the behavior of the water pressure and the outflow versus time. The data shown on figures 7 and 8 for filter No. 9 differed from typical results for CEF tests. (Refer to the "Test Results" section for typical results for a CEF test.) The pressures did reach the maximum value of 40 lb/in^2, and outflows did gradually decrease with time. The reason for this is believed to be the fluctuation in water pressures during the test. When the house water pressure fluctuated, pressure within the test cylinder was lost and a large amount of loose fines would collect on the surface of the filter material. Thus, the hydraulic gradient over the base/filter material interface decreased, which decreased the volume of eroding soil particles and caused the pressure within the cylinder to slowly increase. When testing filter No. 9b, there were no pressure fluctuations and the water pressure within the cylinder remained at 1 lb/in^2.

Teton Dam Material Results

The second base material tested was the Teton material. The Teton material is a Reclamation Base Category 1 material. For this material, Reclamation's filter design criteria require a filter with a D15F less than or equal to 0.3 mm. The NEF test was performed on filters No. 1 to 3. The results of the test for filters No. 2 and 3 were some erosion. The preformed hole collapsed on several tests with filter No. 1. Full water pressure was applied to the sample. No outflows were recorded, and the water within the cylinder remained clear. Filter No. 1 is likely the NEF size (D15F) for the Teton material.

Once the NEF size (D15F) was determined, progressively coarser filters were used to determine the CEF size. Filters No. 4 through 6 were used for the CEF tests on the Teton material. Testing stopped at filter No. 6. Filter No. 6 was unable to seal the concentrated leak, and large amounts of erosion took place.

The gradations for the Teton material and filters No. 1 through 6 are plotted on figure 9 to illustrate the range in filter sizes between the NEF size and the CEF size. The range in filter sizes (D15F) varied from 0.18 mm for the NEF to 1.4 mm for the CEF. Appendix 2 contains the final photos of each test. Table 8 presents a brief summary of each test. A more detailed summary is provided in Appendix 2.

Table 8.—Summary of test results for Teton material

Base soil	Filter No.	Test type	D15F (mm)	Time (min)	Initial hole diameter (mm)	Final hole diameter (mm)	Test result
Teton	1	NEF	0.18	NR	2.0	NR	NE
	2	NEF	0.30	25	2.0	2	SE
	3	NEF	0.49	16	2.0	2	SE
	4	CEF	0.70	20	4.75	7(avg)	SE
	5	CEF	1.00	140	4.75	13	SE
	6	CEF	1.40	40	4.75	38	CE

Figures 10 and 11 illustrate the behavior of the water pressure and the outflow versus time. These graphs illustrate the typical behavior for tests that resulted in no erosion to continuous erosion.

Tracey Fish Screen Facility Material Results

The third base material tested was the Tracey Fish Screen material. The Tracey Fish Screen material is a Reclamation Base Category 1 material. For this material, Reclamation's filter design criteria require a filter with a D15F less than or equal to 0.2 mm. The NEF test was performed on filters No. 1 and 2. The first filter tested was filter No. 2. The result of this test was some erosion. The second filter tested was filter No. 1. The result of this test was no erosion.

Once the NEF size (D15F) was determined, progressively coarser filters were used to determine the CEF size. Filters No. 3 through 7 were used for the CEF tests on the Tracey material. Testing stopped at filter No. 7. Filter No. 7 was unable to seal the concentrated leak, and large amounts of erosion took place.

The gradations for the Tracey Fish Screen material and filters No. 1 through 7 are plotted on figure 12 to illustrate the range in filter sizes between the NEF size and the CEF size. The range in filter sizes (D15F) varied from 0.18 mm for the NEF to 2.0 mm for the CEF. Appendix 3 contains the final photos of each test. Table 9 presents a brief summary of each test. A more detailed summary is provided in Appendix 3.

Table 9.—Summary of test results for Tracey Fish Screen material

Base soil	Filter No.	Test type	D15F (mm)	Time (min)	Initial hole diameter (mm)	Final hole diameter (mm)	Test result
Tracey	1	NEF	0.18	20	2.0	2.0	NE
	2	NEF	0.30	60	2.0	2.0	SE
	3	CEF	0.49	40	4.75	9.5	SE
	4	CEF	0.70	40	4.75	6	SE
	5	CEF	1.00	30	4.75	10	SE
	6	CEF	1.40	48	4.75	6.25	SE
	7	CEF	2.00	40	4.75	13	CE

Figures 13 and 14 illustrate the behavior of the water pressure and the outflow versus time. These graphs illustrate the typical behavior for tests that resulted in no erosion to continuous erosion.

Many Farms Dam Material Results

The fourth base material tested was the Many Farms material. The Many Farms material is a Reclamation Base Category 2 material. For this material, Reclamation's filter design criteria require a filter with a D15F less than or equal to 0.7 mm. The NEF test was performed on filters No. 3 and 4. The first filter tested with the Many Farms material was filter No. 4. The result of this test was some erosion. The second filter tested was filter No. 3. The result of this test was no erosion.

Once the NEF size (D15F) was determined, progressively coarser filters were used to determine the CEF size. Filters No. 3 through 7 were used for the CEF tests on the Many Farms material. Testing stopped at filter No. 7. Filter No. 7 was unable to seal the concentrated leak, and large amounts of erosion took place.

The gradations of the Many Farms material and filters No. 3 through 10 are plotted on figure 15 to illustrate the range in filter sizes between the NEF size and the CEF size. The range in filter sizes (D15F) varied from 0.49 mm for the NEF to 8.1 mm for the CEF. Appendix 4 contains the final photos of each test. Table 10 presents a brief summary of each test. A more detailed summary is provided in Appendix 4.

Table 10.—Summary of test results for Many Farms Dam material

Base soil	Filter No.	Test type	DF15 (mm)	Time (min)	Initial hole diameter (mm)	Final hole diameter (mm)	Test result
Many Farms	3	NEF	0.49	15	2.00	2	NE
	4	NEF	0.70	45	2.00	5	SE
	5	CEF	1.00	40	4.75	19	SE
	6	CEF	2.00	55	4.75	18	SE
	7	CEF	2.00	55	4.75	16	SE
	8	CEF	3.00	45	4.75	25 - 60	SE
	9	CEF	4.80	55	4.75	see photo in Appendix 4	SE
	10	CEF	8.10	50	4.75	see photo in Appendix 4	CE

Figures 16 and 17 illustrate the behavior of the water pressure and the outflow versus time. These graphs illustrate the typical behavior for tests that resulted in no erosion to continuous erosion.

Keechelus Dam Material Results

The last material tested was the Keechelus Dam material. The Keechelus material is a Reclamation Base Category 2 material after the gradation is adjusted to the No. 4 sieve. Reclamation's filter design criteria require that the gradations for all base soils be mathematically adjusted to extract the plus No. 4 sieve-size materials. For this material, Reclamation's filter design criteria require a filter with a D15F less than or equal to 0.7 mm. The NEF test was performed on filters No. 1 through 4. The results of the tests performed on filters No. 2, 3, and 4 were some erosion. Three NEF tests were performed on filter No. 1. Two of the three NEF tests on filter No. 1 had four preformed holes through the base material. During each test on filter No. 1, the hole or holes through the base material collapsed upon contact with the water. No outflows were recorded during each of these tests. Filter No. 1 is likely the NEF size (D15F) for the Keechelus material. The preformed hole through the base collapsed on several of the CEF tests performed on the Keechelus material, but cloudy water could be seen in the lower gravel layer at the start of the test. When performing the NEF test on filter No. 1, the water in the lower gravel layer remained clear.

The NEF size for the Keechelus material is below Reclamation's soil retention criteria. The outflow for the NEF tests on filters No. 2 and 3 was collected in a bucket during the test. The outflow was cloudy. The water in the buckets did not clear up after 2 weeks of being undisturbed. The pinhole and crumb tests were performed to determine if the material was dispersive. The results of the pinhole and crumb test indicate the Keechelus material is nondispersive.

Once the NEF size (D15F) was determined, progressively coarser filters were used to determine the CEF size. Filters No. 5 through 11 were used for the CEF tests on the Keechelus material. Testing stopped at filter No. 11. Filter No. 11 was unable to seal the concentrated leak. The hole through the base increased by approximately 15 mm at the end of the CEF test for filter No. 11. In general, the hole size did not increase significantly for the CEF tests performed on the Keechelus material. During the CEF tests for filters No. 8 through 11, the fines within the material could be seen washing through the filter, leaving the sand and gravel portions retained above the filter. Large amounts of erosion of the finer material did take place for filters No. 10 and 11, but the visible hole size did not increase significantly because the sand and gravel portion did not erode. No settlement was observed as a result of the increase in pore size.

The gradations for the Keechelus material and filters No. 1 through 11 are plotted in figure 18 to illustrate the range in filter sizes between the NEF size and the CEF size. The range in filter sizes (D15F) varied from 0.18 mm for the NEF to 12 mm for the CEF. Appendix 5 contains the final photos of each test. Table 11 presents a brief summary of each test. A more detailed summary is provided in Appendix 5.

Table 11.—Summary of test results for Keechelus Dam material

Base soil	Filter No.	Test type	DF15 (mm)	Time (min)	Initial hole diameter (mm)	Final hole diameter (mm)	Test result
Keechelus	1	NEF	0.18	NR	2.00	collapsed	NE
	2	NEF	0.30	35	2.00	2	SE
	3	NEF	0.49	45	2.00	2	SE
	4	NEF	0.70	16	2.00	4	SE
	5	CEF	1.00	25	4.75	collapsed	SE
	8	CEF	3.00	45	4.75	4.75	SE
	9	CEF	4.80	45	4.75	6	SE
	10	CEF	8.10	70	4.75	7	SE
	11	CEF	12	45	4.75	19	CE

Figures 19 and 20 illustrate the behavior of the water pressure and outflow versus time. The results of these graphs show that the outflow decreased for the CEF test on filter No. 11, but it remained at least two times larger than outflows observed from the previous CEF tests on the Keechelus material. The water pressure for filter No. 11 stayed at 36 to 38 lb/in^2 throughout the test. At the end of this test, there was no material within the hole and the remaining water above the base soil free drained once the water supply was cut off. In the previous CEF tests for the Keechelus material that resulted in some erosion, a thin layer of eroded base material collected on top of the filter material at the completion of the test. There was no evidence of any of the Keechelus material on top of filter No. 11 at the end of the test. This is evidence that the continuing erosion boundary was reached.

Summary of Results

A summary of the NEF sizes and CEF sizes is shown in table 12. The results shown in table 12 are based on the materials gradation. The effects of plasticity were not analyzed as part of this research project.

Table 12.—Summary of results for NEF sizes and CEF sizes

Base material	NEF boundary D15F (mm)	Coarsest filter sealed in CEF tests D15F (mm)	Filter not sealed in CEF tests D15F (mm)	Reclamation standards for soil retention (mm)	Ratio of D15F of coarsest filter sealed to NEF size
Horsetooth	0.7 to 1.0	3.0	4.8	≤ 0.7 mm	3.5
Teton	0.18 to 0.3	1.0	1.4	≤ 0.3 mm	4.2
Tracey	0.18 to 0.3	1.4	2.0	≤ 0.2 mm	5.8
Many Farms	0.49 to 0.7	4.8	8.1	≤ 0.7 mm	8.0
Keechelus	0.18 to 0.3	8.1	12.0	≤ 0.7 mm	33.8

The Horsetooth and Many Farms materials have a similar percentage of fines and sand. The NEF size (D15F) for these materials differed by one filter size. The NEF size (D15F) for the Many Farms material is slightly below Reclamation's standards. However, the volume of eroded base material from the Many Farms sample that passed through filter No. 4 (D15F = 0.7 mm) was very minor. Also, the CEF size found for these materials differed by one filter size. After observing the test and reviewing the results on filter No. 9 for the Many Farms material, the CEF size is likely very close to 4.8 mm. The CEF test on Filter No. 9 for the Many Farms material was the only test that resulted in some erosion where, at one point, outflows were over 1,000 mL/s. Also, the amount of material eroded during the final CEF test on Many Farms material was very large (see photo 6 in Appendix 4), compared to the final CEF test results for the other base materials. The Many Farms material is dispersive and experienced larger amounts of erosion compared to the Horsetooth material, but it is difficult to compare the factors that influenced erosional losses for these materials because the volume of water flowing into the cylinder was greater for the Many Farms material. (See the "Test Equipment" section.)

The Teton and Tracey materials also have a similar percentage of fines and sand. For these materials, the NEF sizes (D15F) found during this study are within the same range of filter sizes. The NEF sizes (D15F) for these materials are within Reclamation's standards. The CEF size found for these materials differed by one filter size. The erosional losses for the Teton material were much higher compared to the Tracey material. This was expected because the Teton material is very erodible. Although the Tracey material is dispersive, large erosional volumes were not observed during the CEF tests. The reason for this could be the high plasticity of the Tracey material.

The NEF size (D15F) for the Keechelus material is below Reclamation's soil retention criteria. At the start of the test for Filters No. 2 and 3, a small volume of very fine material passed through the filter. The likely explanation for this behavior is that the Keechelus material is internally unstable. The unadjusted gradation for the Keechelus material plots within Sherard's unstable band [5]. (See figure 21.) It should also be noted that the Keechelus material was still internally unstable after the gradation was adjusted to the No. 4 sieve. The ratio of the coarsest filter sealed in the CEF test to the NEF size was quite large for the Keechelus material. This material is a broadly graded glacial till with 47 percent sand-sized particles. During the series of CEF tests, the self-filtering capability of this material could be observed. The fines within the lower portion of the sample were eroded, leaving the sand and gravel portions left in place. The percentage of fines retained in the base sample typically increased towards the top of the base sample. This behavior can be observed in photos 7 and 8 shown in Appendix 5. Photo 8 in Appendix 5 illustrates the gradation at the bottom of the base material at the end of the CEF test. Photo 7 in Appendix 5 illustrates the gradation at the top of the base material at the end of the same CEF test. The volume of eroded material from the Keechelus samples is not adequately described by the final hole size because of the large amount of fines washed away during the test. The self-filtering capabilities of the Keechelus material provide the likely explanation for the large ratio between the coarsest filter sealed in the CEF test to the NEF size.

Observations

Hydraulic Gradient

Before the test cylinder was filled with water, the top surface filter material was exposed at the bottom of the preformed hole. During the first few seconds of the test, the outflow from the test cylinder was related to the size of the hole through the base and the permeability of the filter, provided that the hole did not collapse once the cylinder was filled with water. For all of the NEF tests, the water pressure at the start of the test was 40 lb/in^2, which is equivalent to 92 feet of head.

At the end of each test, the initial hole was probed to determine the size of the hole and to observe how much material collected in the hole. For the most part, the hole collapsed once the water pressure was relieved at the end of the test. Typically, there would be about an inch of material at the bottom of the hole. When the hole did not collapse for several of the CEF tests performed on the larger filter sizes, the water remaining on top of the base material freely drained immediately after the surface of the filter material was scratched with a drill bit. This suggests that the thin layer of eroded base material (approximately 1/8 inch) collected on top of the filter was responsible for a 92-foot reduction in head. The hydraulic gradient for this situation is well over 1,000. This assumes the pressure within the filter material was at or close to atmospheric pressure.

At the completion of each test, the base material was carefully removed from the top of the filter material. For tests that showed little to no erosion of the base material, most of the filter material remained free of eroded base materials. This indicates that the eroded base materials are being captured on the surface of the filter material. Sherard [2] describes this observation by saying "there is a thin zone (skin) over the entire upstream face of the filter in which the voids are partially choked with eroded soil particles." In some of the CEF tests that experienced large amounts of erosion, base materials were found throughout the filter. In this case, the permeability of the filter may have gradually decreased and allowed the "filter skin" to develop at the interface of the filter/base material.

