VERIFICATION TESTING OF THE HYDROGUARD HG6 HYDRODYNAMIC SEPARATOR STORMWATER TREATMENT UNIT

FINAL REPORT

By

James T. Mailloux

Amie N. Humphrey

Submitted to

HYDROWORKS, LLC

2008-332-H1323 December 23, 2008

VERIFICATION TESTING OF THE HYDROGUARD HG6 HYDRODYNAMIC SEPARATOR STORMWATER TREATMENT UNIT

By

James T. Mailloux

Amie N. Humphrey

Submitted to

HYDROWORKS, LLC

December 2008

ALDEN RESEARCH LABORATORY, INC.

30 Shrewsbury Street

Holden, MA 01520

TABLE OF CONTENTS

VERIFICATION TESTING OF THE HYDROGUARD
HG6 HYDRODYNAMIC SEPARATOR
STORMWATER TREATMENT UNIT

1.0 INTRODUCTION

Under a contract from Hydroworks, LLC (Hydroworks), verification testing of a 6-foot diameter Hydroguard HG6 Hydrodynamic Separator (HG6) was conducted at Alden Research Laboratory, Inc. (Alden), Holden, Massachusetts. Testing was conducted in three phases: Phase 1 evaluated the re-entrainment conditions, Phase 2 measured headloss values and established hydraulic characteristic curves, and Phase 3 determined the sediment removal efficiencies using a modified mass balance method. Phases 1 and 3 utilized the New Jersey Corporation for Advanced Technology (NJCAT) specified protocol sediment, with a PSD of 1 to 1000 microns and a specific gravity of 2.65. In addition, the weighted treatment efficiency determined in Phase 3 was calculated based on NJCAT weight factors. Refer to **Appendix A** for the NJCAT test procedures.

The HG6 test unit is a circular separating device with internal structures that divides it into three chambers. The unit contains 14-inch influent and effluent pipes oriented on-center, with an influent invert elevation of 73 inches above the wetted floor and an effluent invert of approximately 72 inches. Both pipes were oriented in the test loop with 0.5% slopes. The inner chamber is 48 inches in diameter and has a 22-inch wide by 10.5-inch high rectangular opening with an invert elevation of 71.0 inches. The opening is aligned on-center with the influent pipe. The inner chamber also contains a 36-inche wide by 9-inch high rectangular opening with an invert elevation of 36 inches, which allows flow to pass from the inner chamber to the middle chamber. A two-piece (upper and lower) outlet baffle wall separates the middle chamber from the outer chamber. The lower wall extends from the floor to an elevation of 42 inches. A 15-inch high opening separates the lower and upper walls and allows flow to pass from the middle chamber into the outer chamber and then out the effluent pipe. **Figure 1** shows a layout drawing of the HG6 test unit and **Figure 2** shows a photograph of the unit installed in Alden's test facility.

2.0 TEST FACILITY DESCRIPTION

Figure 3 shows the closed test loop, located in Alden's test facility, which was used to test the HG6 Treatment Unit. Water was supplied to the unit with either a 20HP or 50HP pump (flow capacity of approximately 9cfs), which draw water from a 50,000-gallon supply sump. One of five (5) calibrated flow meters (2, 4, 6, 8, and 12-inch), connected to a manifold, carried the test flow to a section of 12-inch piping, 90-degree elbow, 12-inch by 14-inch expansion and 12 feet (10 diameters) of 14-inch influent pipe. Water then passed through the test unit and 14-inch diameter effluent pipe to return to the laboratory sump. The effluent pipe contained an isokinetic sampling-tube array, located approximately 3 feet downstream of the test unit, to collect the effluent sediment concentration and PSD samples during re-entrainment testing. The array consisted of two (2) vertically adjustable sampling tubes (water level dependent), each containing a flow-control shut-off valve. Sediment was injected into the crown of the influent pipe through a vertical pipe connected to a tee located approximately 2 feet upstream of the test unit.

3.0 INSTRUMENTATION AND MEASURING TECHNIQUES

3.1 Flow

The inflow to the test unit was measured using one of five (5) calibrated flow meters. Each meter was fabricated per ASME guidelines and calibrated in Alden's Calibration Department prior to the start of testing. Flows were set with a butterfly valve and the differential head from the meter was measured using a Rosemount® 0 to 250-inch Differential Pressure (DP) cell, also calibrated at Alden prior to testing. The test flow was averaged and recorded approximately every 9 seconds throughout the duration of the test using a computerized data acquisition (DA) program. The accuracy of the flow measurement is estimated at ±2%. Photographs of the pumps and flow meters are shown on **Figures 4 and 5**.

3.2 Temperature

Water temperature measurements within the sump were obtained using a calibrated Omega® DP41 temperature probe and readout device. The calibration was performed at the laboratory prior to testing. The temperature reading was entered into the DA program at the start of each test for use in the flow measurement calculations.

3.3 Pressure Head

The pressure head readings recorded during Phase 2 testing were measured using a Rosemount® 0 to 60-inch DP cell. The pressure cell was calibrated at Alden prior to testing. A minimum of 1-minute of pressure data was recorded for each pressure tap, under steady-state flow conditions, using a computerized DA program.

3.4 Sediment Injection

During Phase 3, NJCAT protocol sediment was injected into the test unit (PSD of 1 - 1,000 microns, see **Appendix A**.) The test sand was introduced into the influent pipe using an Auger® volumetric screw feeders, model VF-1, shown on **Figure 6**. The Auger feed screws used in testing ranged in size from 0.75 to 1 inch, depending on the test flow. Each auger screw, driven with a variable-speed drive, was calibrated with the test sediment prior to testing, in order to establish a relationship between screw RPM and feed rate in mg/minute. The feeder has a 1.5 cubic foot hopper at the upper end of the auger to provide a constant supply of dry test sand.

3.5 Sample Collection

As described in Section 2.0, isokinetic sampling tubes were located within the effluent piping to collect the sediment concentration samples during Phase 1 testing. The sampling tubes were 0.50 and 0.75 inches in diameter. The tube array was vertically adjusted and calibrated prior to testing, to match the velocities for each flow condition. A photograph of a typical sampling array is shown on **Figure 7**.

3.6 Sample Concentration Analyses

Concentration samples were analyzed using the Suspended Solids Concentration (SSC) method which utilizes the entire sample in the analysis. The samples were processed at Alden as described below.

SSC Analysis:

Collected samples were filtered and analyzed by Alden in accordance with Method B, as described in ASTM Designation: D 3977-97 (Re-approved 2002), "Standard Test Methods for Determining Sediment Concentration in Water Samples". The required silica sand used in the sediment testing did not result in any dissolved solids in the samples and therefore, simplified the ASTM testing methods for determining sediment concentration.

Samples were collected in graduated 2-Liter beakers which were cleaned, dried and weighed to the nearest 0.1-gram, using an Ohaus® 4000g x 0.1g digital scale, model SCD-010, prior to sampling. Collected samples were also weighed to the nearest 0.1-gram using the Ohaus® digital scale. Each collected sample was filtered through a pre-rinsed Whatman® 934-AH, 47-mm, 1.5-micron, glass microfiber filter paper, using a laboratory vacuum-filtering system. Prior to processing, each filter was rinsed and placed in a designated dish and dried in an Oakton® StableTemp gravity convection oven, model 05015-59, at 225 degrees F for a minimum of 2 hours. Each dried filter/dish set was then weighed to the nearest 0.0001-gram, using an AND® analytical balance, model ER-182A. Once filtered, each sample and dish was dried at a temperature between 175 and 220 degrees F (below boiling) for 20 to 30 minutes until visually dry. The oven temperature was increased to 225 degrees F and the samples were dried for an additional 2-½ to 3 hours. The dry samples and dishes were then weighed to the nearest 0.0001-gram, using the AND® balance. Net sediment weight (mg) was determined by subtracting the dried filter weight from the dried sample weight and multiplying the result by 1,000. The net sample volume, in liters, was determined by subtracting the beaker and net sediment weight from the overall sample weight and dividing by 1,000. Each sample sediment concentration, in mg/liter, was determined by dividing the net sediment weight by the net sample volume. The effluent concentration for each flow condition was adjusted for background. The background samples were collected at the pump effluent and processed as described above.

3.7 Test Sediment and Particle Size Distribution

In order to satisfy the particle size distribution (PSD) set forth by NJCAT testing protocol, Alden has developed a sediment mix composed of NJ#00N, OK110 and Min-U-Sil 40 silica sand, available from US Silica. **Figure 8** shows the theoretical PSD of each grade of sand, as well as the mix ratios and resulting percentages. Two random dry samples were analyzed for PSD with a resulting average D_{50} of approximately 70 microns which, as shown on **Figure 9**, matches the NJDEP estimated D_{50} of 67 microns.

In addition to testing with NJCAT protocol sediment, a third re-entrainment test was completed with gradation F-60 sediment. The PSD information provided by U.S. Silica is presented on **Figure 10**.

3.8 Mass Balance Analysis

For tests completed during Phase 3, a modified mass balance method was used to determine sediment removal efficiency. A true mass balance test accounts for all the mass within a system, including total influent, captured and effluent quantities. However, with flows ranging from 0.45 to 2.25 cfs, it is extremely difficult and consequently, expensive to capture the fine effluent sediment without compromising the integrity of the test. Therefore, modified mass balance tests, in which the influent and captured sediment is accounted for, were performed on the HG6 unit. The weight of injected sediment was determined by weighing the loaded screw feeder, which was mounted on a hydraulic table, before and after testing. The scale used was a 0-500 lb Ohaus® Champ SQ digital scale, model CQ250-XL11W, equipped with a 0.05 resolution CW11digital controller. This provided the total mass of sediment introduced into the test unit.

After the completion of each test, water was decanted from the test unit by means of a gravity siphon. The captured sediment and any remaining water were then collected from the test unit using a pre-cleaned wet vacuum. The collected sediment was placed in pre-weighed trays and dried in a Modern Laboratory Equipment® oven, model 155-SS, for approximately 24 hours. The dried sediment was then weighed with the Ohaus scale and the captured weight was calculated by subtracting the tray weight from the gross weight. The removal efficiency for each flow condition was calculated using the following equation:

$$\%\,\boldsymbol{Efficiency} = \frac{\textbf{Net Captured Weight}}{\textbf{Net Injected Weight}} \times \mathbf{100}$$

4.0 TEST PROCEDURES

Test procedures for the HG6 unit were developed by Hydroworks in coordination with Alden and with consultation from NJCAT. The NJCAT testing protocol for Stormwater Treatment Devices was used as guidance (see Appendix A). The testing was conducted in three phases as described below.

4.1 Phase 1 - Re-entrainment and Washout

Re-entrainment tests were performed at flows ranging from 0.4 to 2.0 cfs, with sediment loadings of 100% (9.3 ft^3) and 50% (4.6 ft^3) of the unit's capacity (as stated by Hydroworks). It was estimated (by Hydroworks) that the inner chamber retains approximately 80% of sediment captured by the unit and the remaining 20% is retained in the middle chamber. Therefore, an 80/20 split was used for the sediment loading. The area of the inner chamber is 12.6 ft^2 and the area of the middle chamber is 8.8 ft^2. For the 100% tests, 7 inches of sediment was loaded in the inner chamber and 2.5 inches in the middle chamber. For the 50% tests, 3.5 inches of sediment was loaded in the inner chamber and 1.25 inches in the middle chamber. Three re-entrainment tests were performed: 100% and 50% loading with NJCAT mix (1 to 1,000 microns) and 100% loading with F-60 sediment (75 to 600 microns).

The unit was slowly filled to the invert of the effluent pipe. The shape of the sediment bed was established by incrementally increasing the flow to 1.2 cfs, allowing the system to run until the effluent was clear or for a maximum duration of one hour. The system remained idle for a minimum of 24 hours prior to testing to let the newly established sediment bed settle. Testing was conducted by incrementally increasing the flow of clean water (no influent sediment) into the unit under steady-state conditions, while continuously obtaining flow data. Effluent samples, for SSC and PSD analyses, were obtained at the targeted flows (0.4, 0.8, 1.2, 1.6 and 2.0 cfs.) A series of four (4) samples were collected every 5 minutes at each steady-state target flow, to allow insight into trends and/or anomalies of sediment movement.

4.2 Phase 2 - Hydraulic Capacity and Characteristics

The unit was tested without sediment to determine its hydraulic characteristics. Flow and pressure head measurements across the unit were recorded for 16 conditions. Each test flow was set and allowed to reach steady state, at which time a minimum of 1 minute of flow and pressure data were recorded and averaged for each pressure tap location. Observations were documented throughout the test, including conditions in the inner, middle and outer chambers (internal measurements) and water elevations in the influent and effluent pipes (system measurements). Pressure head measurements were recorded at the following 5 locations (see **Figure 11**): approximately one pipe diameter upstream of the test unit (Tap A), along the wall in the inner chamber (Tap B), along the wall in the middle chamber (Tap C), along the wall in the outer chamber (Tap D), and one pipe diameter downstream of the test unit (Tap E). The discharge and loss coefficients (Cd and K) were calculated for both the internal and system losses.