Limiting Flow Condition

Foster and Fell document in their research report [3] that "the CEF tests using filters significantly coarser than the no erosion boundary filter commonly reached an equilibrium condition where large flows were measured but the flow was clear." They called this the "limiting flow condition." This behavior was observed during this work as well. In all the CEF tests for filters that did not seal the concentrated leak, the volume of eroded material appeared to be limited by the inflow pipe size. This can be seen in the photos located in Appendices 2 through 6.

The inflow pipe size for the tests performed on the Teton and Horsetooth material was 1 inch. A 3/4-inch-diameter hose was supplying water to the 1-inch inflow pipe. The final hole size for the CEF tests for the Horsetooth and Teton materials was slightly larger than the size of the inflow pipe. After viewing these results, the size of the inflow pipe was increased to 1.5 inches. The larger pipe provided the advantage of allowing attachment of a second hose to the inflow pipe, which increased flows and water pressures within the cylinder.

The result of increasing the inflow pipe size can be seen in the final hole size of the Many Farms material during the CEF tests. The volume of eroded material for the Many Farms material is, in general, 1.5 to 2 times larger than the Horsetooth material. Larger amounts of erosion would most likely have taken place if the Horsetooth material had been retested using the larger inflow pipe. Increasing the flow into the cylinder limited the effects of the limiting flow condition but did not eliminate them.

Comparison to Foster and Fell's Results

One of the objectives of Reclamation's research was to verify the results and reproducibility of Foster and Fell's [3] research.

Reclamation used a larger diameter test cylinder throughout the testing program. The purpose of using the larger cylinder was to verify that the NEF test results did not dependent on the size of the test cylinder. The test cylinder used by Foster and Fell was either 5 or 8 inches in diameter, depending on the gradation of the base material. The cylinder being used by Reclamation is 11.25-inches in diameter. When comparing the NEF sizes for Foster and Fell's Doletoric Clay sample and Reclamation's Horsetooth sample, the NEF sizes are similar. This suggests that the results of the NEF test do not depend on the diameter of the test cylinder for these materials.

Based on the results of the CEF tests for base soils with D95B < 2 mm, Foster and Fell found that the largest filter size that would seal the concentrated leak was approximately equal to 9 times the D95B. Table 13 compares the D95B with the largest filter size that sealed the concentrated leak to Foster and Fell's estimate for the four soils Reclamation tested with a D95B < 2 mm. Reclamation's results agree well with Foster and Fell's estimate.

Table 13.—Comparison of test results to Foster and Fell's estimated value

Base soil	D95B (mm)	Foster and Fell's estimate for coarsest filter size that will seal concentrated leak 9 x D95B (mm)	Coarsest filter size Sealed in the CEF tests performed by Reclamation (mm)
Teton	0.1	0.9	1.0
Horsetooth	0.31	2.79	3.0
Tracey	0.08	0.72	1.4
Many Farms	0.3	2.7	4.8

In Foster and Fell's report, there are a number of figures (figures 28, 29, 30, 31, and 32) that are based on the size and volume of eroded base materials. In their test program, outflows were collected and decanted to collect all the eroded particles for analyses. This was not done as part of Reclamation's testing program; therefore, these figures could not be reproduced and compared in this report.

Foster and Fell recommend that NEF size (D15F) should be verified for dispersive soils. Sherard and Dunnigan suggest that the NEF size does not depend on the dispersivity of the base material. The NEF tests performed by Foster and Fell suggest that the NEF size for dispersive materials is finer than what is recommended by Sherard and Dunnigan and Reclamation's design standards. Two dispersive materials were tested in this laboratory study. The NEF size for the Tracey Fish Screen material is within Reclamation's design standards. The NEF size for the Many Farms materials is slightly below Reclamation's design standards. The results of the CEF test on Filter No. 4 (D15F = 0.7 mm) performed on the Many Farms material supports Foster and Fell's recommendation. Noticeable erosion occurred during this test.

Conclusions

A. The results obtained from the NEF test for the Doletoric Clay (UNSW) and Horsetooth (Reclamation) samples are in agreement. The procedures and test results documented by the UNSW [3] were verified and are reproducible.

B. Two Base Category 1 materials (> 85 percent fines) were tested by Reclamation. The NEF size (D15F) for these materials was within Reclamation's guidelines.

C. Foster and Fell's recommendation to perform the NEF test to confirm the NEF size (D15F) for dispersive soils is supported by this research. The NEF size (D15F) for the Many Farms material is less than the NEF size (D15F) provided in Reclamation's design standards. The results from this research project suggest that the NEF size (D15F) for elastic silts should be confirmed as well.

D. The results obtained from this research project are in agreement with Foster and Fell's estimate for the coarsest filter that will seal a concentrated leak for base soils with a D95B < 2.0 mm.

E. One internally unstable material was tested during this research project. The NEF size found during testing for this material was less than the NEF size (D15F) provided in Reclamation's design standards. Additional testing is needed to provide insight into the behavior of additional internally unstable materials.

F. This research project did not test a Reclamation Base Category 3 material (15 to 35 percent fines). Foster and Fell's recommendation to change the fines content for Reclamation Base Category 2 and 3 materials was not examined. Additional testing is needed to verify Foster and Fell's recommendation.

G. The NEF test and the CEF test use downward vertical flow through a hole in the base material to initiate erosion. Downward vertical flow represents one specific flow path and does not simulate all conditions that may be observed in the field. The designer should determine the applicability of the results shown in this report to their particular project.

H. The empirical estimate developed for the coarsest filter that will seal a concentrated leak in the CEF test should not be used when designing new filters. The purpose of the CEF test is to provide a means to evaluate the performance of filters in existing dams that do not satisfy current filter design standards.

References

[1] Bureau of Reclamation, "Protective Filters," *Design Standards No. 13 - Embankment Dams*, Chapter 5, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, October 24, 1994.

[2] Sherard, J.L., and L.P. Dunnigan, "Critical Filter for Impervious Soils," in *Journal of Geotechnical Engineering*, ASCE, 115(7), pp. 927-947.

[3] Foster, M.A., and R. Fell, *Assessing Embankment Dam Filters Which Do Not Satisfy Design Criteria*, UNICIV Report No. R-376, May 1999, University of New South Wales, Sydney, Australia.

[4] Bureau of Reclamation, *Earth Manual*, 3rd Edition, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, 1990.

[5] Sherard, J.L., "Sinkholes in Dams of Coarse, Broadly Graded Soils," in *Thirteenth Congress on Large Dams*, Question 49, R, 2, New Delhi, 1979.

Figure 1 – Erosion Boundaries used for Filter Tests

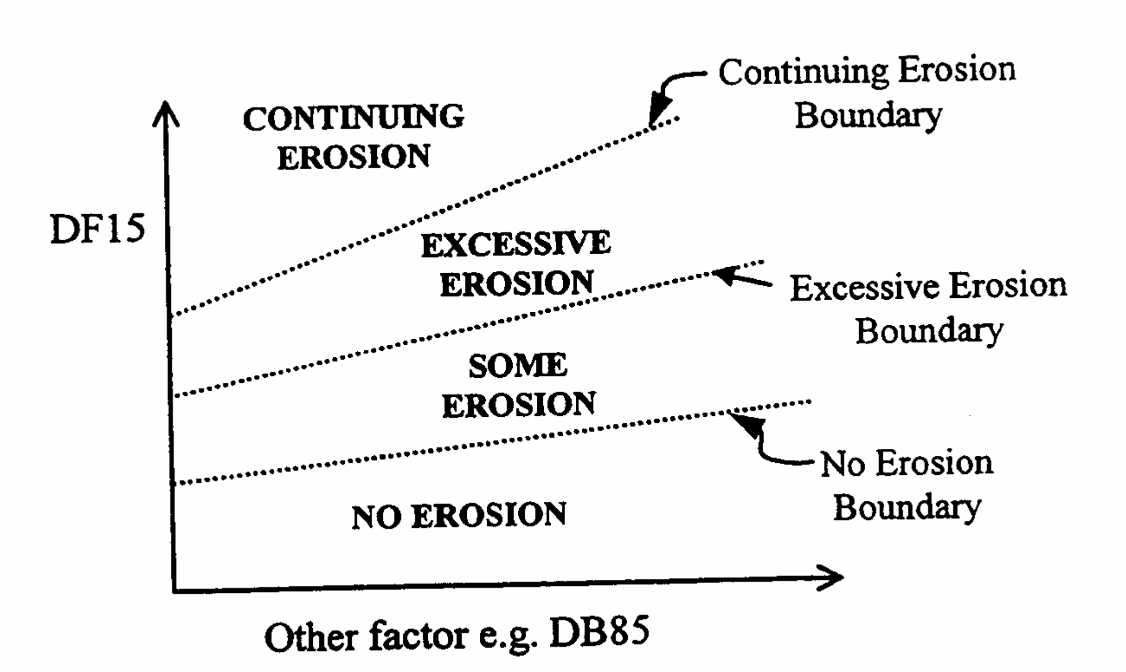


Figure 2 – NEF Test Details

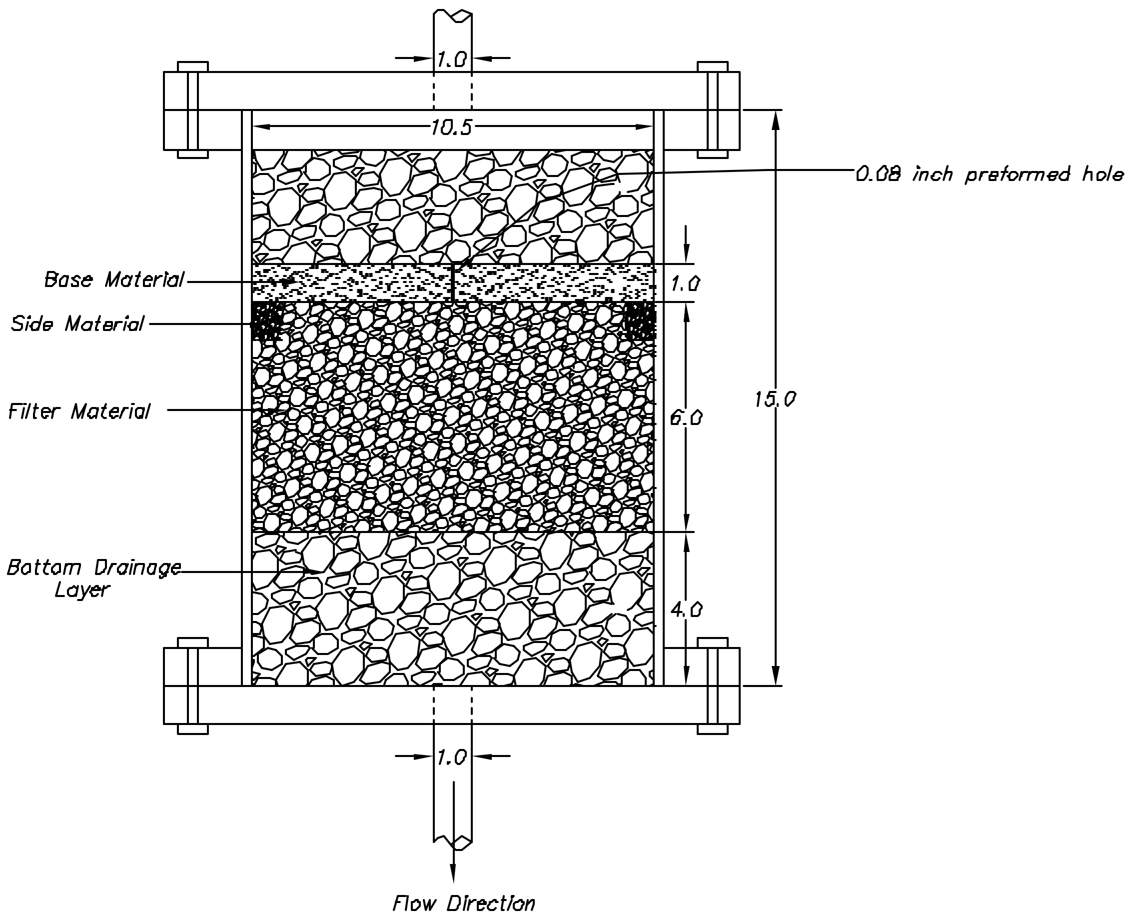
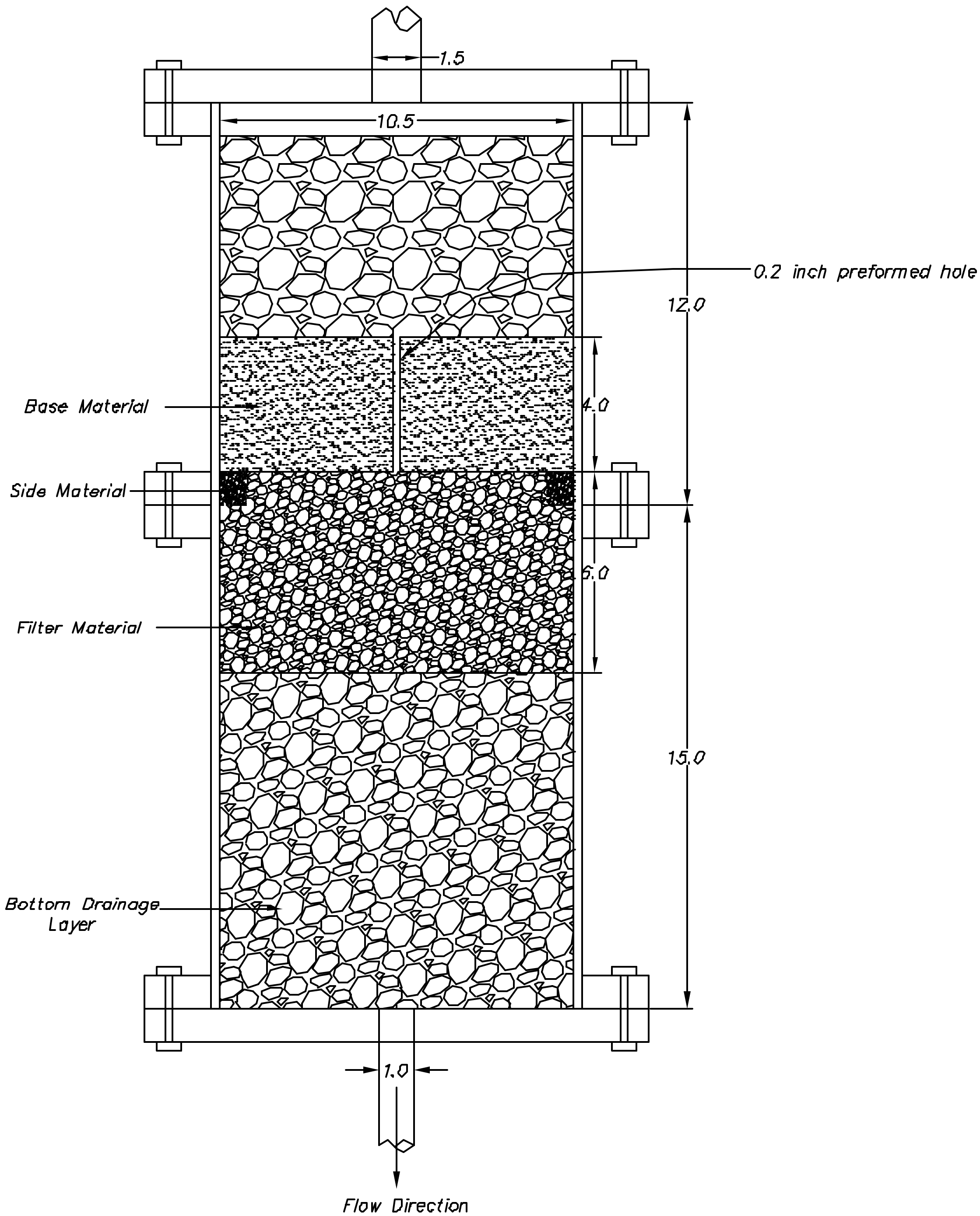


Figure 3 – CEF Test Details



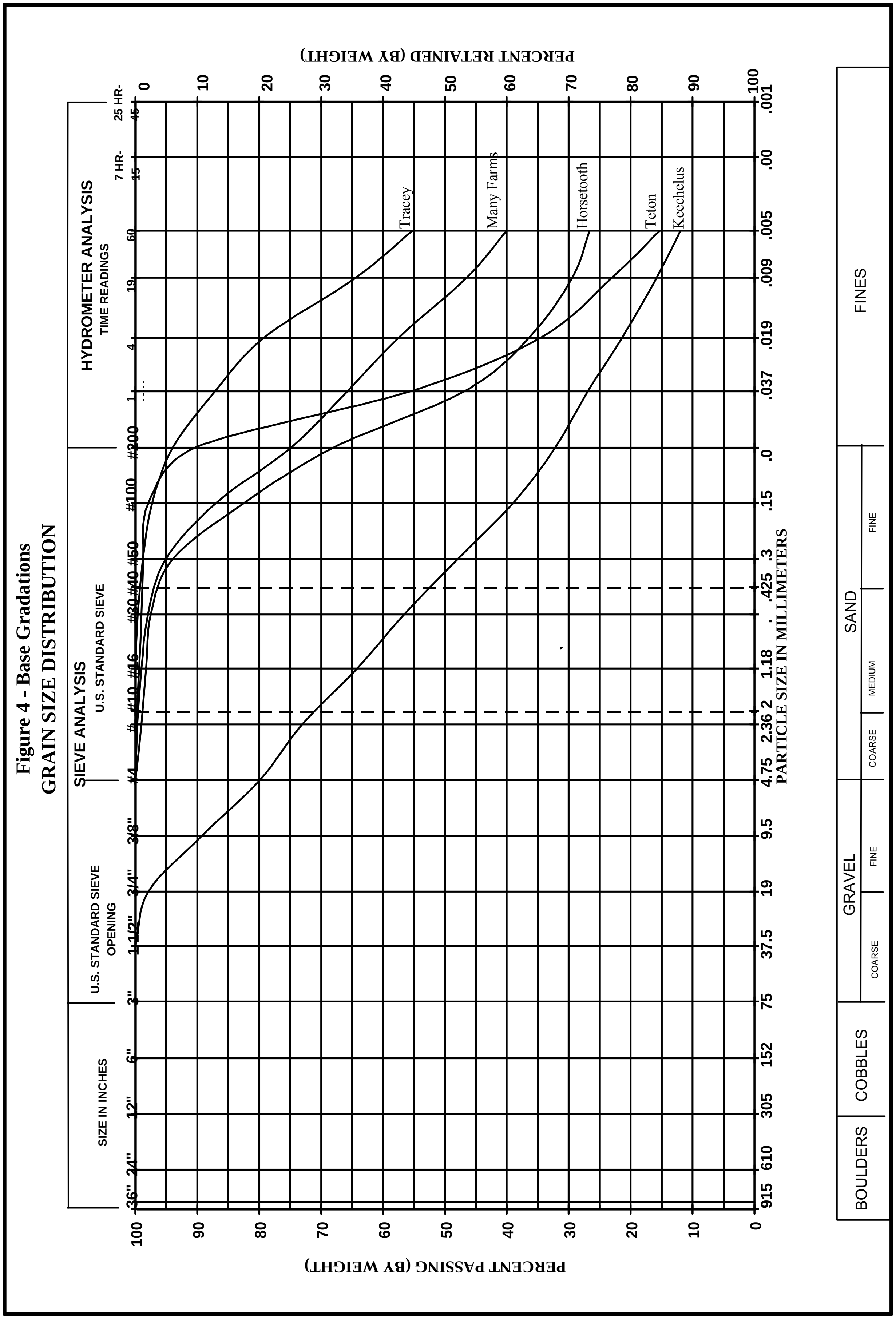


Figure 4 - Base Gradations
GRAIN SIZE DISTRIBUTION

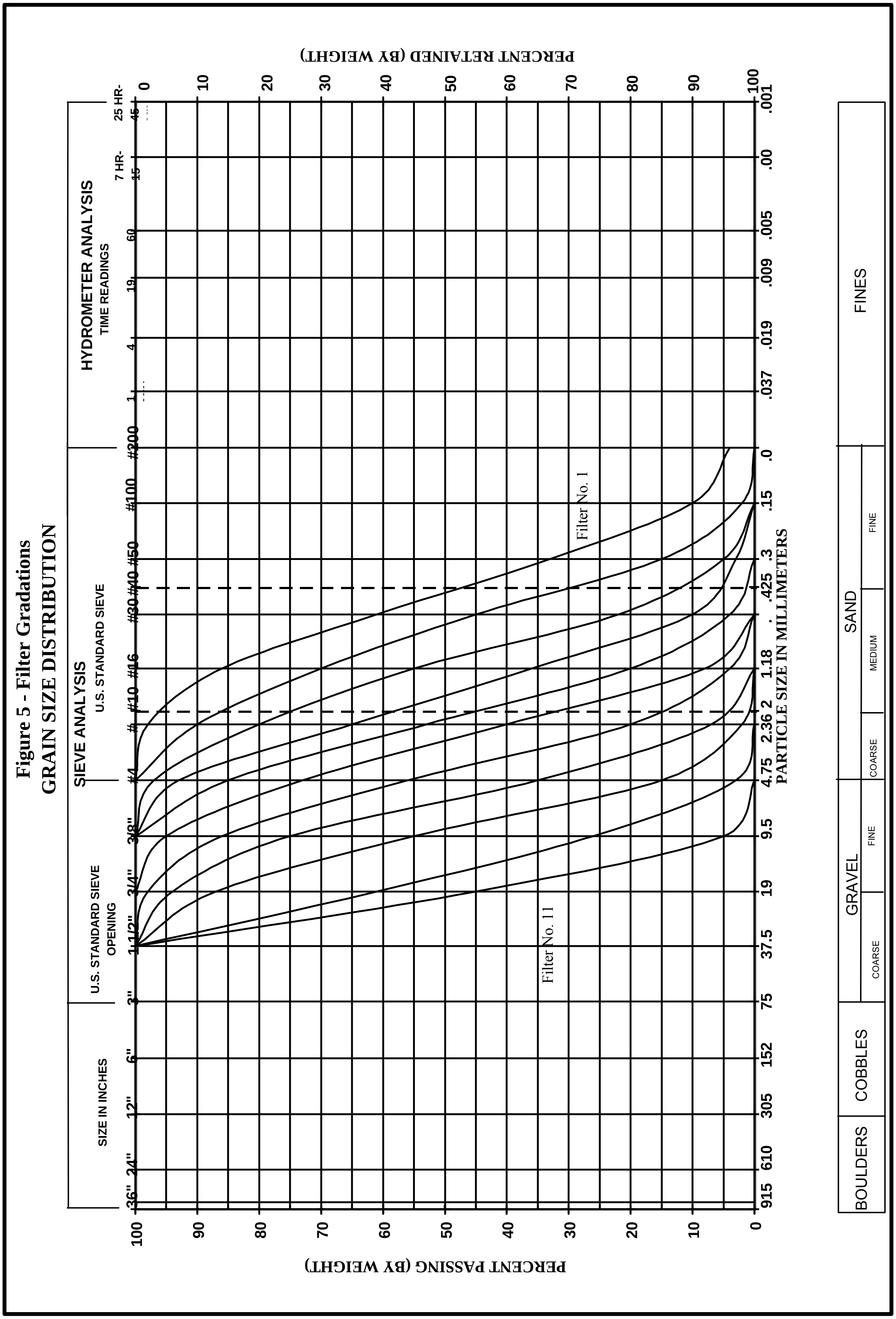


Figure 5 - Filter Gradations

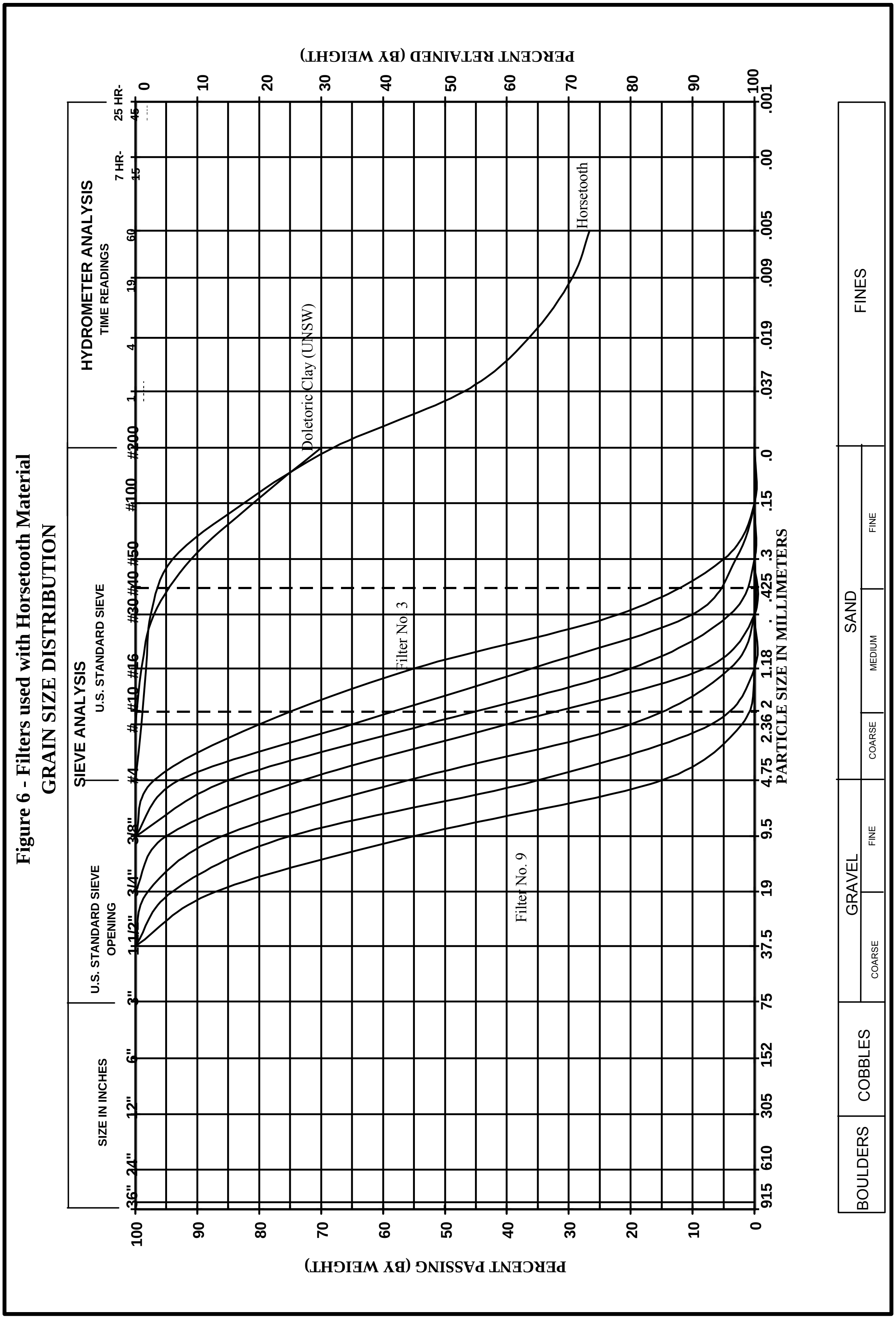


Figure 6 - Filters used with Horsetooth Material

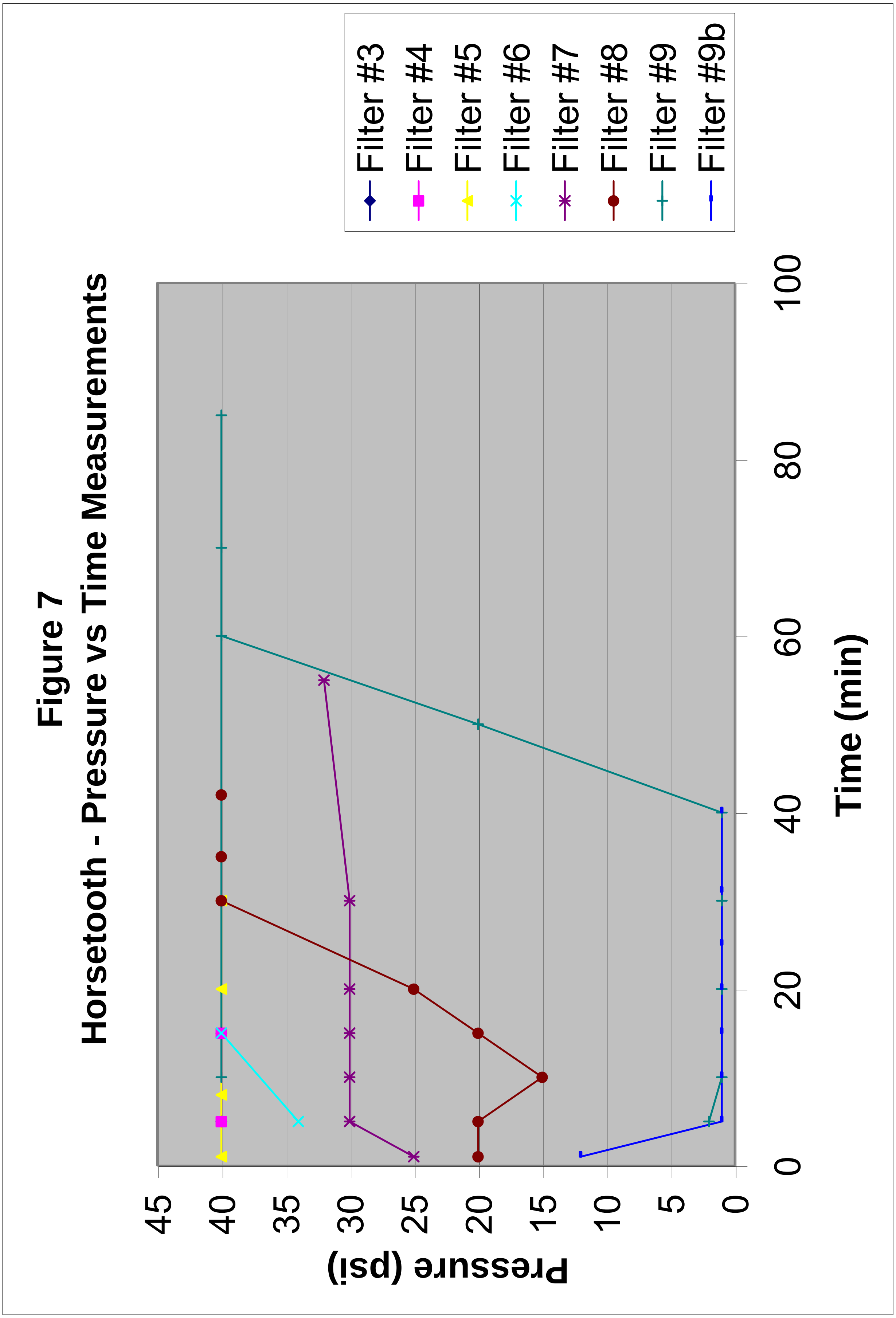


Figure 7
Horsetooth - Pressure vs Time Measurements
Pressure (psi)
Time (min)
0
5
10
15
20
25
30
35
40
45
0
20
40
60
80
100
Filter #3
Filter #4
Filter #5
Filter #6
Filter #7
Filter #8
Filter #9
Filter #9b