4.3 Phase 3 - Sediment Removal Efficiency Testing

The test unit was thoroughly cleaned prior to the start of each test. The test flow was set and allowed to reach steady state. The test sediment was injected into the influent line at a target concentration of 200 mg/L for duration of time sufficient to introduce approximately twenty (20) pounds of sediment into the unit. The sediment injection was stopped and 3 system volumes of water were allowed to pass through the system prior to the termination of the test. The unit was drained and cleaned, and the removal efficiency determined utilizing the modified mass balance methodology described in Section 3.8.

It was observed that each collection tray contained both settled and suspended sediment particles when placed in the drying oven. After full drying of the sediment was complete, an encrusted top layer was present in each tray, which was the result of the fine particles bonding together during the drying process. This bonding of particles did not affect the resulting removal efficiencies. However, the reported PSD results show that the particles still possessed some cohesive qualities, as the smallest measured particle sizes do no correlate well with the resulting efficiencies. Passing the dried sediment through fine screens and preparing the samples as wet samples prior to shipping may have corrected this problem.

5.0 RESULTS

Results of all tests are shown in **Tables 1** through **6**, on **Figures 12** through **27** and are discussed in the following sub-sections.

5.1 Re-entrainment and Washout

Re-entrainment tests were performed at flows ranging from 0.4 to 2.0 cfs, with initial sediment loadings of 100% (9.3 ft^3) and 50% (4.6 ft^3) of the unit's capacity (as stated by Hydroworks). The sediment beds were prepared with a varying deposition profile, as described in Section 4.1, based on field observations supplied by Hydroworks. Each test was conducted by incrementally increasing the flow while collecting effluent samples. A series of four (4) effluent samples were collected for SSC analysis and one for PSD analysis, at the steady-state target flows of 0.4, 0.8, 1.2, 1.6 and 2.0 cfs.

5.1.1 50% Loading – NJCAT Mix

Measured sediment concentrations were considered low for all target flow conditions, with average quantities ranging from 2.2 mg/L (0.4 cfs) to 36.1 mg/L (2.0 cfs). The four sequential samples collected at each target flow showed steady increases, with the exception of the outlier seen at sample #2 during the 1.61 cfs flow. Graphs of the recorded flow data and corresponding sediment concentration analyses are shown on **Figures 12 and 13**. The concentration data is shown in **Table 1.**

The effluent PSD data indicated that, at the maximum flow of 2.0 cfs, the unit was able to retain particles over 25 microns (D_{95}). The corresponding D_{10}, D_{50} and D_{90} sizes were 2.3, 8.2 and 21.5 microns, respectively. The PSD curves for the entire test are shown on **Figure 14**. Photographs of the inner and middle chambers after re-entrainment testing are shown on **Figures 15 and 16**.

5.1.2 100% Loading – NJCAT Mix

Measured sediment concentrations were considered relatively low for all flow conditions, with average quantities ranging from 4.3 (0.4 cfs) to 44.1 mg/L (2.0 cfs). The four samples collected at each target flow typically had the lowest concentrations, with a spike in concentration at the second sample. The 2.0 cfs condition had the highest concentration at the first sample, with diminishing concentrations at each subsequent sample. Graphs of the recorded flow data and corresponding sediment concentration analyses are shown on **Figures 17 and 18**. The concentration data is shown in **Table 2**.

The effluent PSD data indicated that, at the maximum flow of 2.0 cfs, the unit is able to retain particles over 30 microns (D_{95}). The corresponding D_{10}, D_{50} and D_{90} sizes were 2.5, 10.1 and 25.4 microns, respectively. The PSD curves for the entire test are shown on **Figure 19**. Photographs of the inner and middle chambers after re-entrainment testing are shown on **Figures 20 and 21**.

5.1.3 100% Loading – F-60 Sediment

Measured sediment concentrations were considered low for all flow conditions, with average quantities ranging from 2.1 (0.4 cfs) to 13.5 mg/L (2.0 cfs). The collected samples at each target flow were all similar, with maximum deviations of approximately +/- 2 mg/L. Graphs of the recorded flow data and corresponding sediment concentration analyses are shown on **Figures 22 and 23**. The concentration data is shown in **Table 3**.

A PSD sample was not collected for this test condition.

5.2 Hydraulic Capacity

Flow (gpm) and water level (inches) within the unit were measured for 19 flows ranging from 0.4 to 7.9 cfs. The influent pipe was estimated to be flowing full at approximately 3.3 cfs. The entrance to the effluent pipe was submerged at approximately 3.3 cfs, and the effluent pipe was measured to be flowing full at the tap at approximately 5 cfs. There was no rounding installed at the entrance to the effluent pipe, resulting in formation of a vena contracta at full-pipe flow. This resulted in erroneous low-pressure readings at full pipe. The loss coefficient (K) associated with the sharp-cornered entrance is approximately 0.5. The addition of a 1.5 to 2-inch radius at the entrance would reduce the coefficient to an approximate value of 0.1 for a 14-inch pipe. The flow did not overtop the baffle walls at maximum flow. The Elevation Curves for each pressure tap location are shown on **Figure 24**. The effluent curve is flat at full pipe due to the reasons discussed above.

The loss coefficient (Cd) was calculated throughout the range of flows using the following equation:

$$\boldsymbol{Cd = Q/A\sqrt{2g\Delta h}}$$

Where,

Q = flow in cfs

A = area of the outlet baffle opening in ft^2

Δh = headloss across the unit in ft

As seen on **Figure 25**, the calculated System Cd (influent to effluent) ranged from 0.015 to 0.08 for recorded flows of 181 to 1,789 gpm (0.40 to 4.0 cfs), and 0.103 to 0.137 for flows of 2016 to 3556 gpm (4.5 to 7.9 cfs). The calculated internal Cd (inner chamber to outlet chamber) ranged from 0.168 to 0.306 for recorded flows of 359 to 3556 gpm (0.8 to 7.9 cfs).

A system K value was established based on full-pipe flow in the influent and effluent pipes using the following equation:

$$\boldsymbol{K = \Delta H \times \frac{2g}{V^2}}$$

Where,

ΔH = head differential between the influent and effluent pipes

V = velocity in the influent pipe

A K value of 1.09 was calculated at 2277 gpm (5.1 cfs), which corresponds to full effluent pipe flow. Additional values for producing an average were not attainable due to the lack of effluent pressure readings discussed earlier. A substantial reduction in the K value is anticipated with the addition of an effluent rounding. The hydraulic data is shown in **Table 4**.

5.3 Sediment Removal Efficiency

Removal efficiency tests were conducted at five (5) flows ranging from 0.45 to 2.25 cfs with a target influent sediment concentration of 200 mg/l. The calculated removal efficiencies ranged from 43.1% to 74.1% for the five tests conducted. The testing data summary is shown in **Table 5** and the efficiency curve is shown on **Figure 26**. One random sample was collected from the captured sediment during each test for particle size distribution (PSD) analysis. Each sample was analyzed using the Beckman Multisizer3 Coulter Counter. It needs to be noted that the smallest measured particle size for all tests except the 0.75 cfs test (26 microns) do not correlate with the measured removal efficiency results. This is most likely due to the limitations of the PSD analysis methodology to break down the coagulated particles (caused by the drying process, as described in Section 4.3) to their smallest grain size. PSD curves for each test are shown on **Figure 27**.

Data points corresponding to 50%, 75% and 100% flows, based on the upper and lower range, were interpolated in order to calculate an NJCAT weighted efficiency of 60.3%. The weighted efficiency data is shown in **Table 6**. Complete test results are discussed in the following sub-sections.

5.3.1 Sediment Removal Efficiency – 2.25 cfs

The average flow recorded for the entire test was 1014.5 gpm (2.26 cfs), with a standard deviation (SD) of 1.96. The recorded temperature for the test was 65.0 degrees F. The net weight of sediment injected was 21.7 lbs. The net weight captured was 9.35 lbs. The resulting sediment removal efficiency was 43.1%. The background concentrations taken at the start and end of the test were 5.31 and 11.55 mg/L.

The smallest captured particle measured was greater than 88 microns. This data correlates fairly well with the measured removal efficiency of 43.1%, which has an estimated particle size of approximately 100 microns.

5.3.2 Sediment Removal Efficiency – 1.88 cfs

The average flow recorded for the entire test was 847.7 gpm (1.89 cfs), with a standard deviation (SD) of 3.48. The recorded temperature for the test was 63.1 degrees F. The net weight of sediment injected was 24.2 lbs. The net weight captured was 11.70 lbs. The resulting sediment removal efficiency was 48.3%. The background concentrations taken at the start and end of the test were 1.40 and 5.96 mg/L.

The smallest captured particle measured was greater than 88 microns. This data shows a larger particle size than anticipated for a removal efficiency of 48.3%, which has an estimated particle size of approximately 80 microns.

5.3.3 Sediment Removal Efficiency – 1.5 cfs

The average flow recorded for the entire test was 677.6 gpm (1.51 cfs), with a standard deviation (SD) of 1.43. The recorded temperature for the test was 70.6 degrees F. The net weight of sediment injected was 21.0 lbs. The net weight captured was 11.50 lbs. The resulting sediment removal efficiency was 54.8%. Background concentration samples were not taken during the test; however, background levels were observed to be minimal.

The smallest captured particle measured was greater than 74 microns. This data shows a larger particle size than anticipated for a removal efficiency of 54.8%, which has an estimated particle size of approximately 60 microns.

5.3.4 Sediment Removal Efficiency – 0.75 cfs

The average flow recorded for the entire test was 337.6 gpm (0.75 cfs), with a standard deviation (SD) of 1.04. The recorded temperature for the test was 63.5 degrees F. The net weight of sediment injected was 26.4 lbs. The net weight captured was 16.90 lbs. The resulting sediment removal efficiency was 64.0%. The background concentrations taken at the start and end of the test were 0.29 and 5.08 mg/L.

The smallest captured particle measured was greater than 26 microns. This data correlates fairly well with the measured removal efficiency of 64.0%, which has an estimated particle size of approximately 25 microns.

5.3.5 Sediment Removal Efficiency – 0.45 cfs

The average flow recorded for the entire test was 203.3 gpm (0.45 cfs), with a standard deviation (SD) of 0.50. The recorded temperature for the test was 64.1 degrees F. The net weight of sediment injected was 18.5 lbs. The net weight captured was 13.70 lbs. The resulting sediment removal efficiency was 74.1%. The background concentrations taken at the start and end of the test were 5.13 and 6.26 mg/L.

The smallest captured particle measured was greater than 62 microns. This data shows a larger particle size than anticipated for a removal efficiency of 74.1%, which has an estimated particle size of approximately 12 microns.

6.0 SUMMARY & CONCLUSIONS

Under a contract from Hydroworks, LLC (Hydroworks), verification testing of a 6-foot diameter Hydroguard HG6 Hydrodynamic Separator (HG6) was conducted at Alden Research Laboratory, Inc. (Alden), Holden, Massachusetts. Testing included the evaluation of re-entrainment of the sediment bed, measured headlosses and established hydraulic characteristic curves, and determination of the sediment removal efficiencies using a modified mass balance method. Sediment testing utilized the New Jersey Corporation for Advanced Technology (NJCAT) specified protocol sediment, with a PSD of 1 to 1000 microns and a specific gravity of 2.65.

Hydraulic testing was performed on the unit for flows ranging from 0.4 to 7.9 cfs. There was no rounding installed at the entrance to the effluent pipe, resulting in formation of a vena contracta at full-pipe flow. This resulted in erroneous low-pressure readings at full pipe. The loss coefficient (K) associated with the sharp-cornered entrance is approximately 0.5. The addition of a 1.5 to 2-inch radius at the entrance would reduce the coefficient to an approximate value of 0.1 for a 14-inch pipe. The flow did not overtop the baffle walls at maximum flow. The calculated System Cd (influent to effluent) ranged from 0.015 to 0.08 for recorded flows of 181 to 1,789 gpm (0.40 to 4.0 cfs), and 0.103 to 0.137 for flows of 2016 to 3556 gpm (4.5 to 7.9 cfs). The calculated internal Cd (inner chamber to outlet chamber) ranged from 0.168 to 0.306 for recorded flows of 359 to 3556 gpm (0.8 to 7.9 cfs). A system K value was established based on full-pipe flow in the influent and effluent pipes. A K value of 1.09 was calculated at 2277 gpm (5.1 cfs), which corresponds to full effluent pipe flow. A substantial reduction in the K value is anticipated with the addition of an effluent inlet rounding.