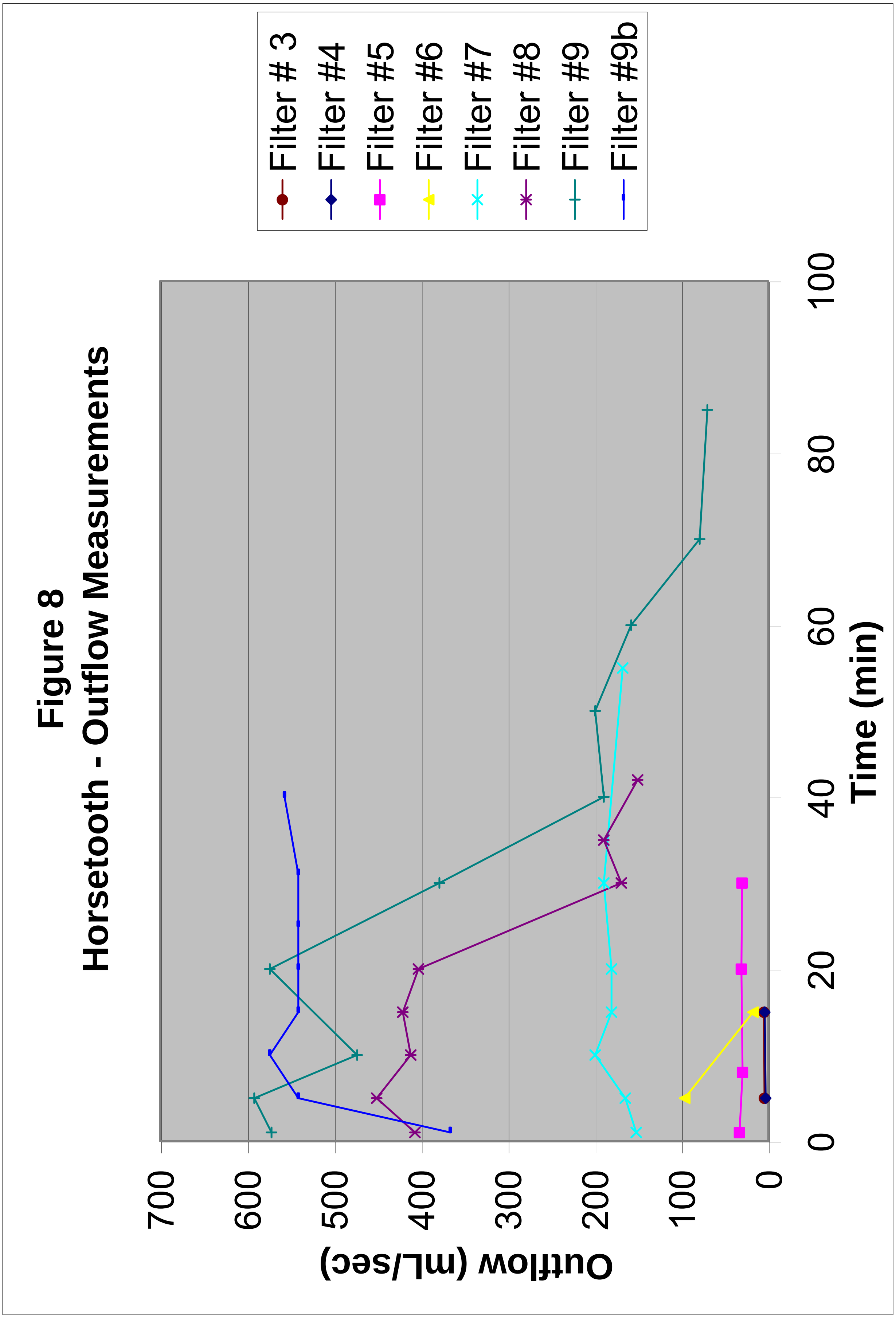


Figure 8
Horsetooth - Outflow Measurements
Outflow (mL/sec)
0
100
200
300
400
500
600
700
Time (min)
0
20
40
60
80
100
Filter # 3
Filter #4
Filter #5
Filter #6
Filter #7
Filter #8
Filter #9
Filter #9b

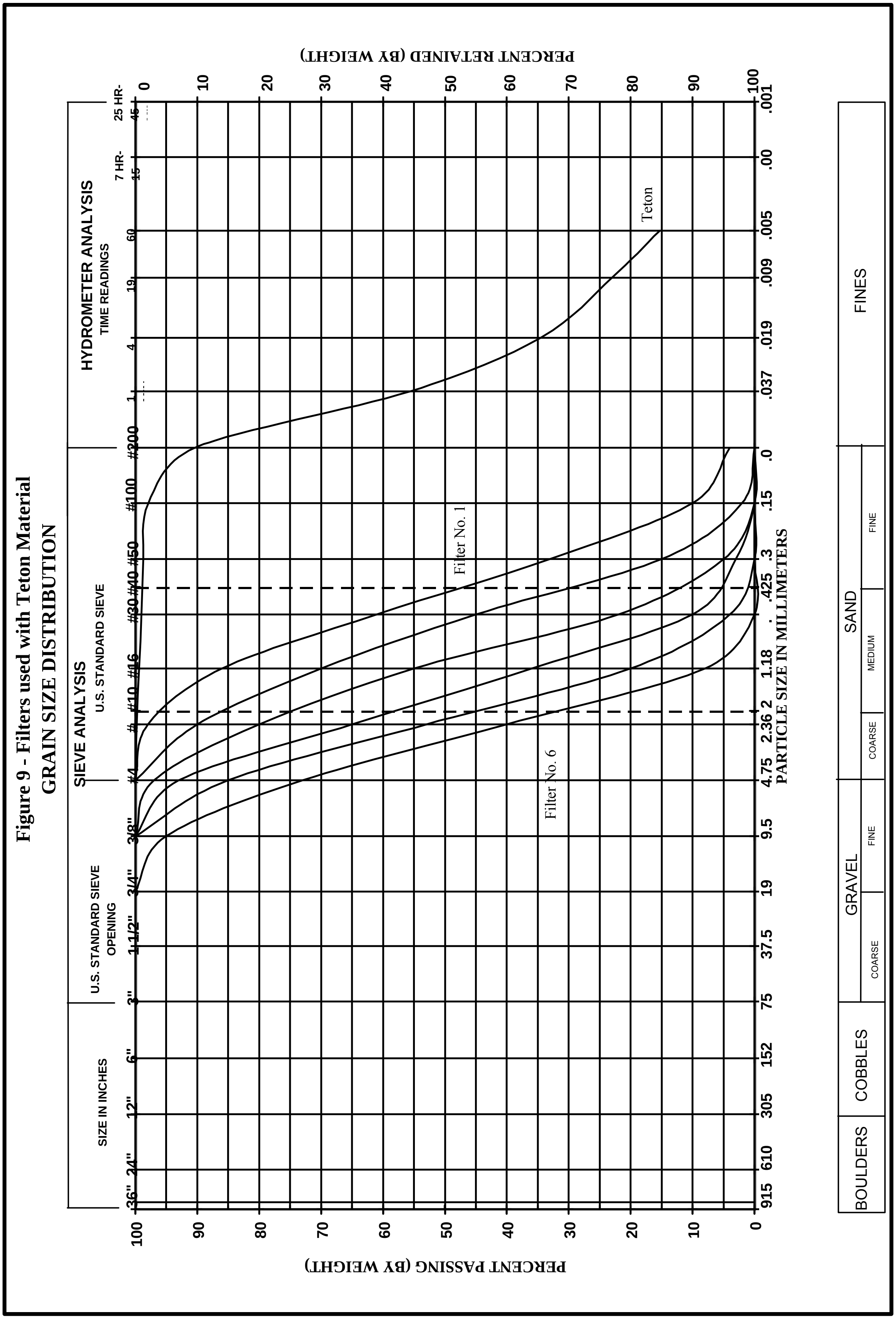


Figure 9 - Filters used with Teton Material

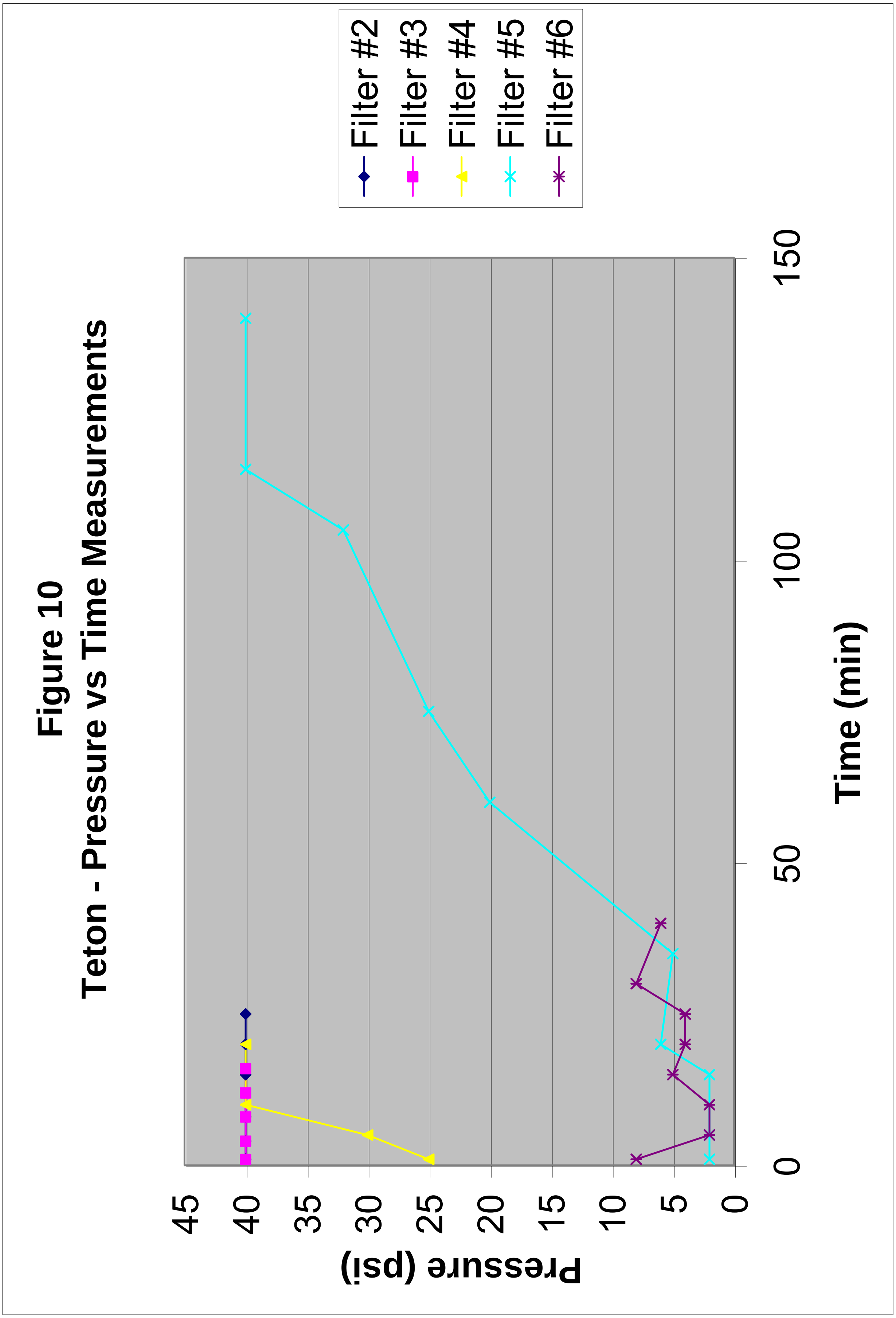


Figure 10
Teton - Pressure vs Time Measurements

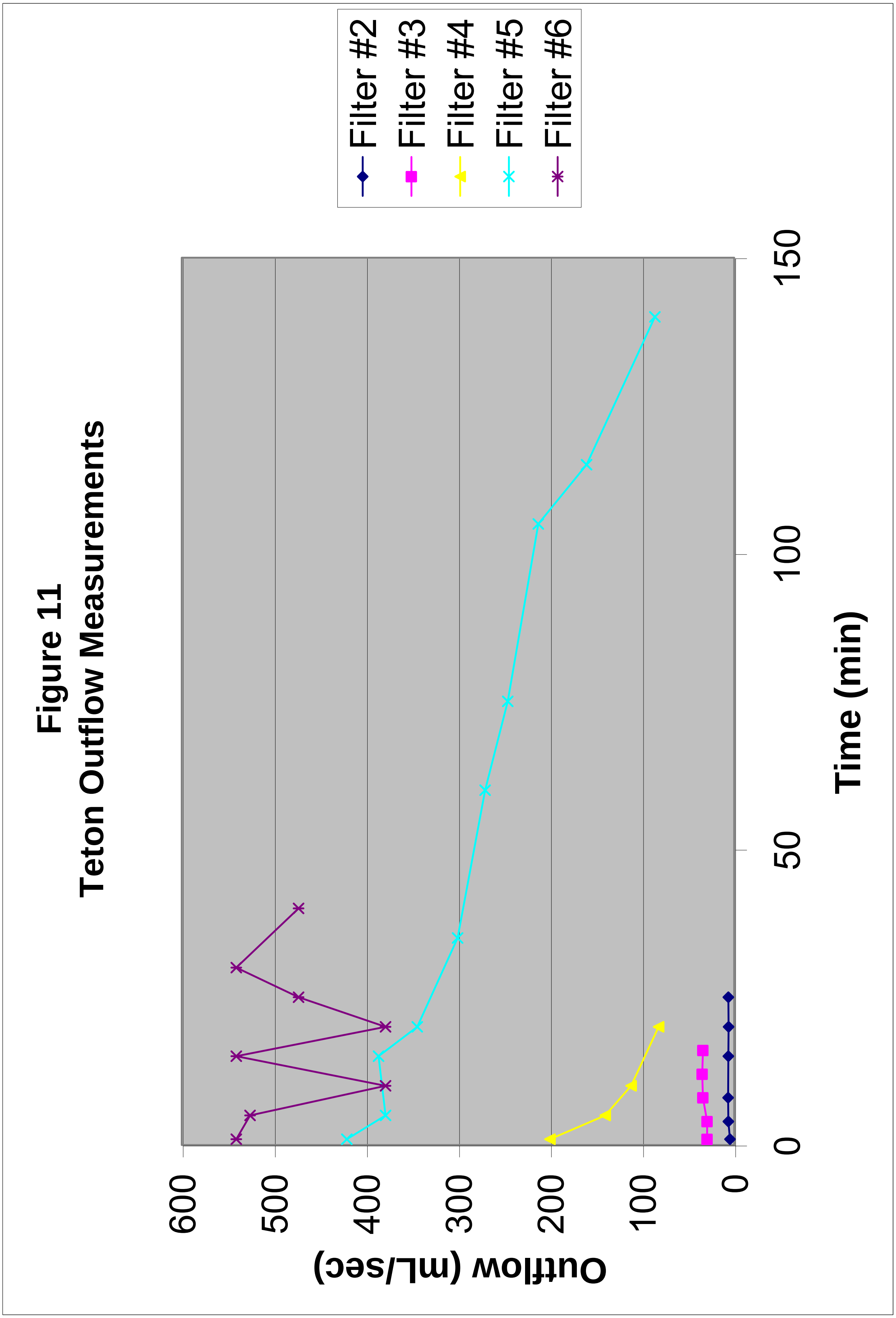
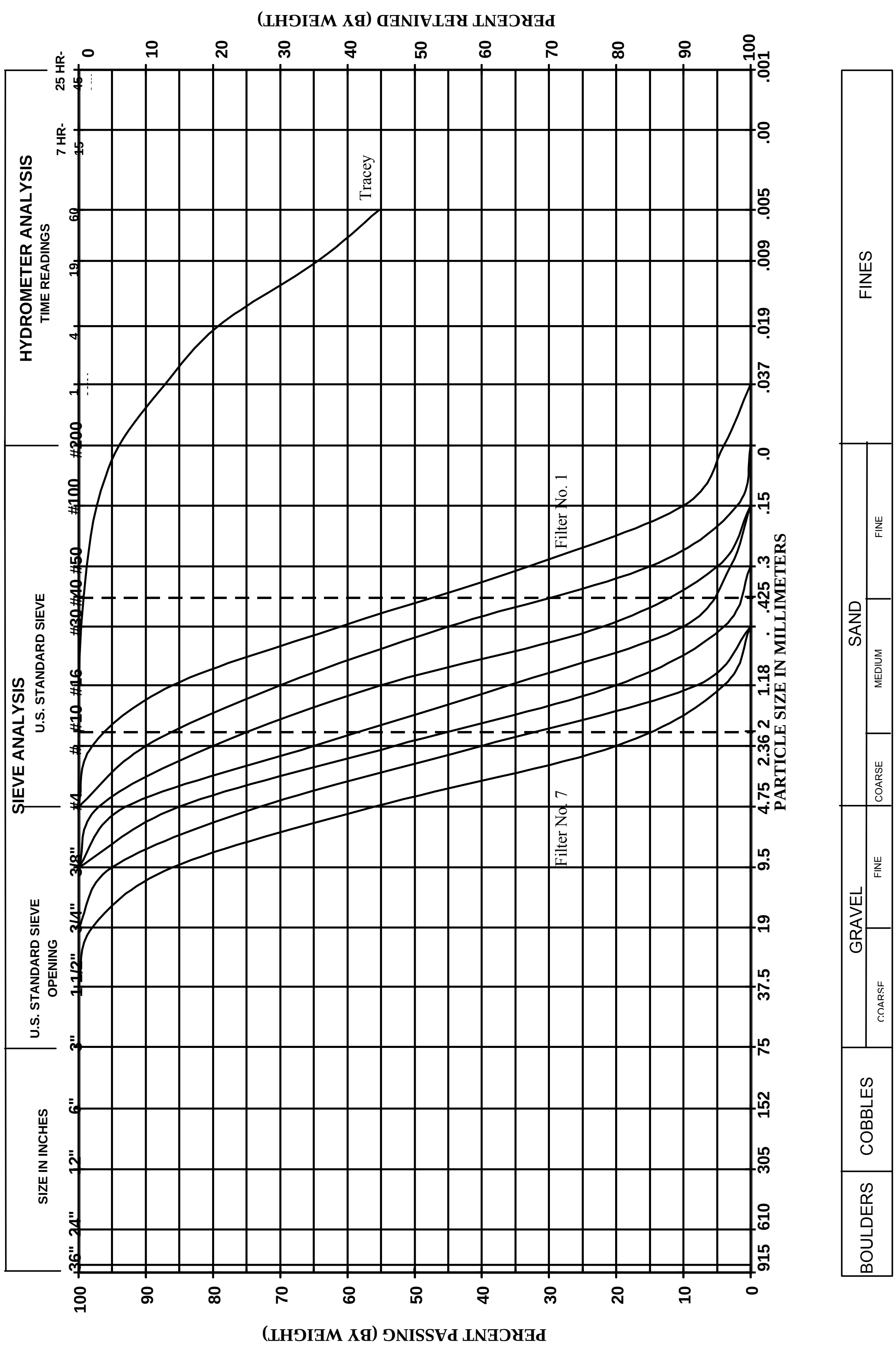


Figure 11
Teton Outflow Measurements
Outflow (mL/sec)
600
500
400
300
200
100
0
0
50
100
150
Time (min)
Filter #2
Filter #3
Filter #4
Filter #5
Filter #6

Figure 12 - Filters used with Tracey Material

GRAIN SIZE DISTRIBUTION



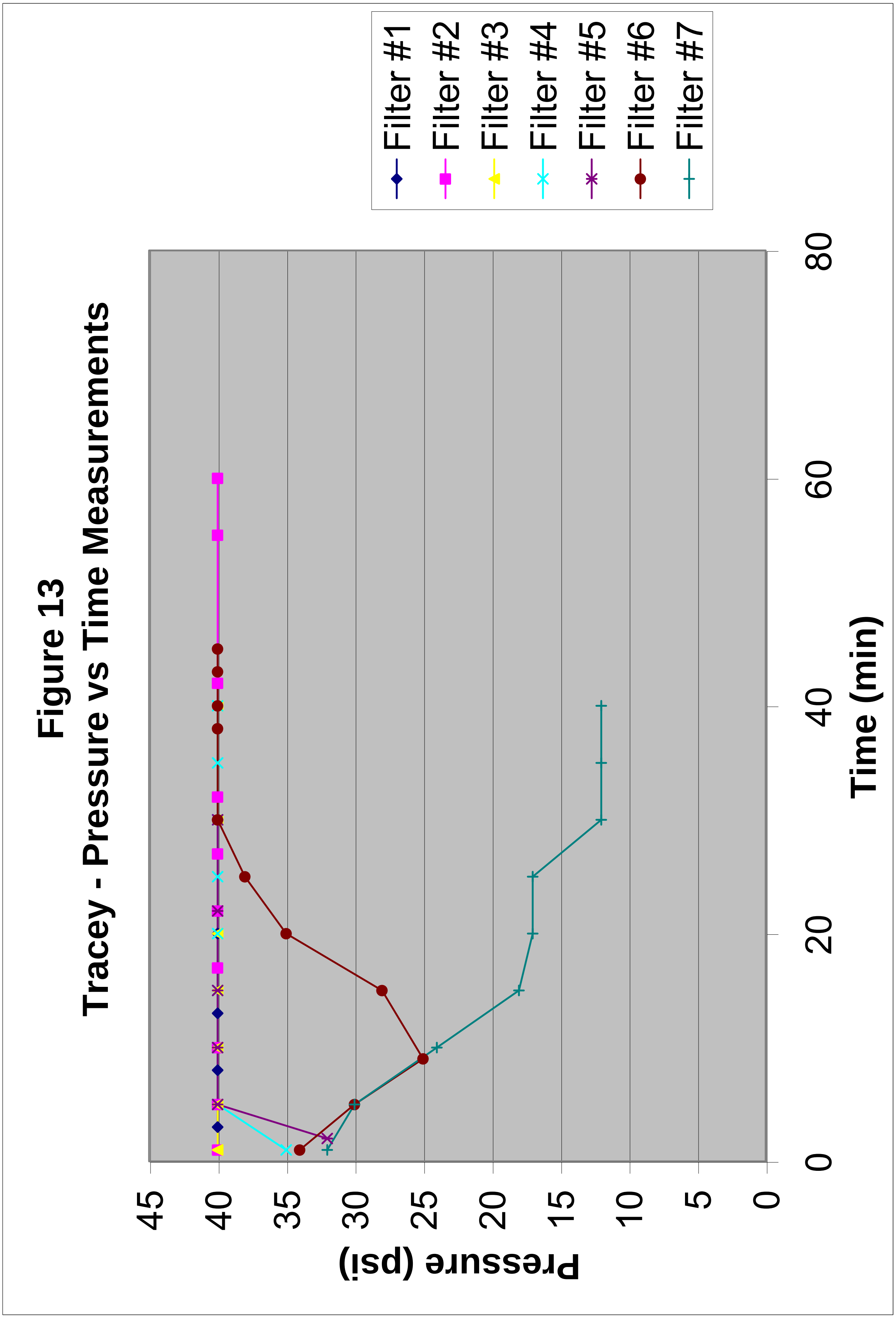


Figure 13
Tracey - Pressure vs Time Measurements
Pressure (psi)
Time (min)
0
5
10
15
20
25
30
35
40
45
0
20
40
60
80
Filter #1
Filter #2
Filter #3
Filter #4
Filter #5
Filter #6
Filter #7

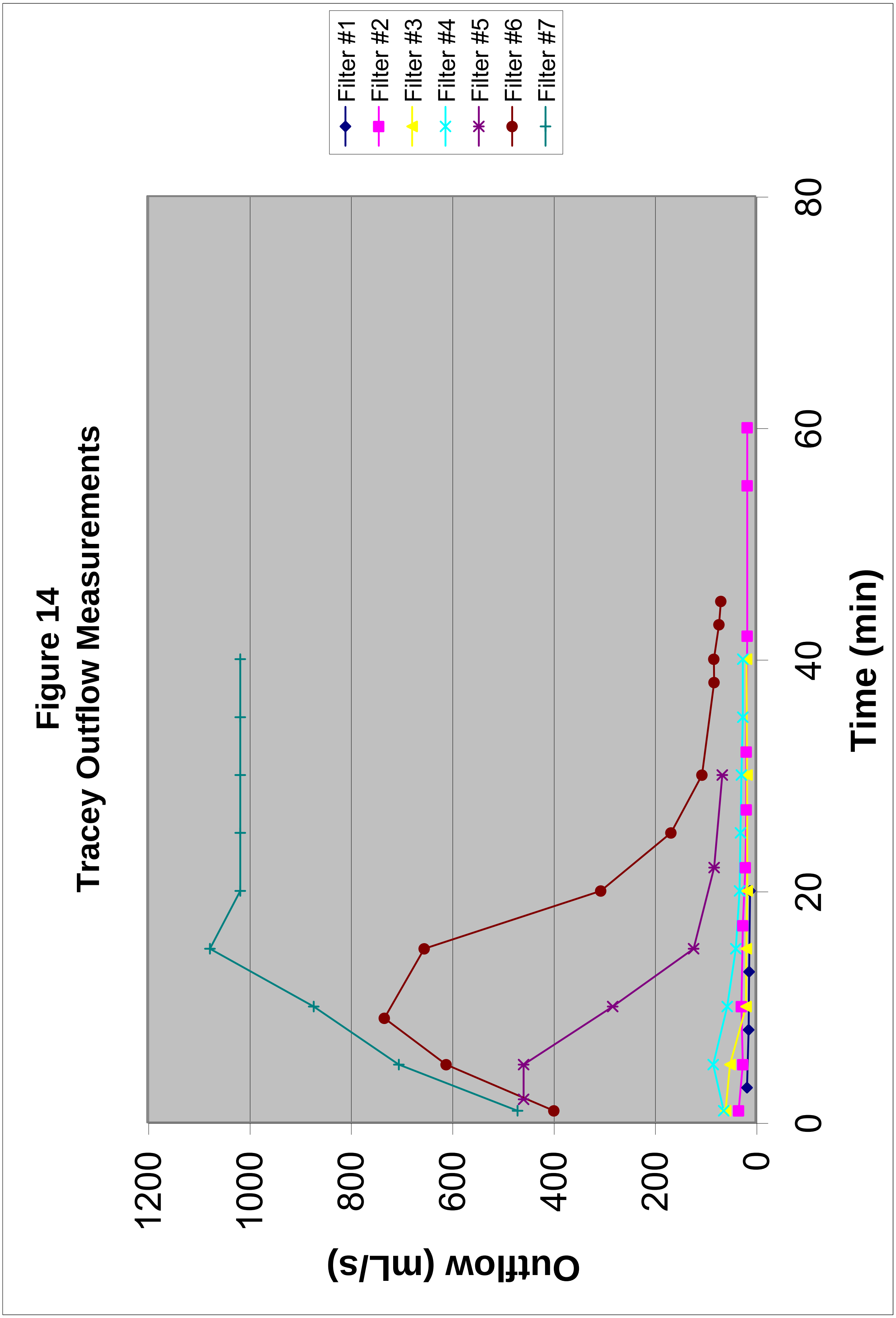


Figure 14
Tracey Outflow Measurements
Outflow (mL/s)
Time (min)
1200
1000
800
600
400
200
0
0
20
40
60
80
Filter #1
Filter #2
Filter #3
Filter #4
Filter #5
Filter #6
Filter #7