Removal efficiency tests were conducted at five (5) flows ranging from 0.45 to 2.25 cfs with a target influent sediment concentration of 200 mg/l. A mass balance methodology was utilized for all tests. One random sample was collected from the captured sediment during each test for particle size distribution (PSD) analysis. The calculated removal efficiencies ranged from 43.1% (2.25 cfs) to 74.1% (0.45 cfs) for the five tests conducted, with an NJCAT weighted efficiency of 60.3%. The smallest measured captured particle size was greater than 26 microns for all tests.

Re-entrainment tests were performed at flows ranging from 0.4 to 2.0 cfs, with initial sediment loadings of 100% and 50% of the stated unit's capacity using the NJCAT sediment PSD. An additional test was performed with an initial loading of 100% using F60 sediment. The sediment beds were prepared with a varying deposition profile, based on field observations supplied by Hydroworks. Maximum average sediment concentrations for the 50% and 100% loading conditions were 36.1 mg/L and 44.1 mg/L, respectively, using the NJCAT PSD mix. The effluent PSD data indicated that, at the maximum flow of 2.0 cfs, the unit was able to retain particles over 25 microns (D_{90}) for the 50% and 100% conditions. Correlation of this data with the removal efficiency PSD data results in no negative impact on the overall removal efficiency performance for all flows tested below 0.45 cfs, since the largest re-entrained particle is smaller than the smallest measured and estimated captured particle(approximately 75% of the re-entrained particles were < 15 microns). Although the 0.45 cfs test indicates that sufficiently-small particles could be present in the chamber which could be re-entrained (12-25 microns), it is anticipated that the effect on overall efficiency will be minimum, since only particles at the surface of the bed will be re-entrained and not the entire volume. The effluent re-entrained concentrations were negligible for flows up to 0.8 cfs (approximately 5 mg/L) and minimal at the flow rate of 1.21 cfs (< 18 mg/L). The F-60 test resulted in a maximum average effluent concentration of 13.5 mg/L at 2.0 cfs and 100% bed load. No PSD samples were collected for this test condition.

CONCLUSIONS:

- The Hydroguard HG6 removed 74% to 43% of the NJDEP particle size distribution at flow rates ranging from 2.25 cfs to 0.45 cfs respectively. The NJDEP particle size distribution represents a distribution of sediment where 45% of the particles are less than 50 um and 20% of the particles are less than 8 um in size.

- The smallest measured particle captured by the Hydroguard HG6 for these flow conditions was 26 um. This may be considered conservative due to the cohesive properties of the fine captured particles observed after drying.

- Scour testing indicates prevention of scour for particles larger than 25 um (D_{90}).

- Hydraulic testing indicates a system K value of 1.09 at full-pipe flow conditions for headloss calculations.

TABLES

Table 1
Re-entrainment, 50% Sediment Loading, NJCAT Mix
SSC Sample Analysis

Flow rate (cfs)	**0.40**		**0.80**		**1.21**		**1.61**		**2.00**	
Background Sample (mg/L)	B2	4.41	B3	2.96	B4	3.78	B5	12.64	B6	13.71
Effluent Sample (mg/L)	1	2.69	1	1.66	1	13.40	1	15.59	1	32.50
(adjusted for background)	2	1.93	2	2.40	2	14.78	2	44.16	2	34.00
	3	1.81	3	3.18	3	15.38	3	27.12	3	38.20
	4	2.35	4	2.43	4	24.35	4	28.02	4	39.76
Average Effluent (mg/L)		**2.20**		**2.42**		**16.98**		**28.73**		**36.12**

Table 2
Re-entrainment, 100% Sediment Loading, NJCAT Mix
SSC Sample Analysis

Flow rate (cfs)	**0.40**		**0.80**		**1.21**		**1.61**		**2.00**	
Background Sample (mg/L)	B2	1.65	B3	0	B4	2.25	B5	10.61	B6	18.87
Effluent Sample (mg/L)	1	4.27	1	3.72	1	12.65	1	26.39	1	53.71
(adjusted for background)	2	4.30	2	5.70	2	22.19	2	53.49	2	45.54
	3	4.12	3	6.38	3	19.98	3	43.88	3	33.54
	4	4.40	4	5.83	4	16.76	4	52.78	4	33.08
Average Effluent (mg/L)		**4.27**		**5.40**		**17.90**		**44.14**		**41.47**

Table 3
Re-entrainment, 100% Sediment Loading, F-60
SSC Sample Analysis

Flow rate (cfs)	**0.41**		**0.80**		**1.21**		**1.60**		**2.01**	
Background Sample (mg/L)	B2	0	B3	0	B4	0	B5	0	B6	0
Effluent Sample (mg/L)	1	1.74	1	2.26	1	3.85	1	6.23	1	11.37
(adjusted for background)	2	2.51	2	0.68	2	5.41	2	10.33	2	13.89
			3	1.27	3	5.00	3	5.95	3	15.06
					4	4.35	4	8.59	4	13.57
Average Effluent (mg/L)		**2.21**		**1.41**		**4.65**		**7.78**		**13.47**

Table 4
Hydraulic Testing Data

Flow		**Elevation readings**									**Discharge Coefficient**				**Velocity**				**K**
		Influent (A)		**Inner Chamber (B)**		**Middle Chamber (C)**		**Outer Chamber (D)**		**Effluent (E)**	**Internal**		**External (System)**		**Inlet**		**Outlet**		
gpm	**cfs**	**Inches from E**	**Inches from invert**	**Inches from E**	**Inches from bottom**	**Inches from E**	**Inches from bottom**	**Inches from E**	**Inches from bottom**	**Inches**	**delta B-D (feet)**	**Cd**	**delta A-E (feet)**	**Cd**	**Area (ft^2)**	**(ft/s)**	**Area (ft^2)**	**(ft/s)**	
181.4	0.40	5.01	4.00	5.05	77.05	5.05	77.05	5.04	77.04	2.52	0.00	0.249	0.21	0.015	0.25	1.60	0.13	3.08	
358.9	0.80	7.05	6.05	7.16	79.16	7.10	79.10	7.08	79.08	3.56	0.01	0.168	0.29	0.025	0.44	1.81	0.21	3.74	
449.2	1.00	7.72	6.72	7.88	79.88	7.81	79.81	7.77	79.77	3.90	0.01	0.172	0.32	0.030	0.51	1.97	0.24	4.12	
543.3	1.21	8.70	7.69	8.89	80.89	8.75	80.75	8.73	80.73	4.63	0.01	0.175	0.34	0.035	0.60	2.01	0.31	3.92	
722.7	1.61	10.15	9.15	10.45	82.45	10.21	82.21	10.20	82.20	5.50	0.02	0.184	0.39	0.043	0.74	2.18	0.39	4.13	
903.3	2.01	11.46	10.45	11.69	83.69	11.44	83.44	11.32	83.32	6.13	0.03	0.193	0.44	0.051	0.86	2.35	0.45	4.47	
937.2	2.09	11.47	10.46	11.88	83.88	11.62	83.62	11.42	83.42	6.13	0.04	0.179	0.44	0.052	0.86	2.44	0.45	4.64	
1078.9	2.40	12.73	11.73	13.06	85.06	12.85	84.85	12.61	84.61	6.93	0.04	0.205	0.48	0.058	0.96	2.51	0.53	4.55	
1350.8	3.01	14.29	13.28	14.86	86.86	14.59	86.59	14.31	86.31	7.51	0.05	0.235	0.57	0.067	1.05	2.87	0.58	5.16	
1363.5	3.04	14.29	13.28	14.72	86.72	14.58	86.58	14.25	86.25	7.56	0.04	0.258	0.56	0.068	1.05	2.90	0.59	5.16	
1475.2	3.29	14.98	13.97	15.27	87.27	15.34	87.34	14.81	86.81	8.00	0.04	0.281	0.58	0.072	1.07	3.07	0.63	5.21	
1629.8	3.63	16.09	15.08	16.91	88.91	16.63	88.63	16.01	88.01	8.47	0.08	0.221	0.64	0.076	1.07	3.40	0.68	5.37	
1789.1	3.99	17.02	16.02	17.98	89.98	17.59	89.59	17.04	89.04	8.64	0.08	0.239	0.70	0.080	1.07	3.73	0.69	5.76	
2022.8	4.51	18.90	17.90	20.41	92.41	19.58	91.58	19.10	91.10	9.41	0.11	0.228	0.79	0.085	1.07	4.22	0.76	5.90	
2276.8	5.07	18.59	17.58	19.17	91.17	19.29	91.29	18.25	90.25	14.00	0.08	0.306	0.38	0.137	1.07	4.75	1.07	4.75	1.09
2683.2	5.98	21.54	20.53	22.75	94.75	22.38	94.38	21.09	93.09	14.00	0.14	0.269	0.63	0.126	1.07	5.59	1.07	5.59	1.29
2699.9	6.02	20.63	19.62	22.68	94.68	21.72	93.72	20.74	92.74	14.00	0.16	0.250	0.55	0.135	1.07	5.63	1.07	5.63	1.12
3189.3	7.11	26.67	25.66	28.55	100.55	28.16	100.16	25.88	97.88	14.00	0.22	0.252	1.06	0.116	1.07	6.65	1.07	6.65	1.54
3555.6	7.92	30.45	29.44	32.25	104.25	32.05	104.05	29.69	101.69	14.00	0.21	0.287	1.37	0.113	1.07	7.41	1.07	7.41	1.61

Table 5
Sediment Removal Efficiency Testing Summary
Modified Mass Balance Method

Target Flow (cfs)	Recorded Flow (cfs)	Injected wt. (lbs)	Captured wt. (lbs)	Efficiency %
2.25	2.26	21.70	9.35	43.1
1.88	1.89	24.20	11.70	48.3
1.50	1.51	21.00	11.50	54.8
0.75	0.75	26.40	16.90	64.0
0.45	0.45	18.50	13.70	74.1

Table 6
Sediment Removal Weighted Efficiency

	Flow (cfs)	Efficiency	NJ Weighting	Weighted Eff.
125%	2.26	43.1	0.1	4.31
100%	1.81	49.7	0.15	7.46
75%	1.36	56.6	0.2	11.33
50%	0.90	62.2	0.3	18.65
25%	0.45	74.1	0.25	18.51
				60.3

*Note: Efficiencies for 100%, 75% and 50% are interpolated linearly from the two test flowrates on either side of the required flowrate.