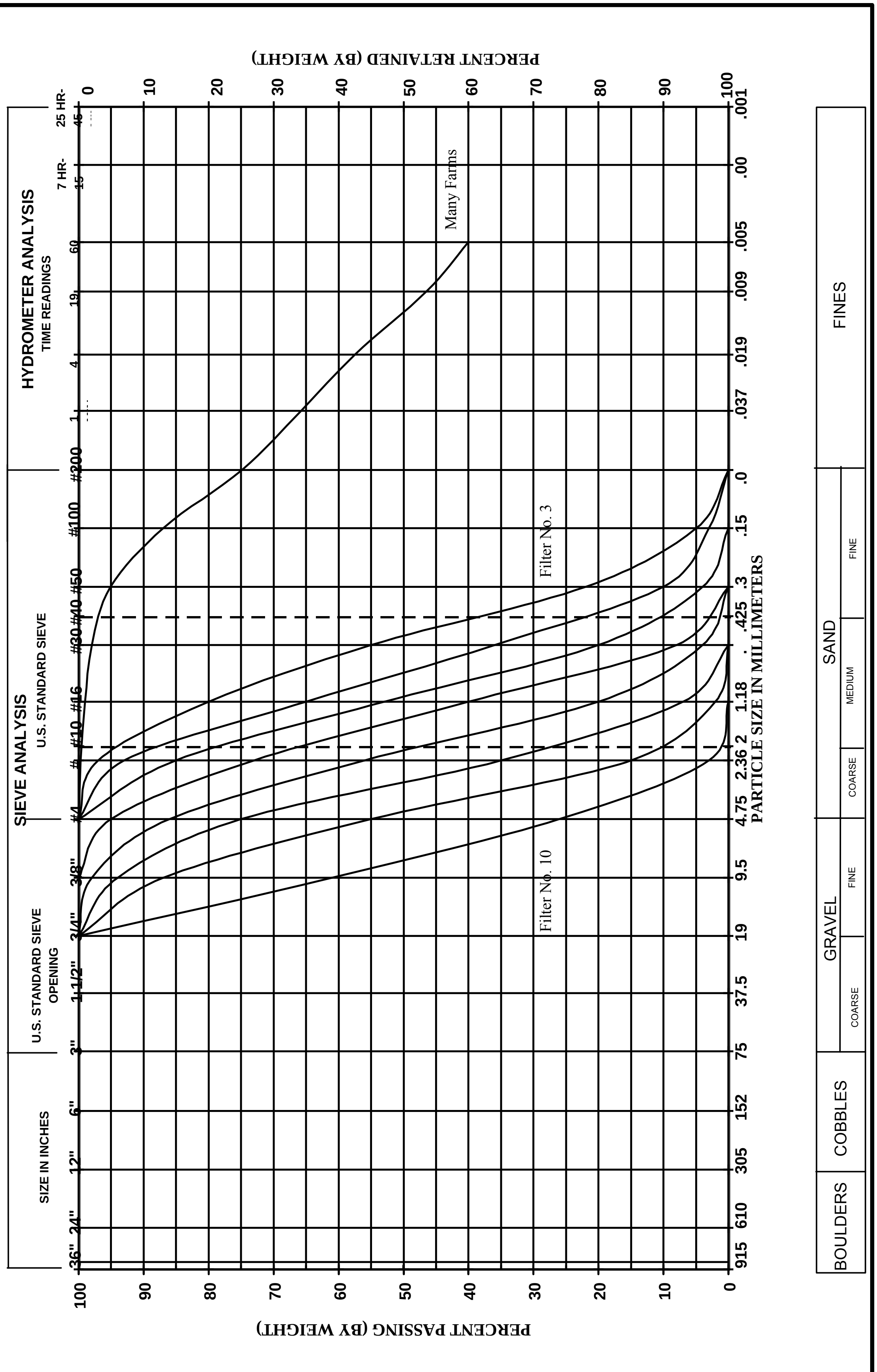


Figure 15 - Filters used with Many Farms Material

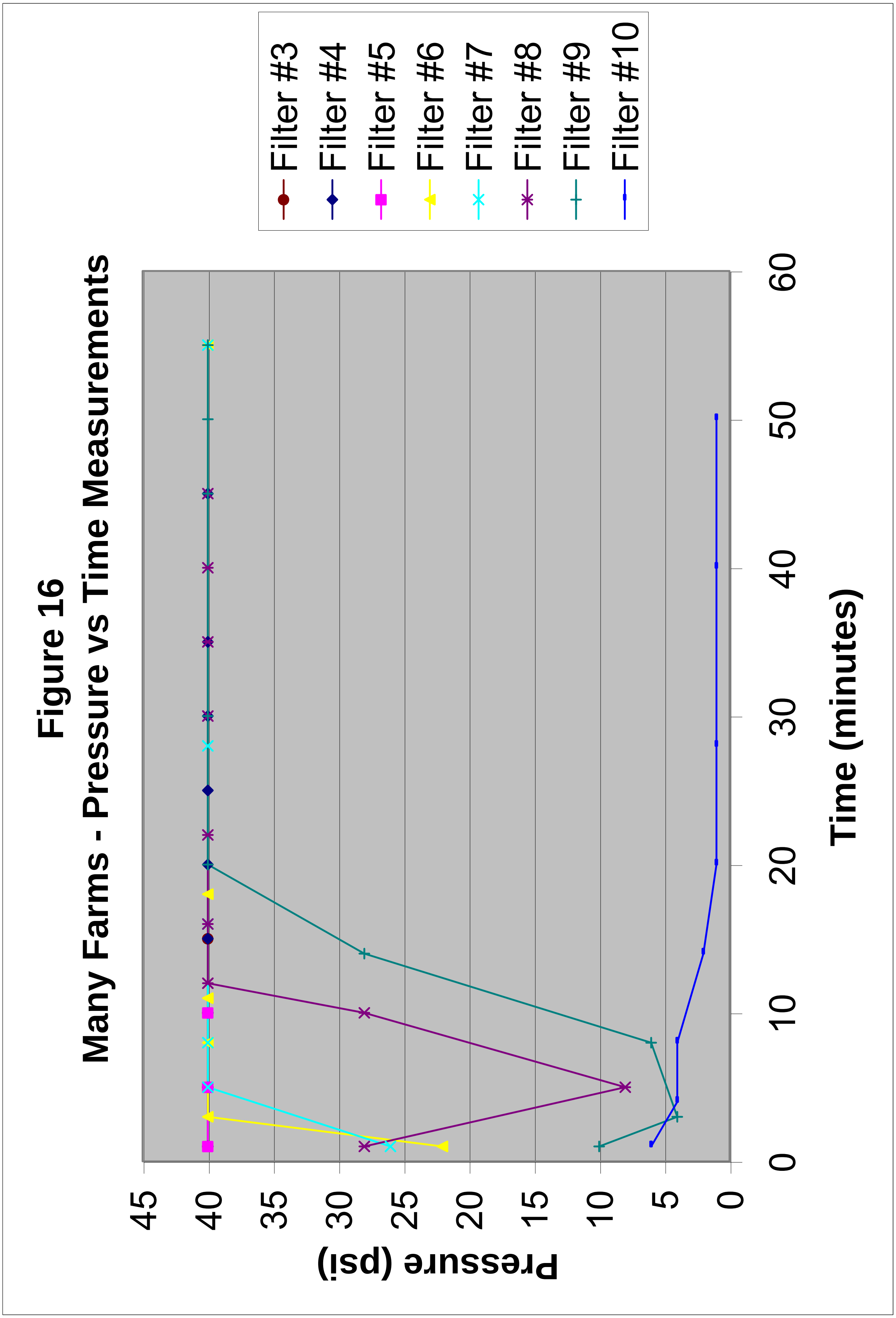


Figure 16
Many Farms - Pressure vs Time Measurements
Pressure (psi)
Time (minutes)
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
Filter #3
Filter #4
Filter #5
Filter #6
Filter #7
Filter #8
Filter #9
Filter #10

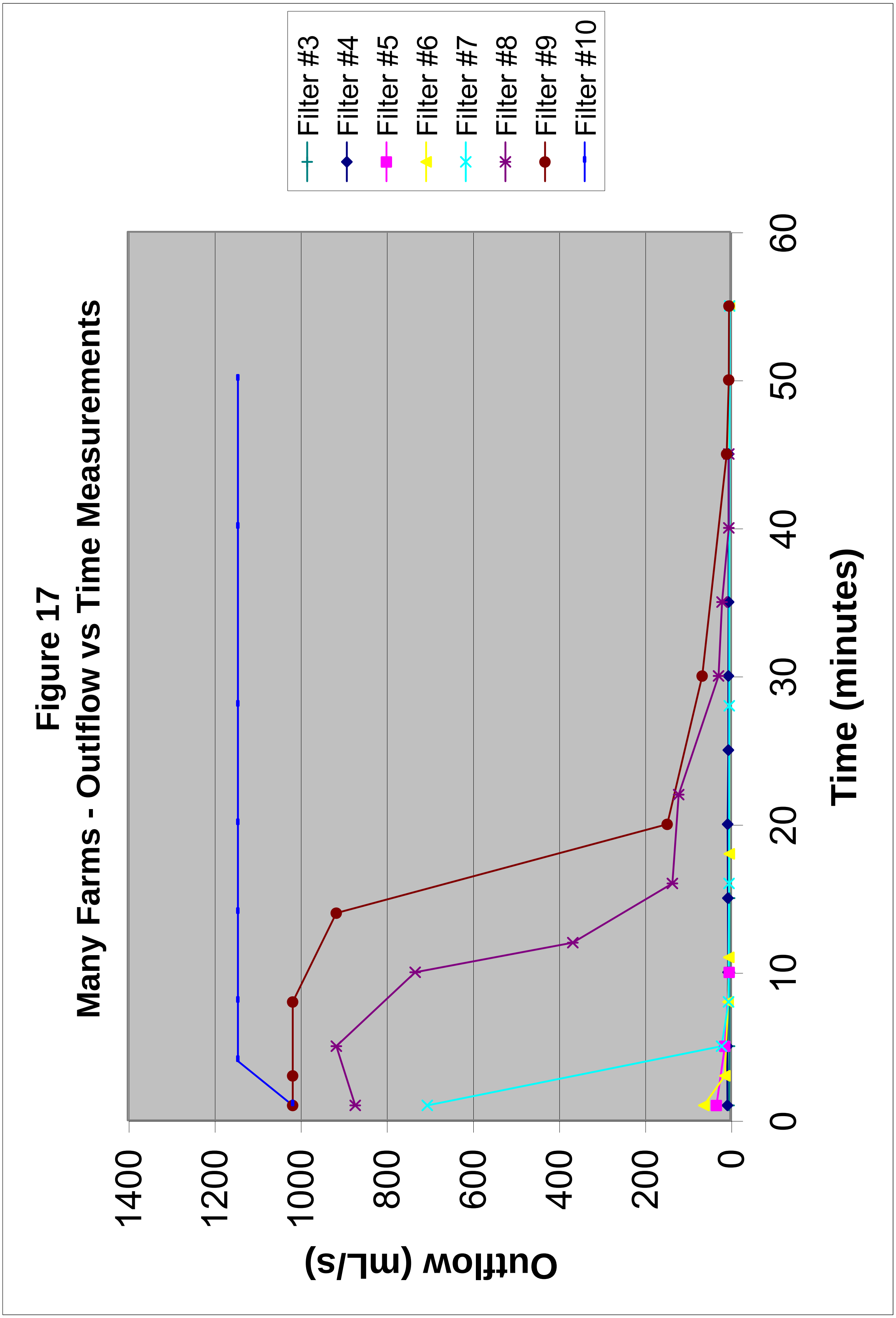
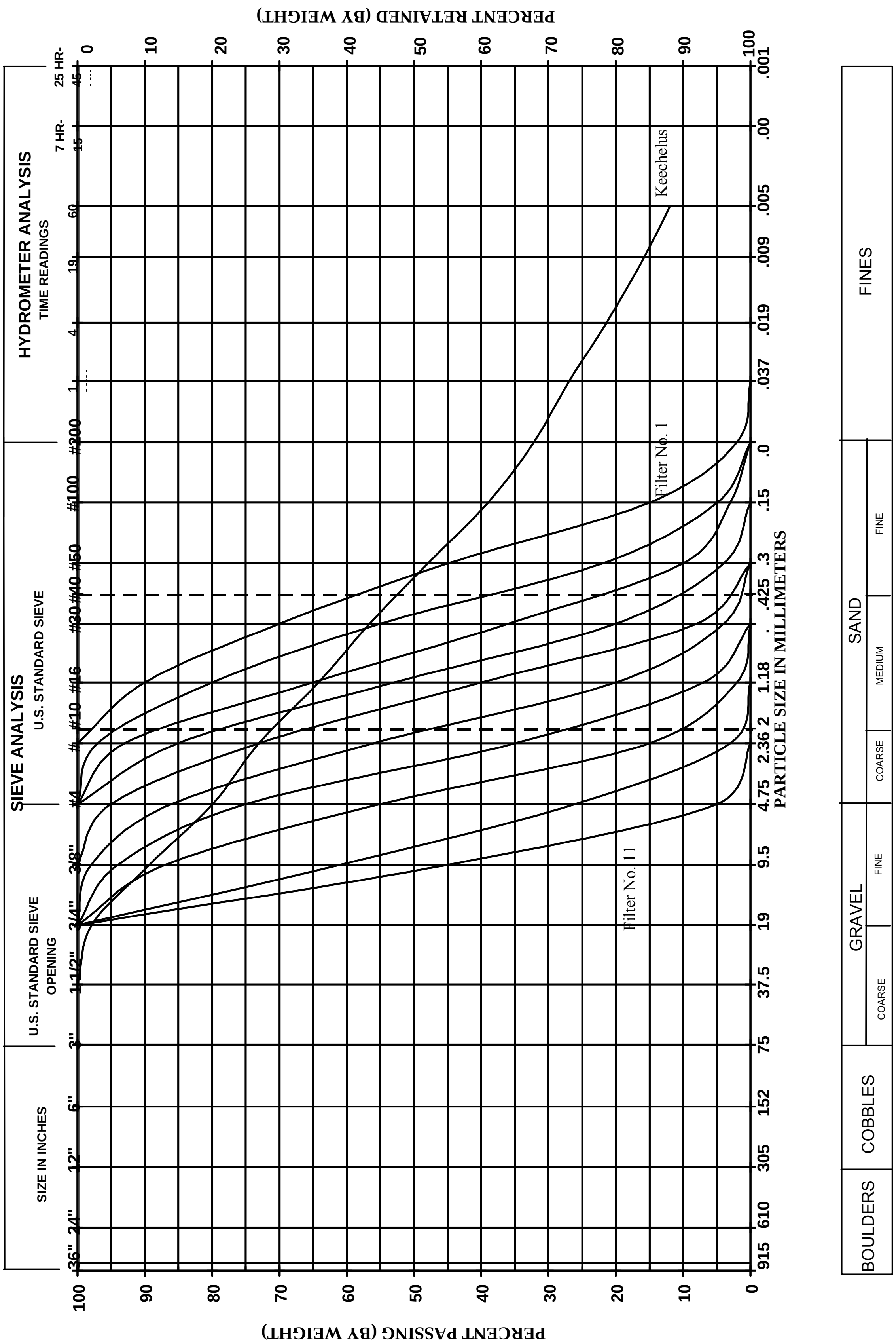


Figure 17
Many Farms - Outflow vs Time Measurements
Outflow (mL/s)
Time (minutes)
0
200
400
600
800
1000
1200
1400
0
10
20
30
40
50
60
Filter #3
Filter #4
Filter #5
Filter #6
Filter #7
Filter #8
Filter #9
Filter #10

Figure 18 - Filters used with Keechelus Material

GRAIN SIZE DISTRIBUTION



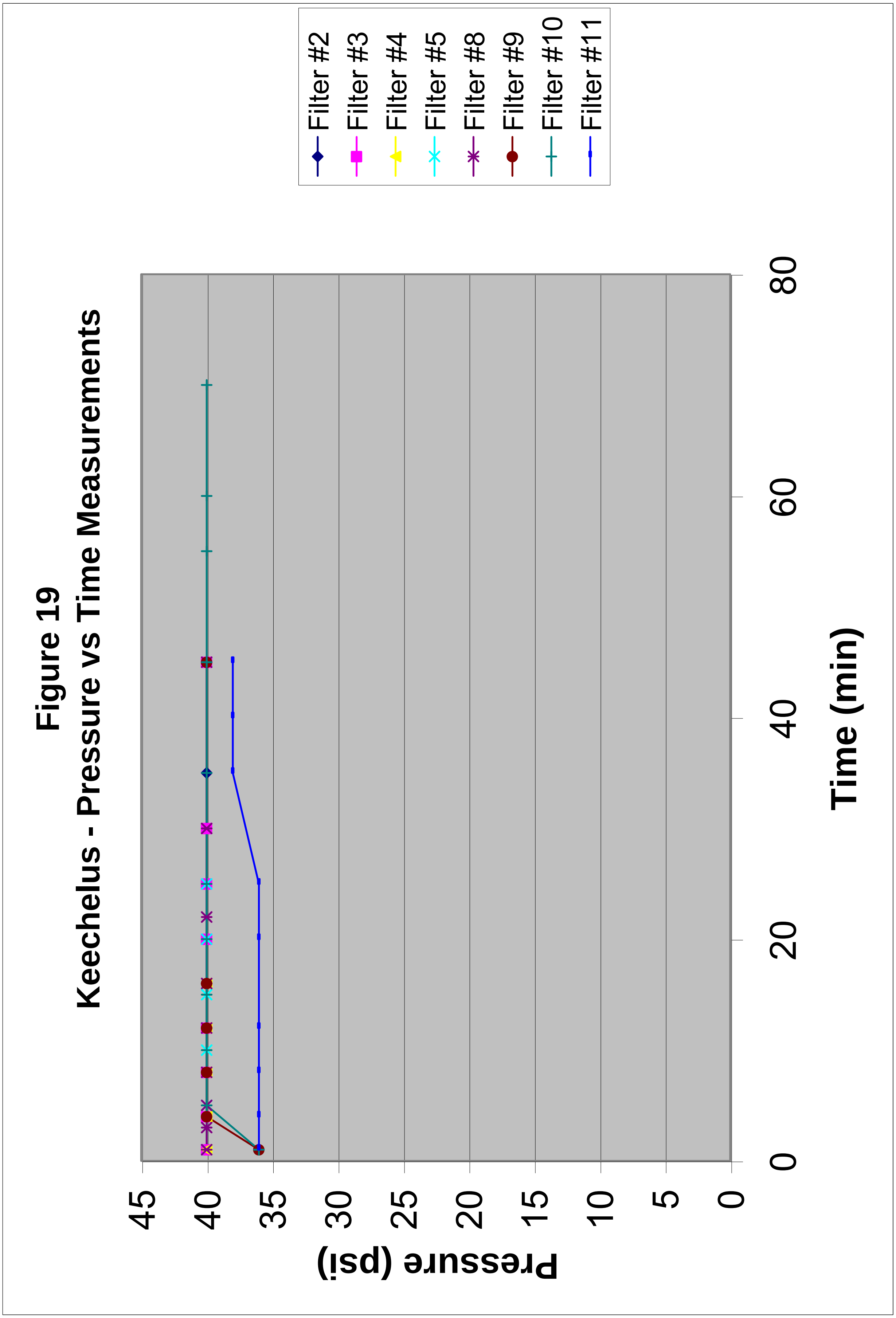


Figure 19
Keechelus - Pressure vs Time Measurements
Pressure (psi)
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
Time (min)
Filter #2
Filter #3
Filter #4
Filter #5
Filter #8
Filter #9
Filter #10
Filter #11

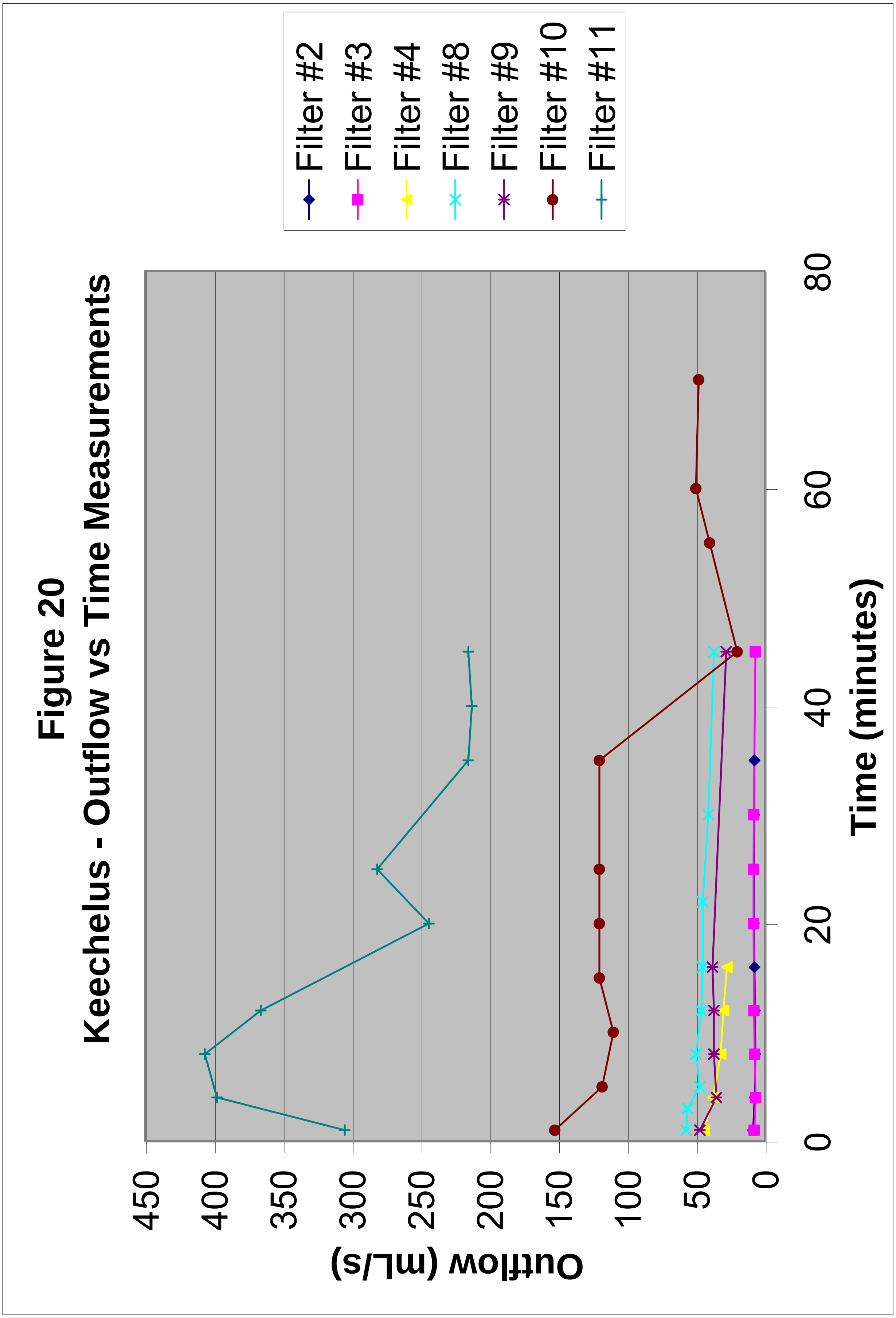


Figure 20
Keechelus - Outflow vs Time Measurements
Outflow (mL/s)
450
400
350
300
250
200
150
100
50
0
0
20
40
60
80
Time (minutes)
Filter #2
Filter #3
Filter #4
Filter #8
Filter #9
Filter #10
Filter #11

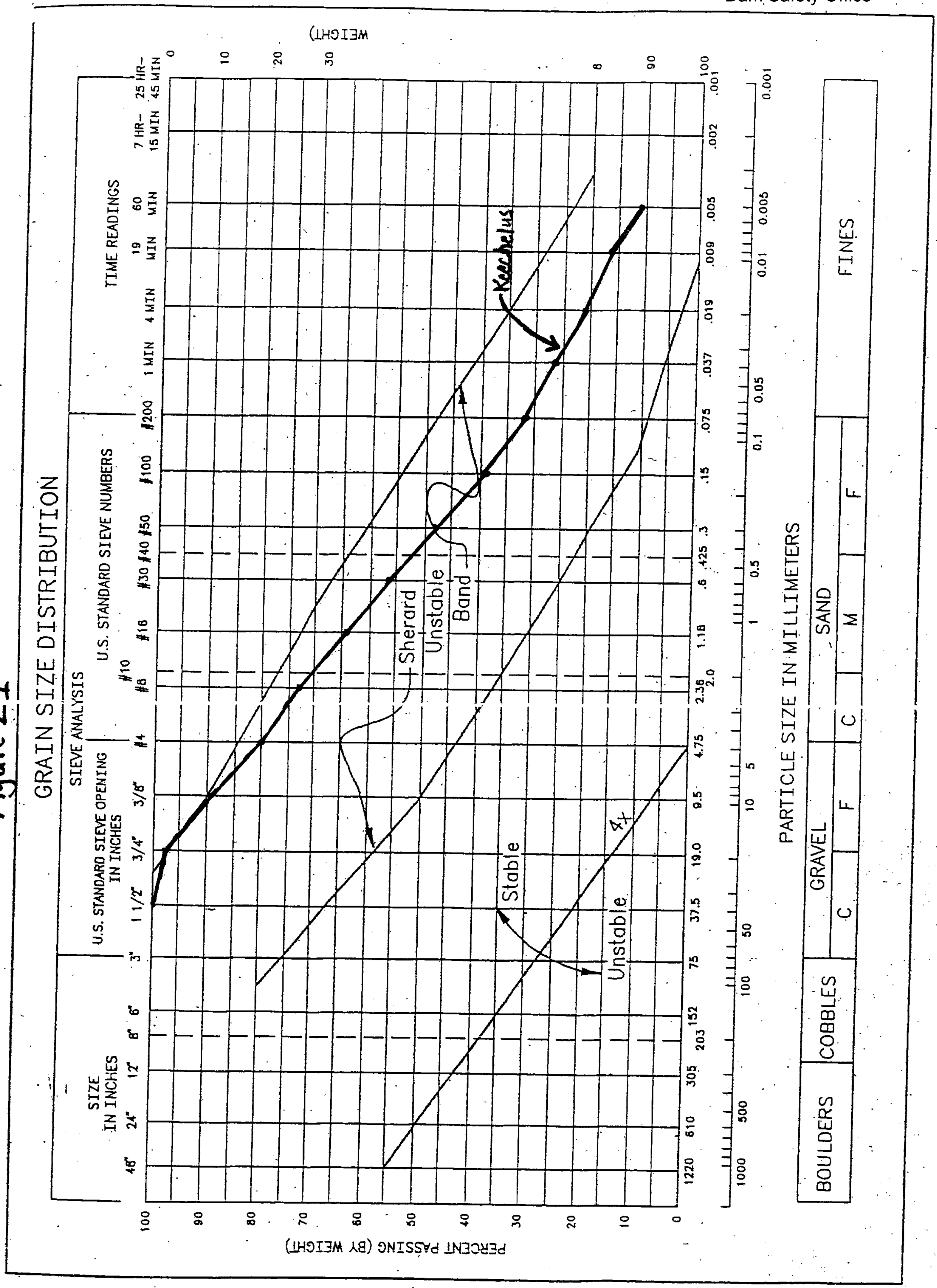

GRAIN SIZE DISTRIBUTION
SIEVE ANALYSIS
TIME READINGS
25 HR-45 MIN
7 HR-15 MIN
60 MIN
19 MIN
4 MIN
1 MIN
U.S. STANDARD SIEVE NUMBERS
#200
#100
#50
#40
#30
#16
#10
#8
#4
U.S. STANDARD SIEVE OPENING IN INCHES
3/8"
3/4"
1 1/2"
3"
SIZE IN INCHES
6"
8"
12"
24"
48"
PERCENT PASSING (BY WEIGHT)
100
90
80
70
60
50
40
30
20
10
0
.001
.002
.005
.009
.019
.037
.075
.15
.3
.425
.6
1.18
2.0
2.36
4.75
9.5
19.0
37.5
75
152
203
305
610
1220
PARTICLE SIZE IN MILLIMETERS
0.001
0.005
0.01
0.05
0.1
0.5
1
5
10
50
100
500
1000
FINES
SAND
F
M
C
GRAVEL
F
C
COBBLES
BOULDERS
Keechelus
Sherard Unstable Band
Stable
Unstable
4x

Figure 21

Appendix 1

Base Soil	Filter #	Test Type	DF15 (mm)	D, Base (lb/ft^3)	MC (%)	% of max standard proctor	D, Filter (lb/ft^3)	Time (min)	Initial Hole Diameter (mm)	Finial Hole Diameter (mm)	Test Result
Horsetooth	3	NEF	0.49	114.1	14.0	99.2	112.00	30	2.00	2.0	NE
	4	NEF	0.70	115.1	13.0	100.1	109.00	20	2.00	2.0	NE
	5	NEF	1.00	114.0	14.1	99.1	114.20	60	2.00	2.0	SE
	6	CEF	1.40	114.8	13.4	99.8	109.90	20	4.75	4.75	SE
	7	CEF	2.00	113.8	14.4	99.0	114.20	55	4.75	7.00	SE
	8	CEF	3.00	113.1	14.9	98.3	112.00	42	4.75	11.00	SE
	9	CEF	4.80	113.5	14.3	98.7	111.30	85	4.75	see picture	CE
	9b	CEF	4.80	113.4	15.0	98.6	114.87	40	4.75	see picture	CE