FIGURES

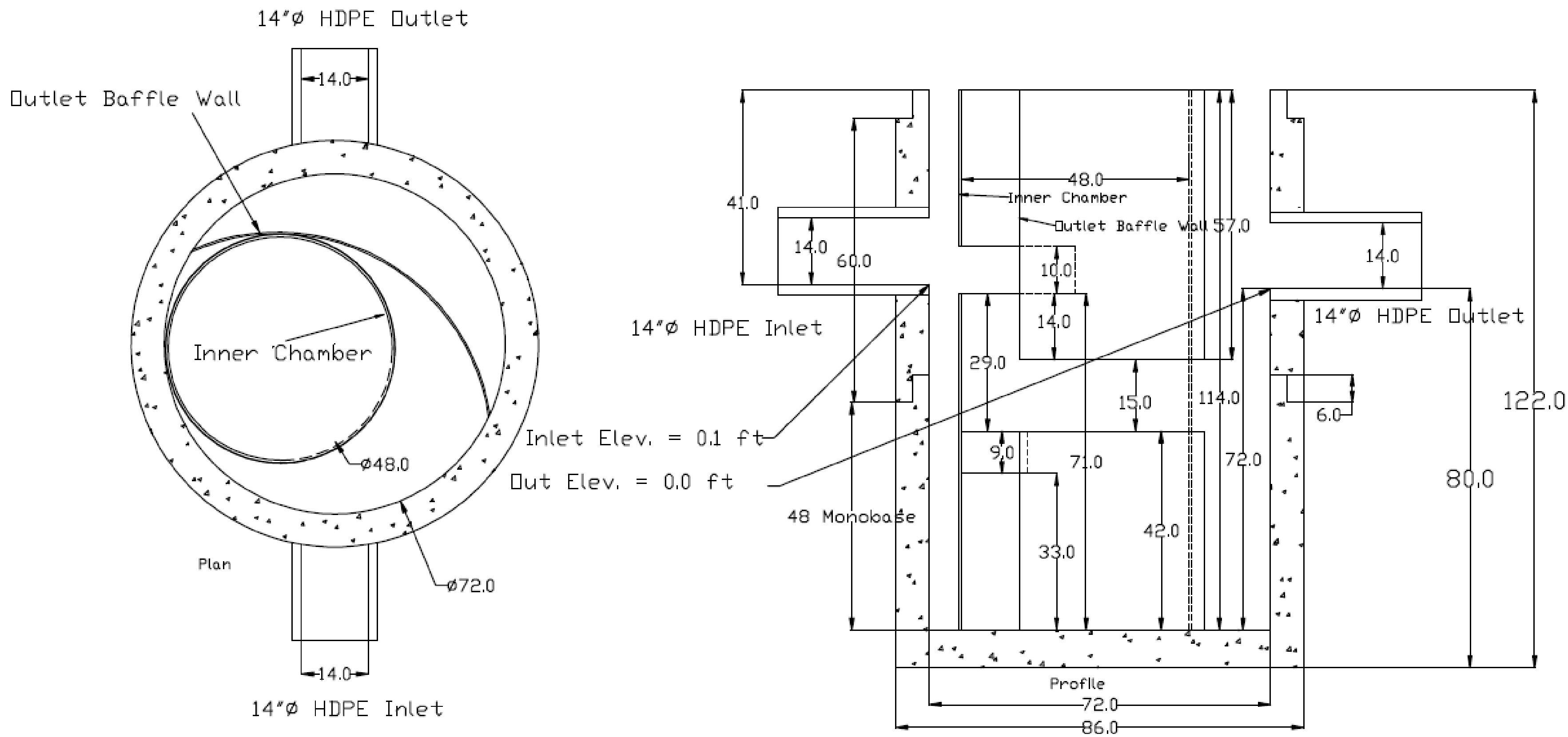


Figure 1: Hydroworks HG6 Test Unit

ALDEN

Figure 2: HG6 in Alden's Test-Loop

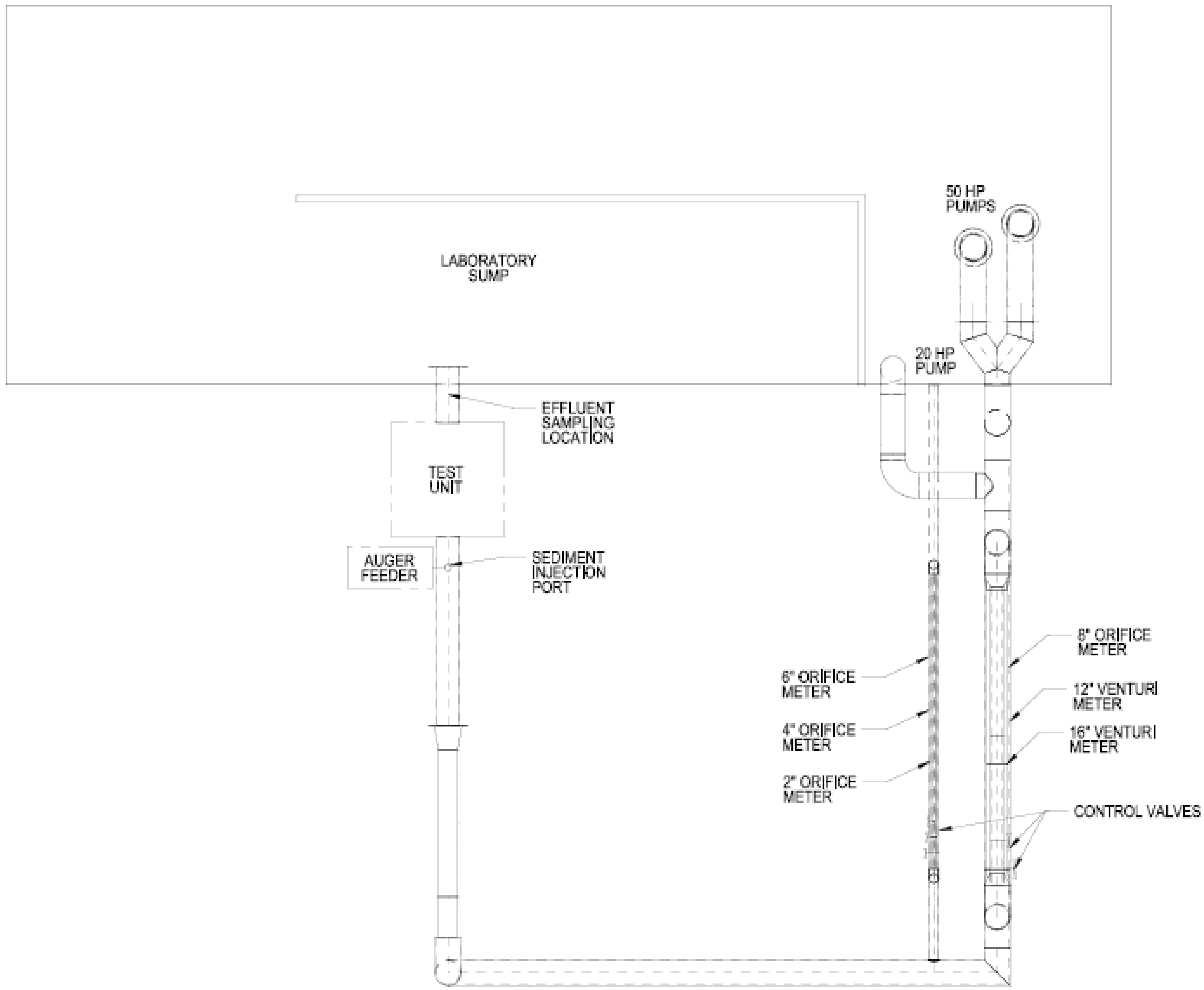
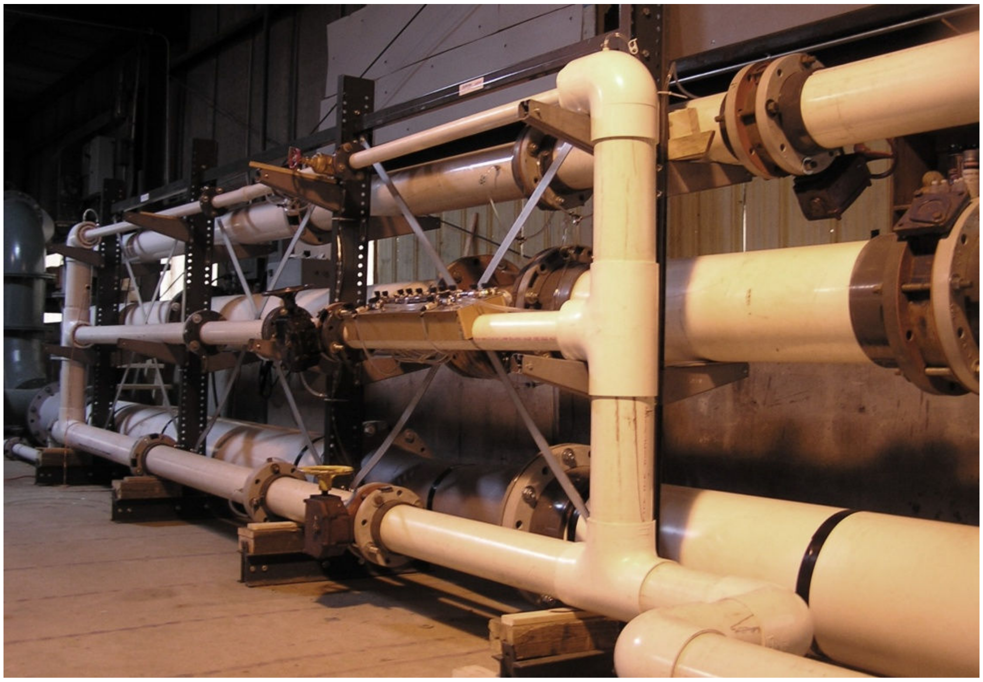
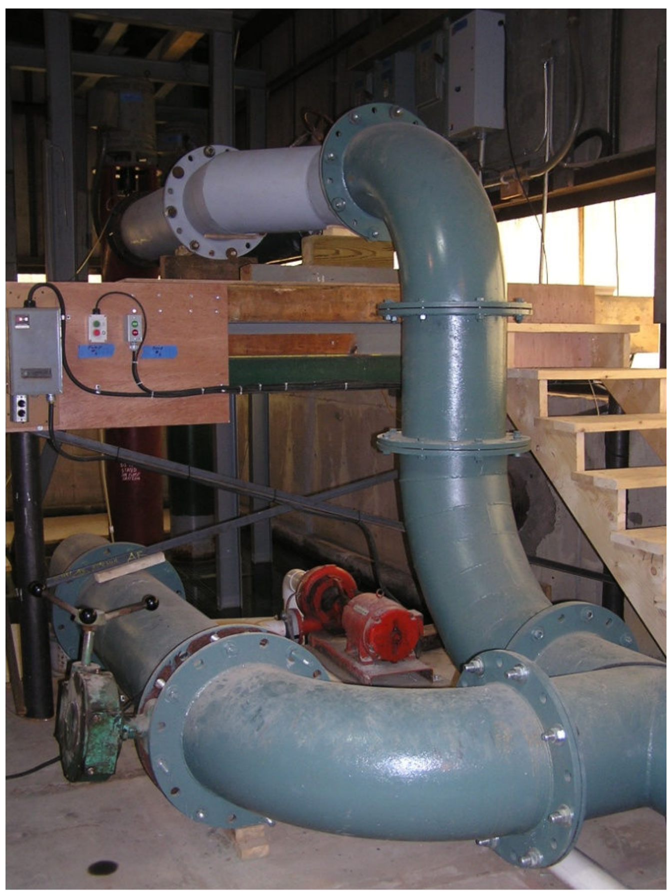
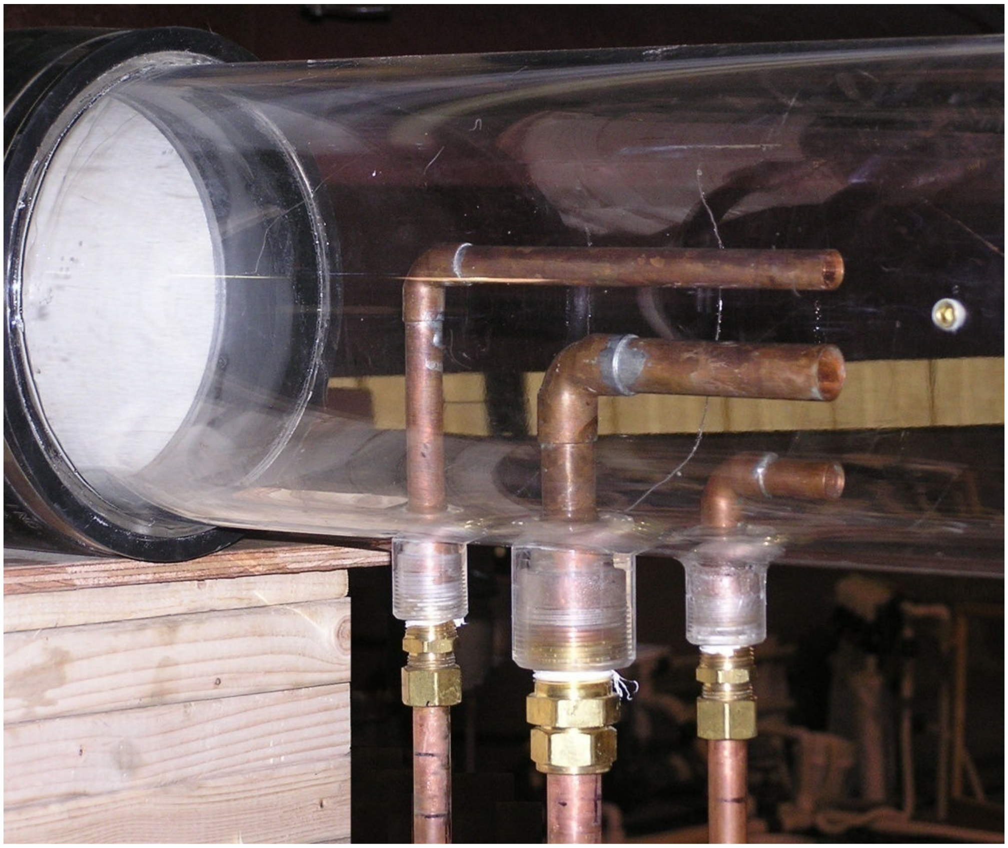