Photo 1 – NEF Test, Horsetooth Material, Filter #3

Photo 2 – NEF Test, Horsetooth Material, Filter #4

Photo 3 – NEF Test, Horsetooth Material, Filter #5

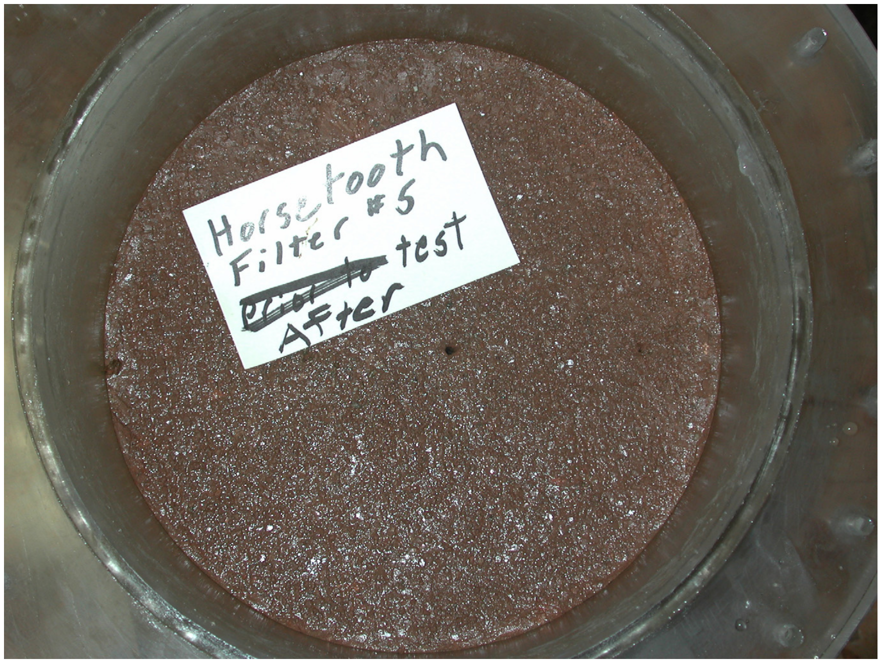


Photo 4 – CEF Test, Horsetooth Material, Filter #6

\Photo 5 – CEF Test, Horsetooth Material, Filter #7

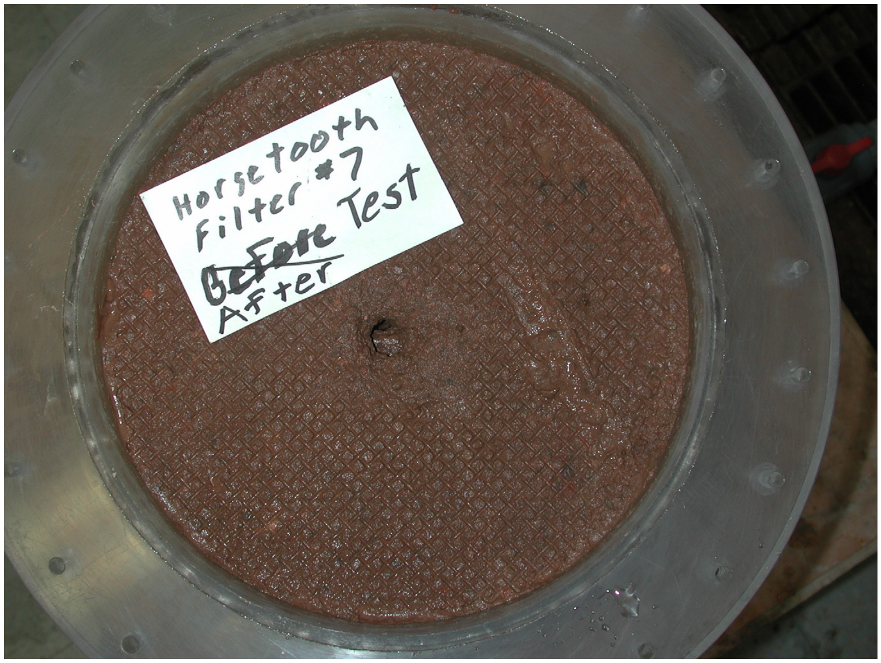


Photo 6 – CEF Test, Horsetooth Material, Filter #8

Photo 7 – CEF Test, Horsetooth Material, Filter #9

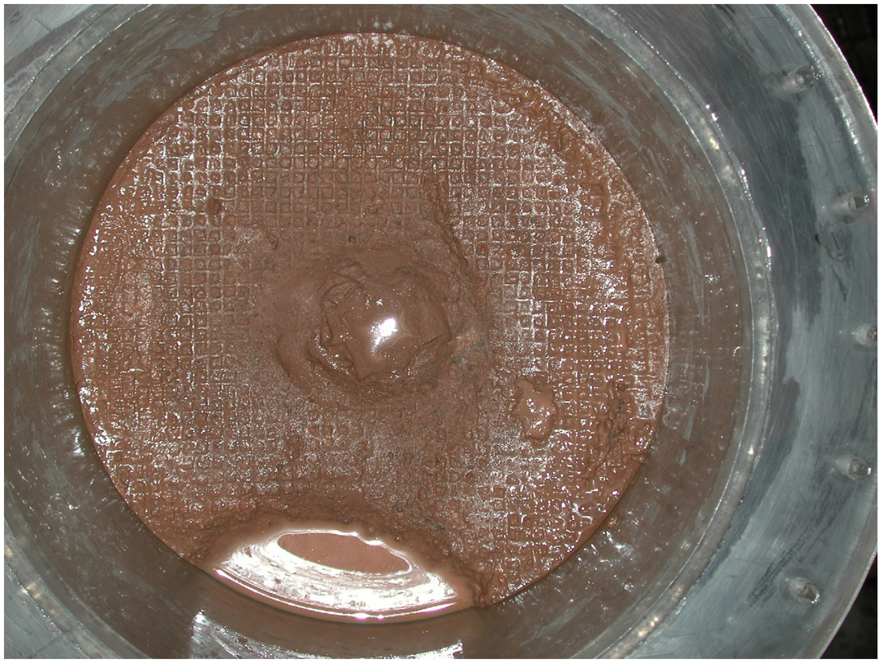
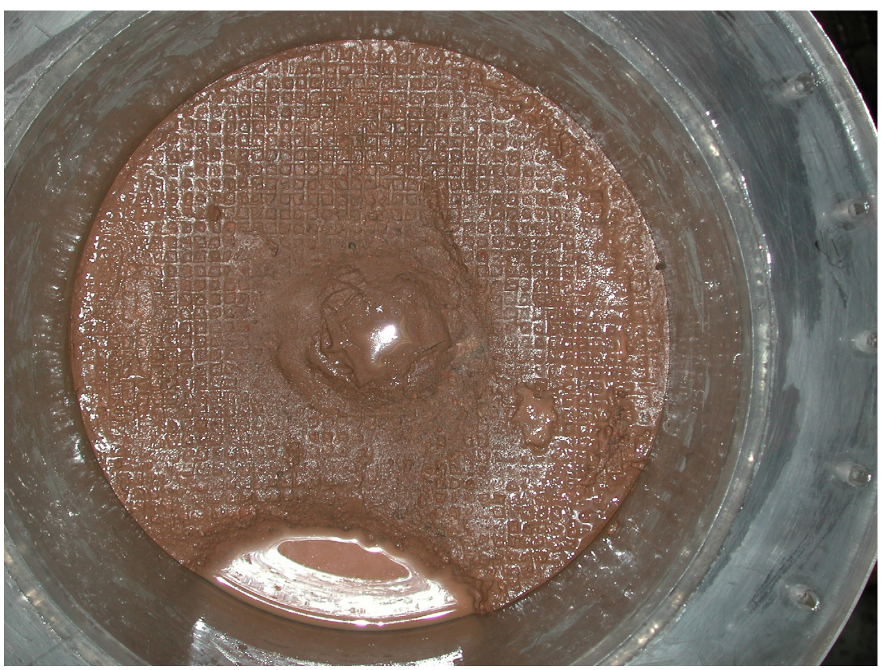


Photo 8 – CEF Test, Horsetooth Material, Filter #9B



Appendix 2

Base Soil	Filter #	Test Type	DF15 (mm)	D, Base (lb/ft^3)	MC (%)	% of max standard proctor	D, Filter (lb/ft^3)	Time (min)	Initial Hole Diameter (mm)	Finial Hole Diameter (mm)	Test Result
Teton	1	NEF	0.18		NR	NR		NR	2.00	collapsed	NE
	2	NEF	0.30		16.8	98.9		25	2.00	2	SE
	3	NEF	0.49		17.4	98.1		16	2.00	2	SE
	4	CEF	0.70		17.3	98.4		20	4.75	7(avg)	SE
	5	CEF	1.00		17	95.3		140	4.75	13	SE
	6	CEF	1.40		17	98.7		40	4.75	38	CE

Photo 1 – NEF Test, Teton Material, Filter #2

Photo 2 – NEF Test, Teton Material, Filter #3

Photo 3 – CEF Test, Teton Material, Filter #4

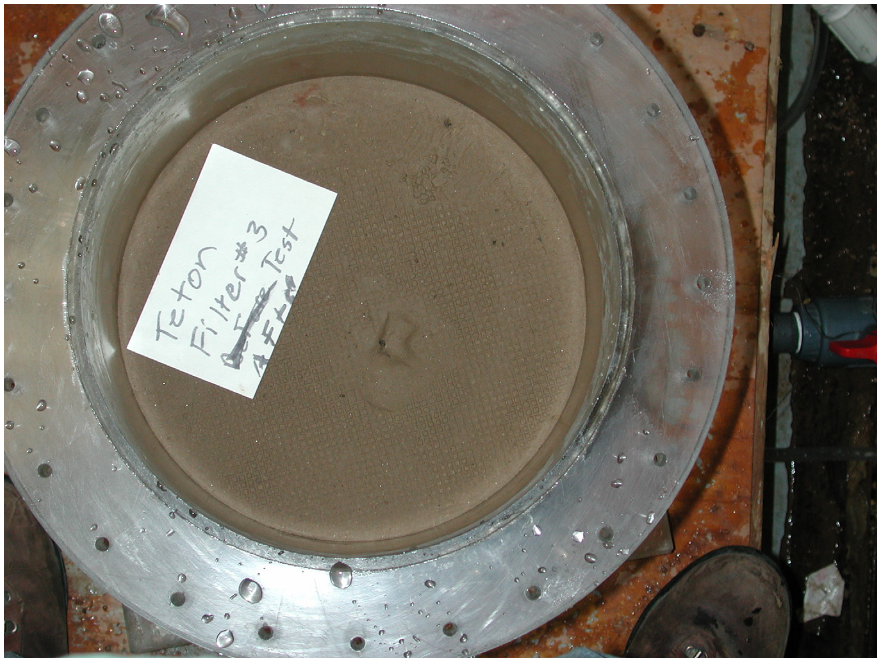


Photo 4 – CEF Test, Teton Material, Filter #5

Photo 5 – CEF Test, Teton Material, Filter #6

Appendix 3

Base Soil	Filter #	Test Type	DF15 (mm)	D, Base (lb/ft^3)	MC (%)	% of max standard proctor	D, Filter (lb/ft^3)	Time (min)	Initial Hole Diameter (mm)	Finial Hole Diameter (mm)	Test Result
Tracey	1	NEF	0.18		19.7	95.0		20	2.00	2.0	NE
	2	NEF	0.30		20	93.6		60	2.00	2.0	SE
	3	CEF	0.49		17.5	95.7		40	4.75	9.5	SE
	4	CEF	0.70		22.2	92.5		40	4.75	6	SE
	5	CEF	1.00		18	96.0		30	4.75	10	SE
	6	CEF	1.40		20.2	94.3		48	4.75	6.25	SE
	7	CEF	2.00		21.7	96.3		40	4.75	13	CE

Photo 1 – NEF Test, Tracey Material, Filter #1

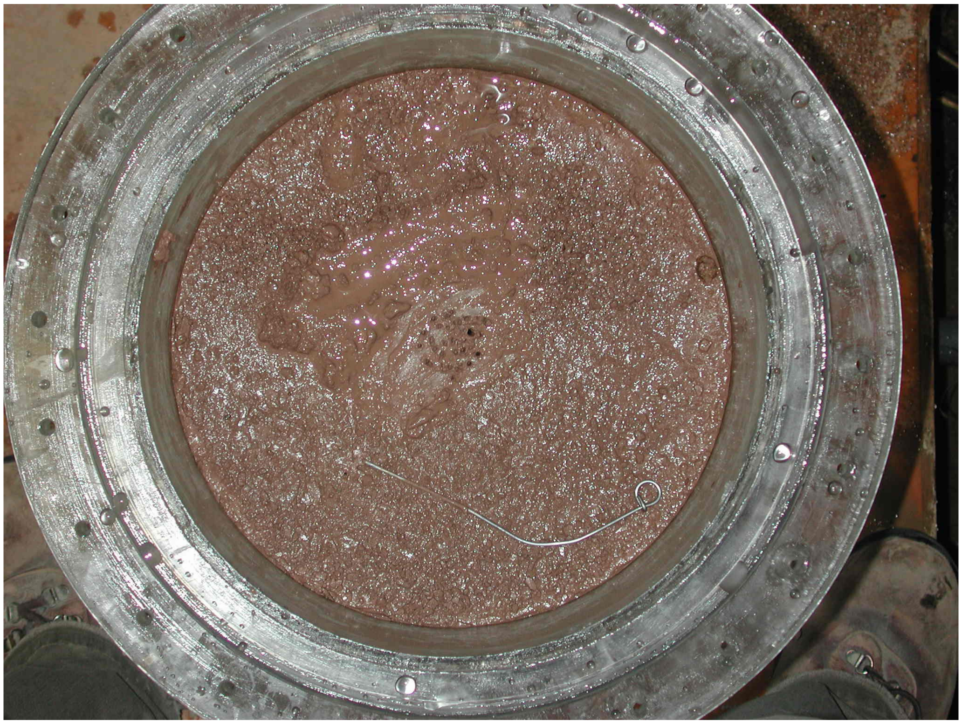


Photo 2 – NEF Test, Tracey Material, Filter #2

Photo 3 – CEF Test, Tracey Material, Filter #3

Photo 4 – CEF Test, Tracey Material, Filter #4

Photo 5 – CEF Test, Tracey Material, Filter #5

Photo 6 – CEF Test, Tracey Material, Filter #6

Photo 7 – CEF Test, Tracey Material, Filter #7

Appendix 4

Base Soil	Filter #	Test Type	DF15 (mm)	D, Base (lb/ft^3)	MC (%)	% of max standard proctor	D, Filter (lb/ft^3)	Time (min)	Initial Hole Diameter (mm)	Finial Hole Diameter (mm)	Test Result
Many Farms	3	NEF	0.49		16.8	96.8		15	2.00	2	NE
	4	NEF	0.70		16.7	96.0		45	2.00	5	SE
	5	CEF	1.00		15.2	99.0		40	4.75	19	SE
	6	CEF	2.00		16.9	96.4		55	4.75	18	SE
	7	CEF	2.00		16.4	96.8		55	4.75	16	SE
	8	CEF	3.00		16.5	96.7		45	4.75	25 - 60	SE
	9	CEF	4.80		18.5	95.0		55	4.75	see picture	SE
	10	CEF	8.10		20	94.2		50	4.75	see picture	CE

Photo 1 – NEF Test, Many Farms Material, Filter # 3

Photo 2 – CEF Test, Many Farms Material, Filter # 5

Photo 3 – CEF Test, Many Farms Material, Filter # 6

Photo 4 – CEF Test, Many Farms Material, Filter # 7

Photo 5 – CEF Test, Many Farms Material, Filter # 8

Photo 6 – CEF Test, Many Farms Material, Filter # 10

Appendix 5

Base Soil	Filter #	Test Type	DF15 (mm)	D, Base (lb/ft^3)	MC (%)	% of max standard proctor	D, Filter (lb/ft^3)	Time (min)	Initial Hole Diameter (mm)	Finial Hole Diameter (mm)	Test Result
Keechelus	1	NEF	0.18		NR	NR		NR	2.00	collapsed	NE
	2	NEF	0.30		15.5	103.1		35	2.00	2	SE
	3	NEF	0.49		15.65	103.0		45	2.00	2	SE
	4	NEF	0.70		15.8	102.8		16	2.00	4	SE
	5	CEF	1.00		17.4	100.7		25	4.75	collapsed	SE
	8	CEF	3.00		15.9	101.9		45	4.75	4.75	SE
	9	CEF	4.80		18	100.1		45	4.75	6	SE
	10	CEF	8.10		16.7	102.0		70	4.75	7	SE
	11	CEF	12		15.9	102.7		45	4.75	19	CE

Photo 1 – NEF Test, Keechelus Material, Filter #2

Photo 2 – NEF Test, Keechelus Material, Filter #3

Photo 3 – NEF Test, Keechelus Material, Filter #4

Photo 4 – CEF Test, Keechelus Material, Filter #5

Photo 5 – CEF Test, Keechelus Material, Filter #8

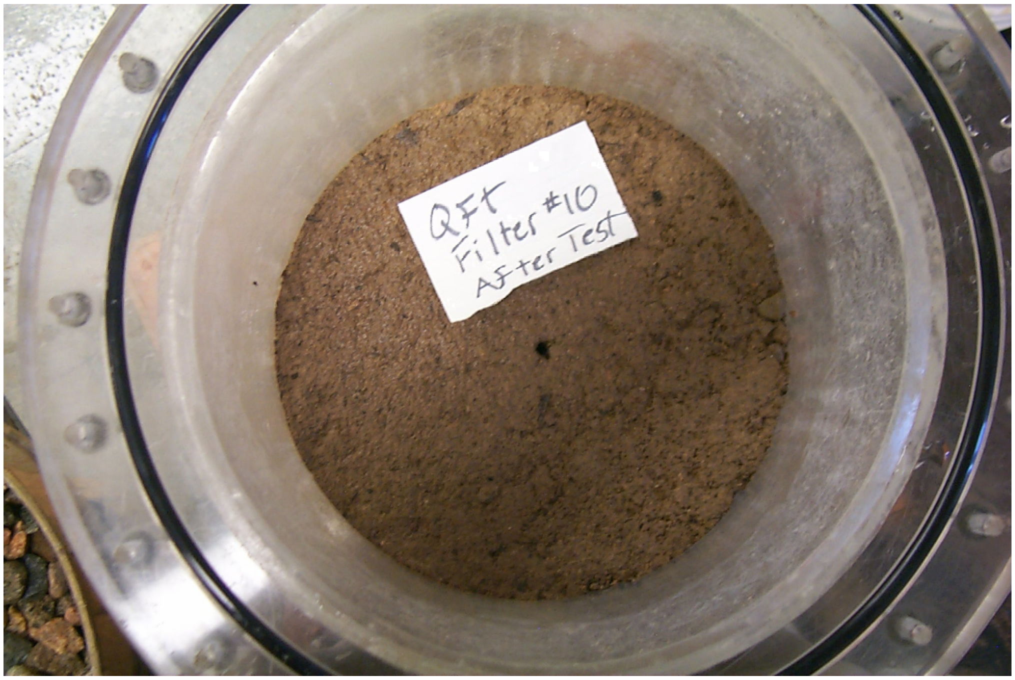


Photo 6 – CEF Test, Keechelus Material, Filter #9

Photo 7 – CEF Test, Keechelus Material, Filter #10 (Top of Base Material)

Photo 8 – CEF Test, Keechelus Material, Filter #10 (Bottom of Base Material)

Photo 9 – CEF Test, Keechelus Material, Filter #11

Mission Statements

U.S. Department of the Interior

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.