Figure 3: Alden's Stormwater Laboratory Flow Loop





Figures 4 & 5: Test Loop Flow Meters and 50 HP Pumps



Figures 6 & 7: Sampling Tube Array and Volumetric Screw Feeder

Range	**Target**	Mesh	Microns	NJ # 00N	OK-110	Min-U-Sil 40	%	%	%	**Total**
	NJCAT			11%	46%	43%				
		20	850							
500-1000	**5%**	30	600	45			5.0			**5.0**
		40	425	52			5.7			
250-500	**5%**	50	300	3			0.3			**6.1**
		70	212							
		100	150		1			0.5		
100-250	**30%**	120	125		15			6.9		
		140	106		48			22.1		**29.4**
		170	88		24			11.0		
50-100	**15%**	200	75		9.7			4.5		
		270	53		1.9			0.9		**16.4**
8-50	**25%**					60			25.8	**25.8**
2-8	**15%**					28			12.0	**12.0**
1-2	**5%**					12			5.2	**5.2**
		Total		100	99.6	100				**99.8**

Figure 8: Test sediment mix using commercially available US Silica sand

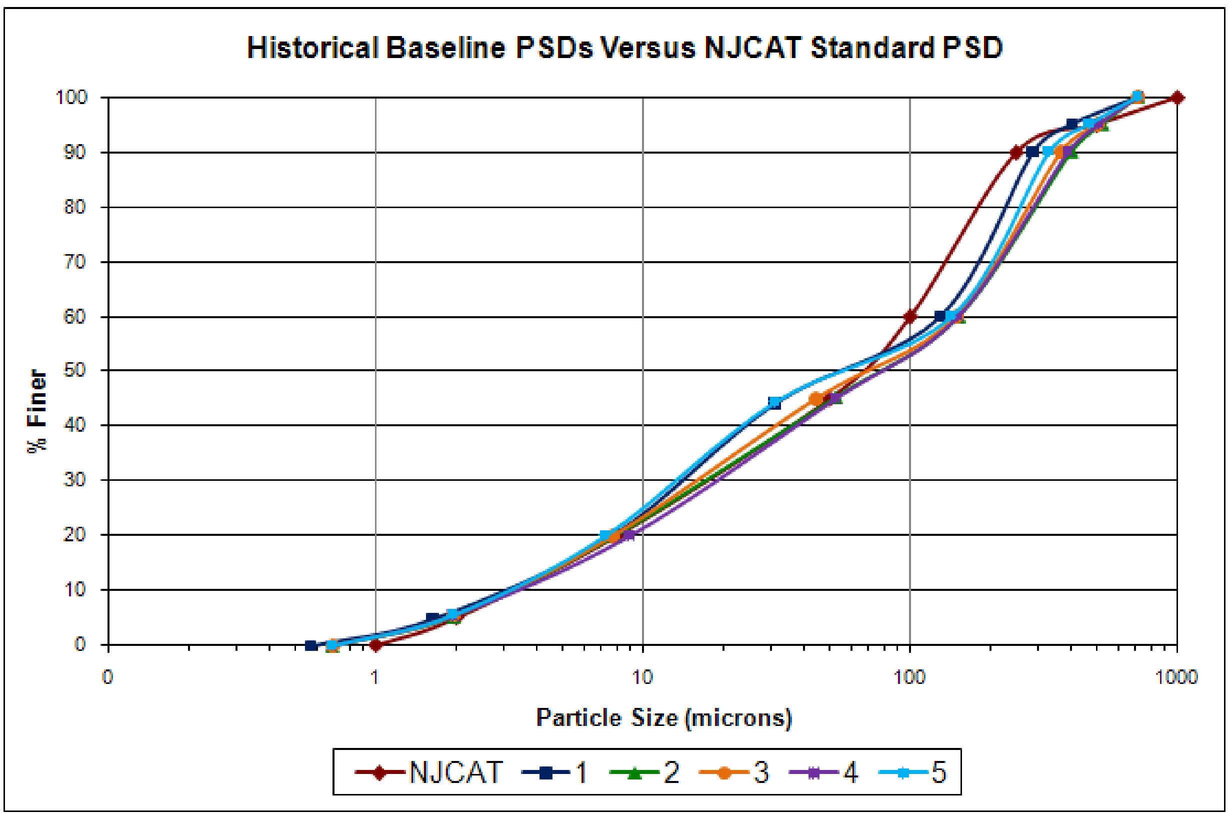


Figure 9: Test sediment mix PSD

F60 (as provided by US Silica)

mesh	microns	% retained	% Finer
30	600	0	100
40	425	4	96
50	300	19	77
70	212	35	42
100	150	29	13
140	106	11	2
200	75	2	0

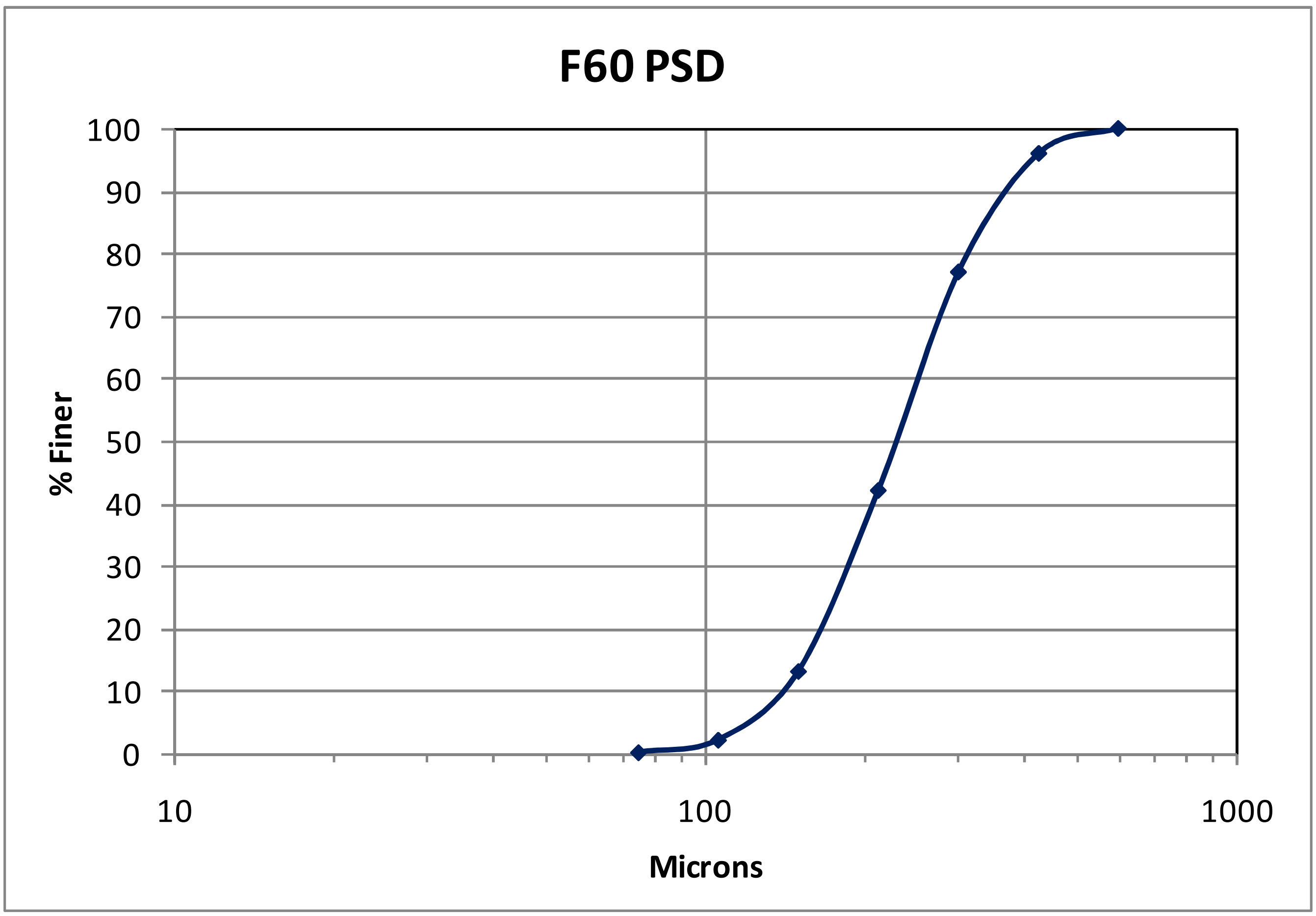


Figure 10: US Silica F60 Test Sediment PSD

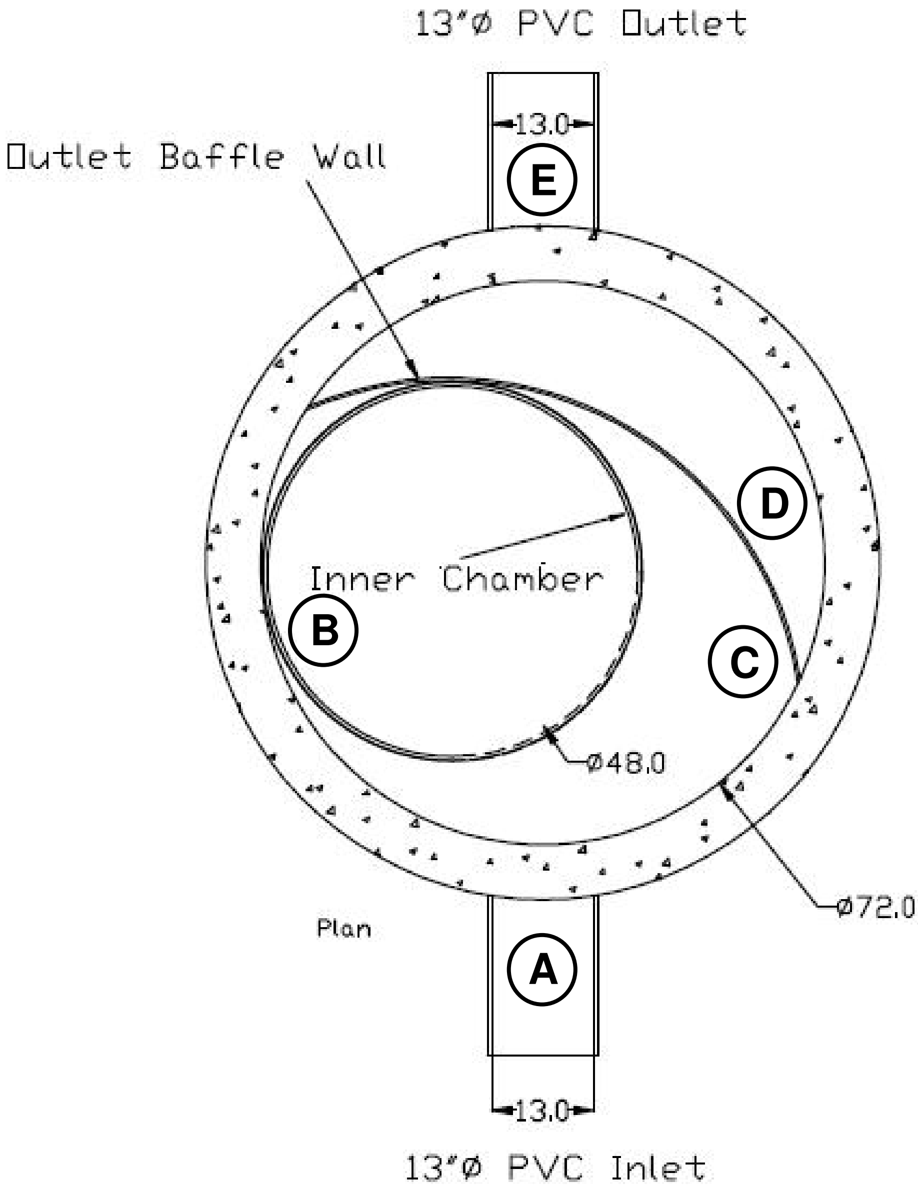


Figure 11: Pressure Tap Locations

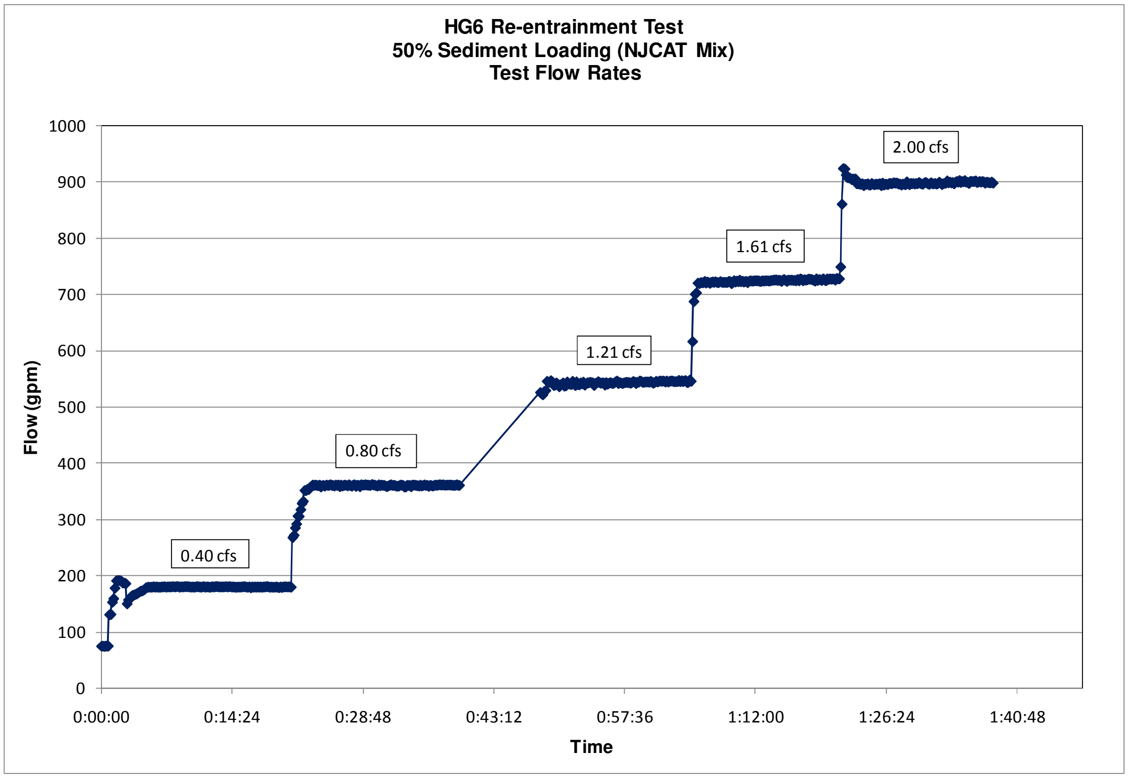


Figure 12: 50% Flow Trace Graph

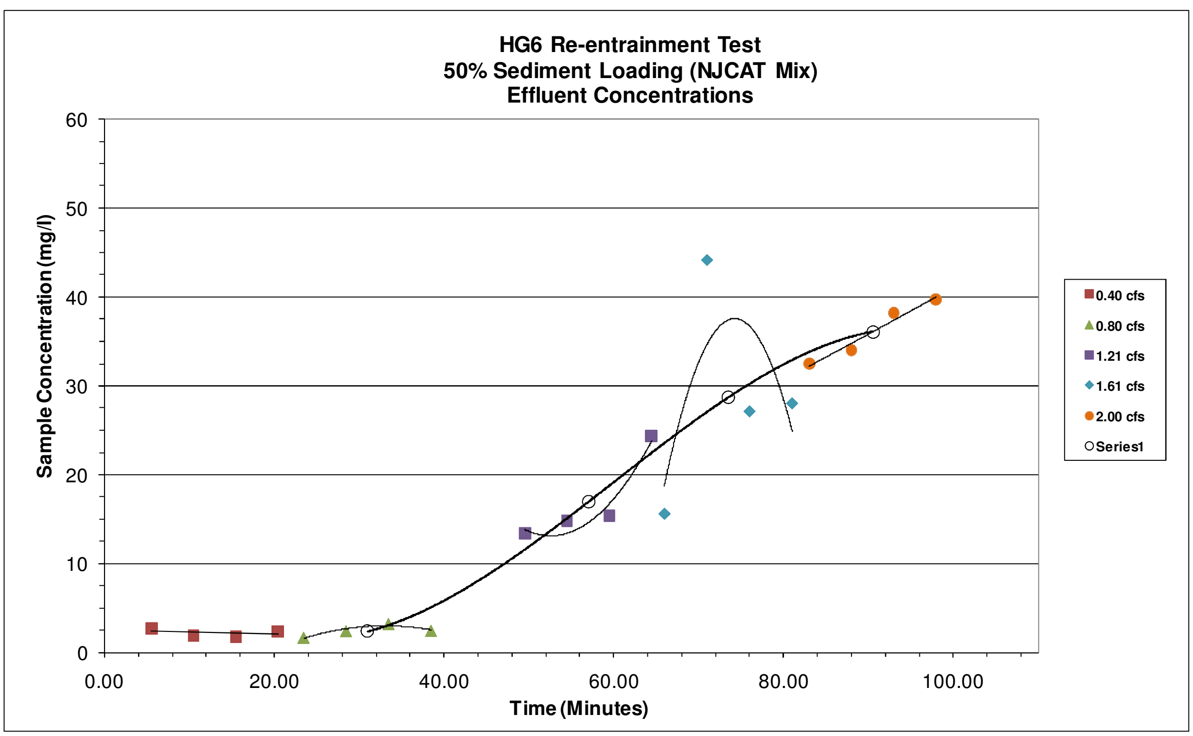


Figure 13: Re-entrainment Effluent Sample Concentrations at 50% Loading Capacity

2.00 cfs		1.61 cfs		1.21 cfs		0.8 cfs		0.4 cfs	
conc.	36.1	conc.	28.7	conc.	17.0	conc.	2.4	conc.	2.2
Size (um)	% Finer	Size (um)	% Finer	Size (um)	% Finer	Size (um)	% Finer	Size (um)	% Finer
0.711	0	0.711	0	0.711	0	0.711	0	0.711	0
2.331	10	2.600	10	1.799	10	1.138	10	1.233	10
4.379	25	5.021	25	4.031	25	2.497	25	2.166	25
8.236	50	9.438	50	8.777	50	5.339	50	4.048	50
14.56	75	16.70	75	17.26	75	11.04	75	8.978	75
21.48	90	24.93	90	27.40	90	19.44	90	19.24	90
44.35	98.64	44.35	98.56	38.83	95.05	31.20	98.56	37.20	99.03
48.43	100	48.43	100			34.07	100	44.35	100

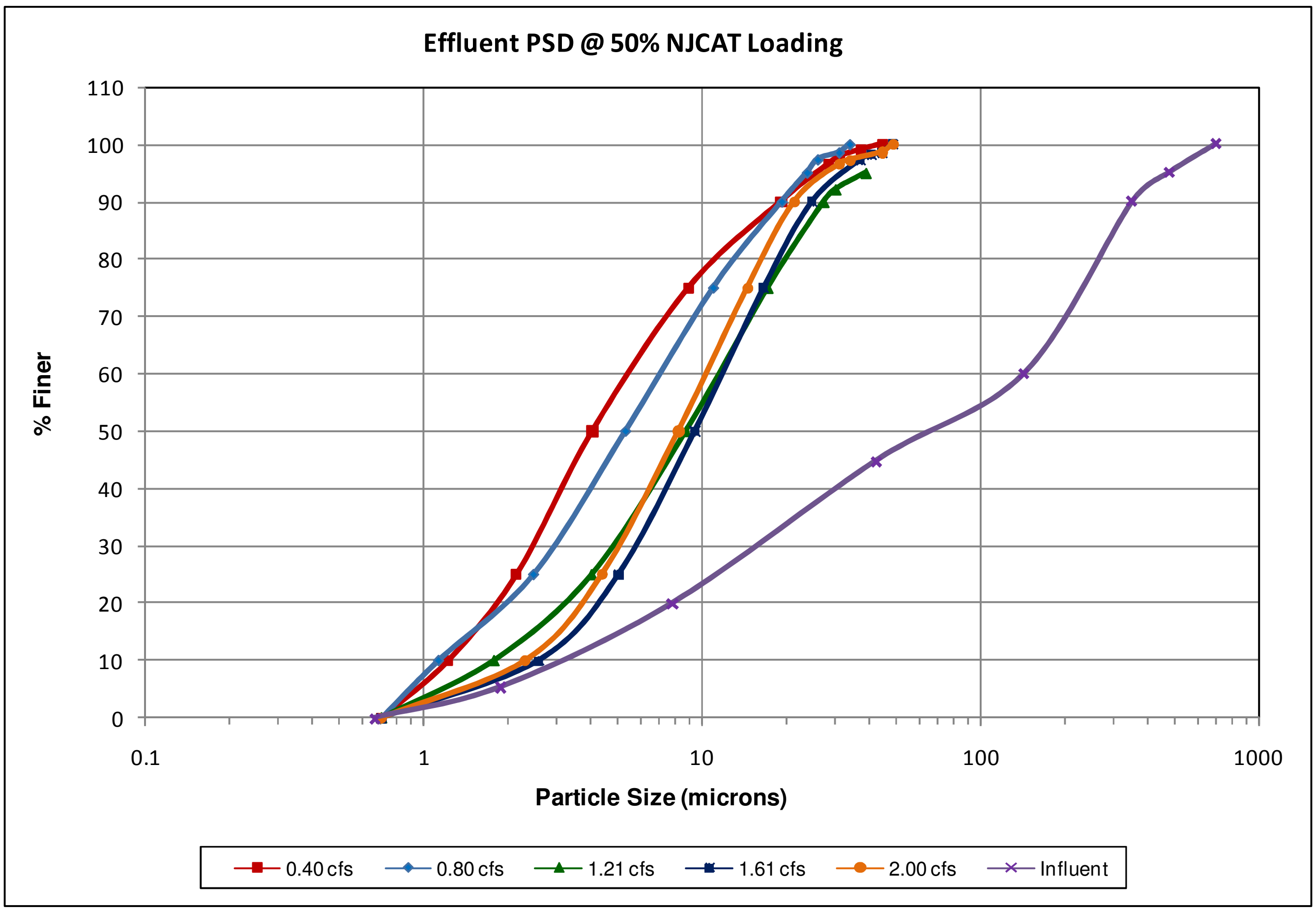


Figure 14: Re-Entrainment Effluent PSD Analyses at 50% Loading Capacity

Figure 15: 50% Sediment Bed After Re-entrainment Testing – Inner Chamber

Figure 16: 50% Sediment Bed After Re-entrainment Testing – Middle Chamber

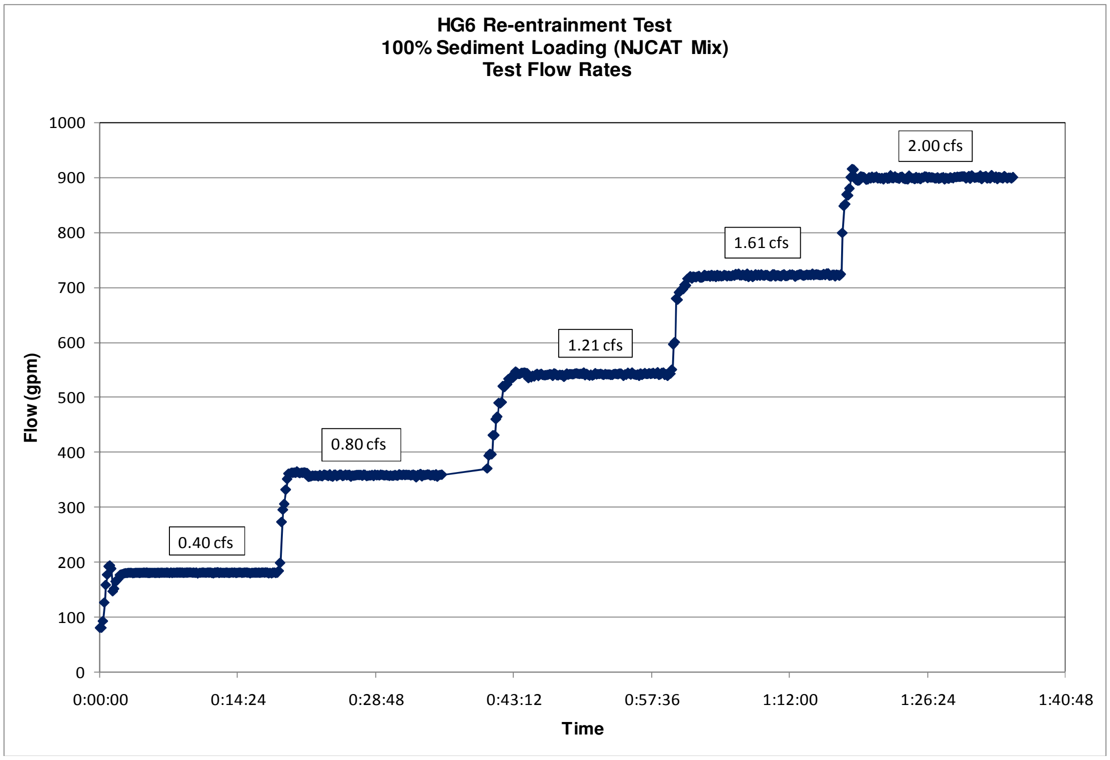


Figure 17: 100% Flow Trace Graph

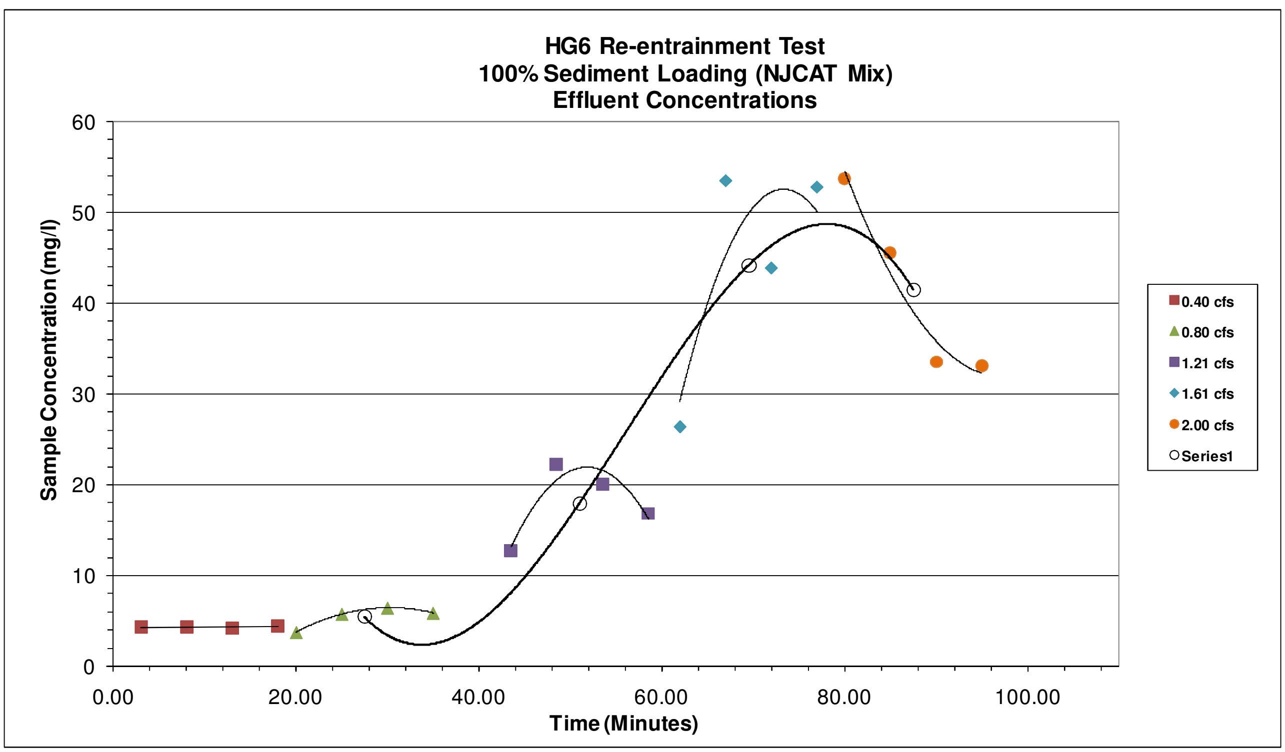


Figure 18: Re-entrainment Effluent Sample Concentrations at 100% Loading Capacity

2.00 cfs		1.61 cfs		1.21 cfs		0.8 cfs		0.4 cfs	
conc.	41.5	conc.	44.1	conc.	17.9	conc.	5.4	conc.	4.3
Size (um)	% Finer	Size (um)	% Finer	Size (um)	% Finer	Size (um)	% Finer	Size (um)	% Finer
0.711	0	0.711	0	0.711	0	0.711	0	0.711	0
2.516	10	2.836	10	2.608	10	1.532	10	1.004	10
4.985	25	5.534	25	5.253	25	3.251	25	1.772	25
10.08	50	11.03	50	10.82	50	7.671	50	3.753	50
18.10	75	18.82	75	18.88	75	16.10	75	11.23	75
25.39	90	26.58	90	26.8	90	24.46	90	23.88	90
40.62	98.99	48.43	99.15	48.43	98.44	39.33	99.25	44.22	96.36

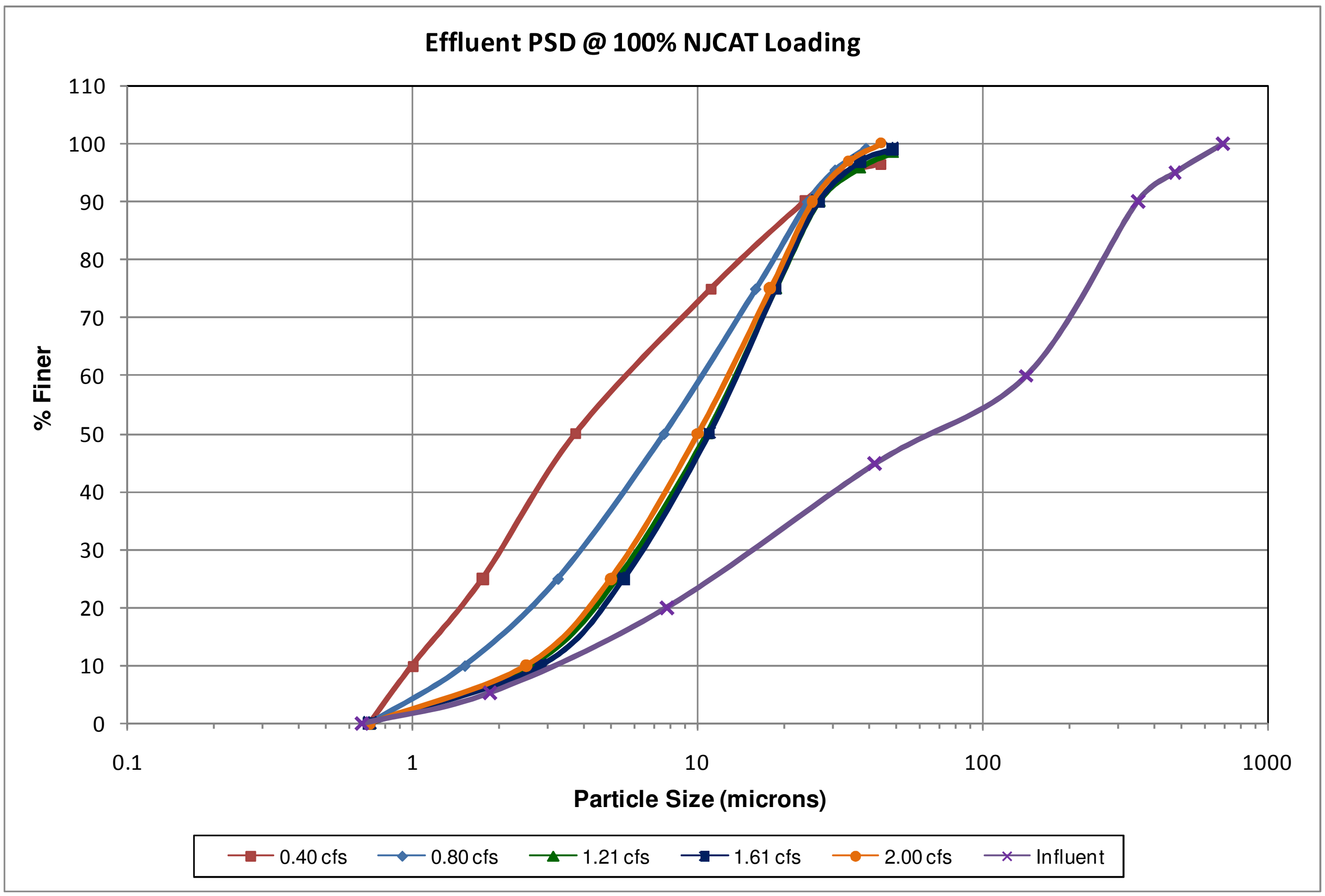


Figure 19: Re-Entrainment Effluent PSD analyses at 100% Loading Capacity

Figure 20: 100% Sediment Bed After Re-entrainment Testing – Inner Chamber

Figure 21: 100% Sediment Bed After Re-entrainment Testing – Middle Chamber

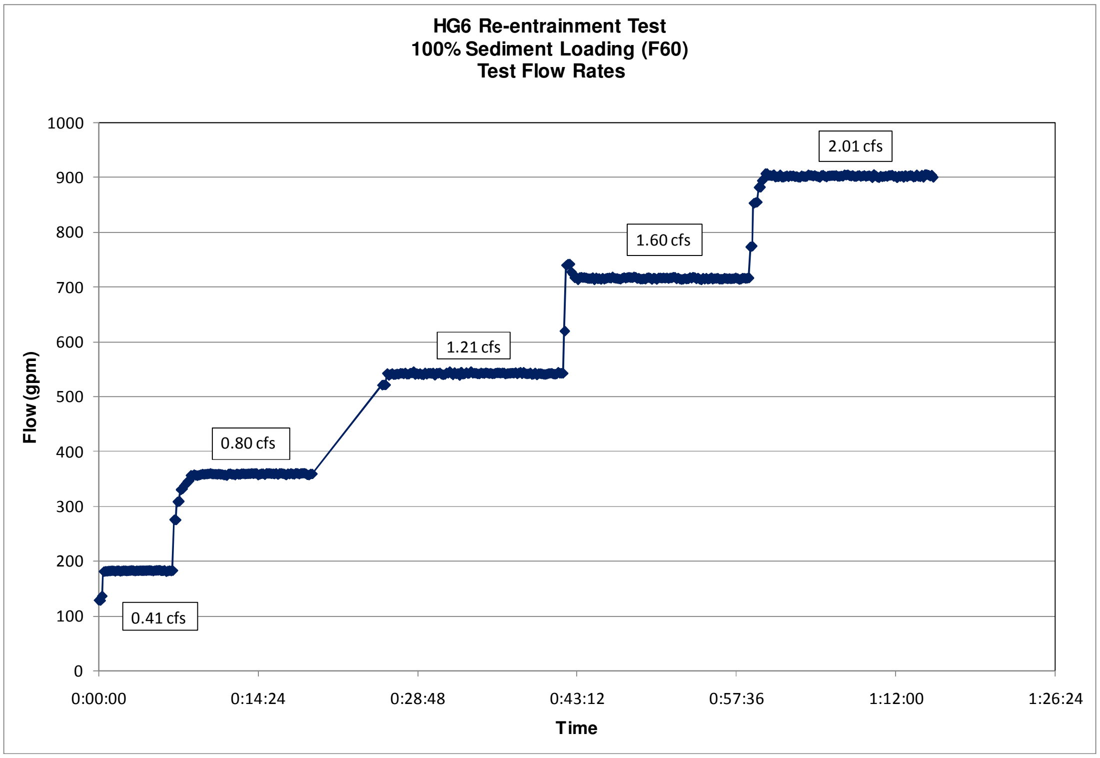


Figure 22: F60 Re-entrainment Test Flow Trace Graph

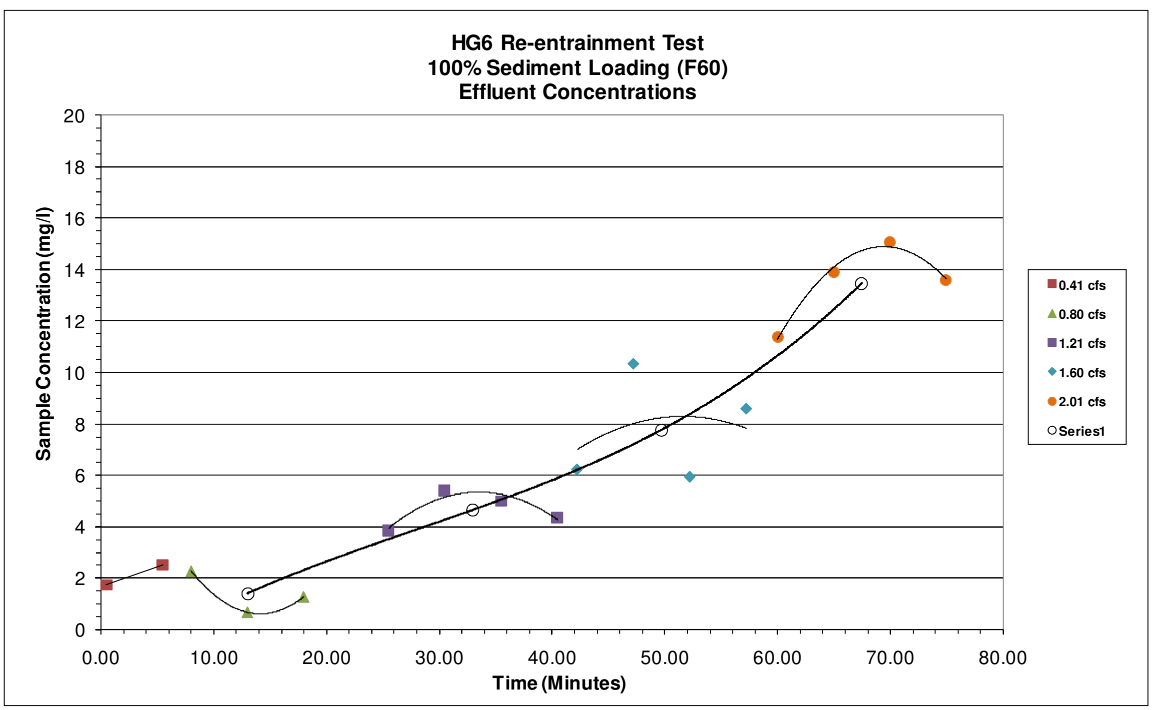


Figure 23: F60 Re-entrainment Test Effluent Sample Concentrations
at 100% Loading Capacity

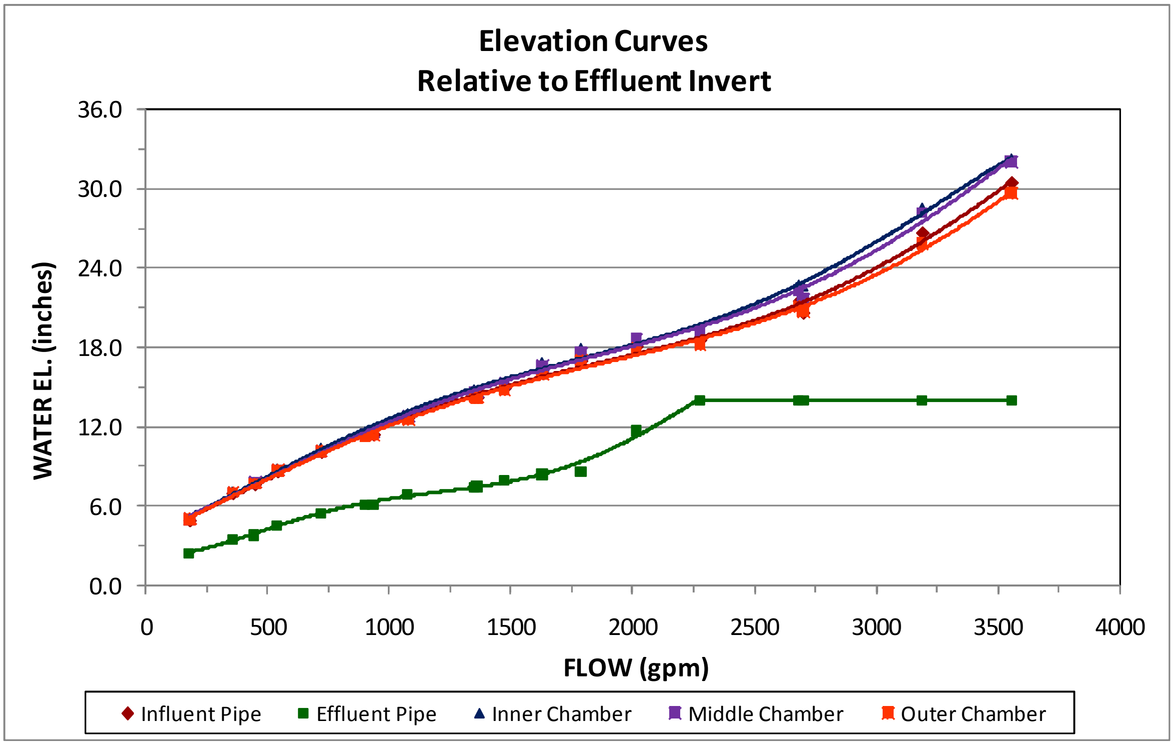


Figure 24: Elevation Curves

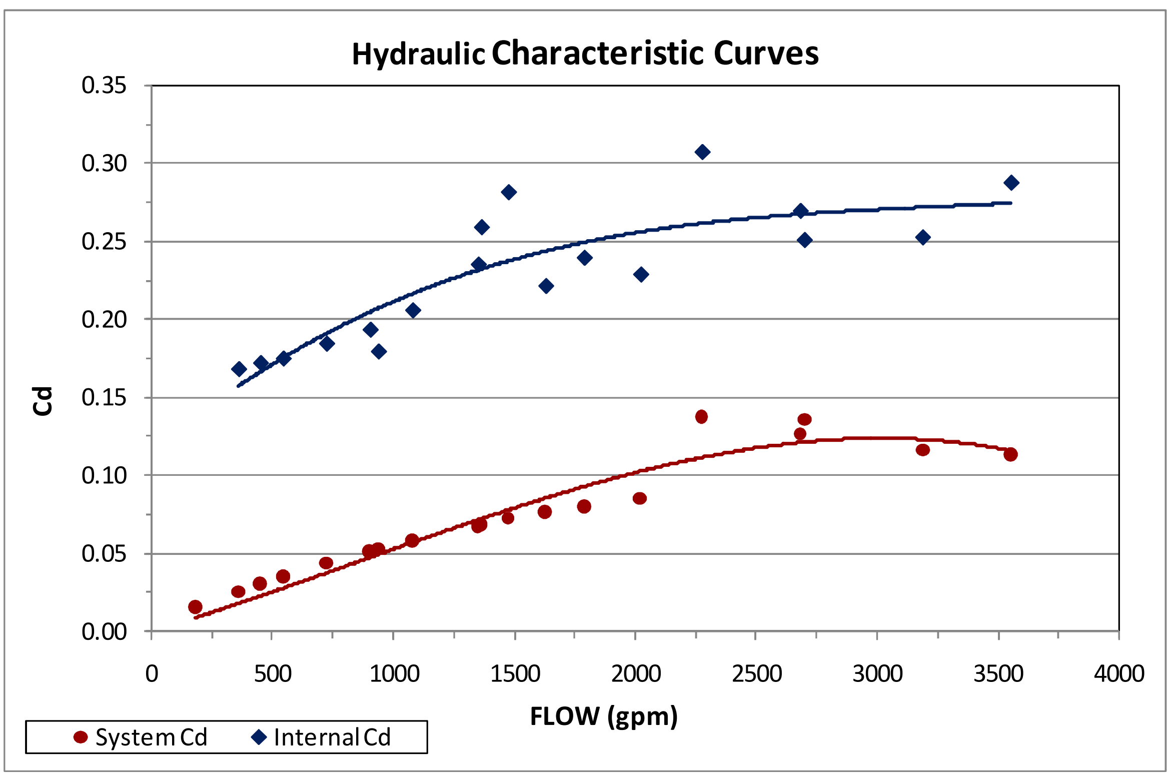


Figure 25: Hydraulic Characteristic Curves

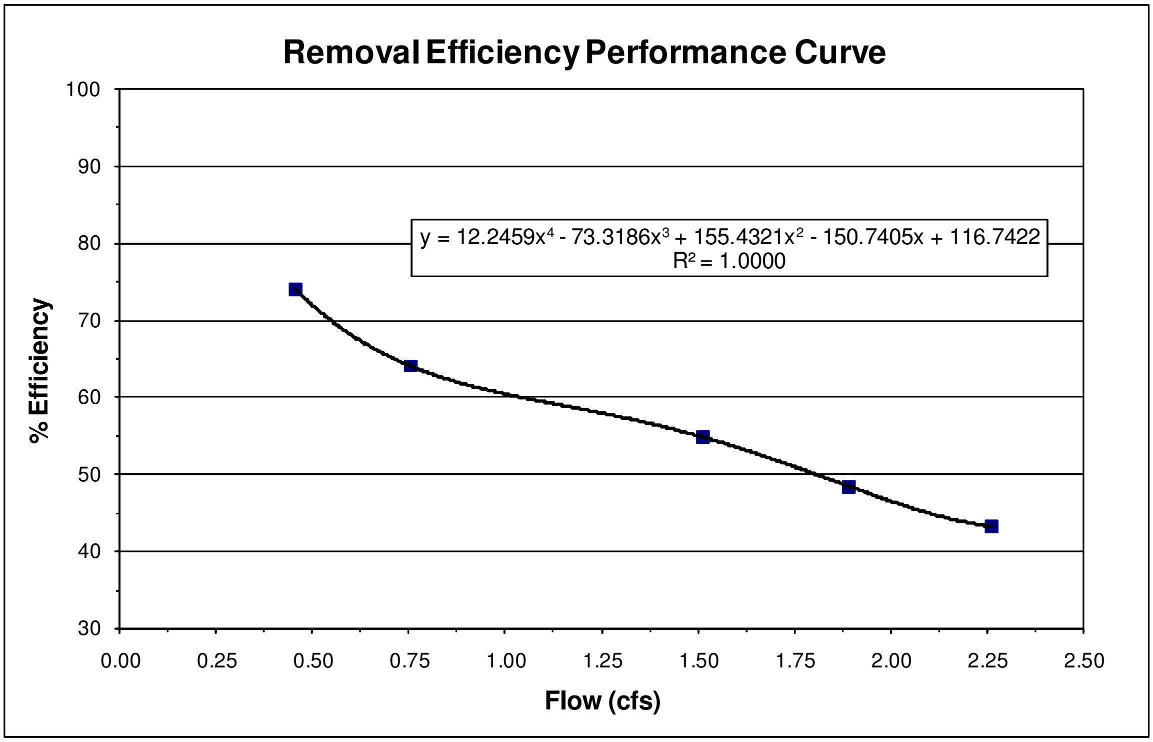


Figure 26: Removal Efficiency Curve

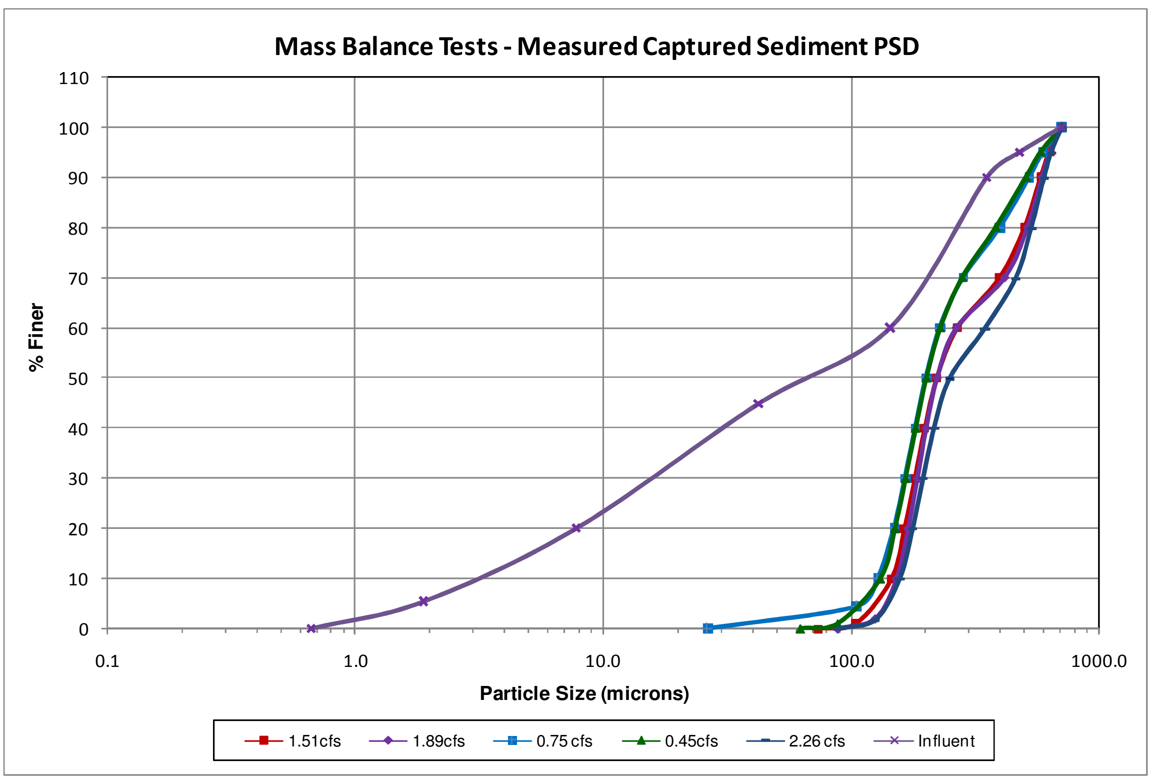


Figure 27: Captured Sediment PSD

APPENDIX A
NJCAT LABORATORY TESTING PROTOCOL

December 23, 2003

Total Suspended Solids Laboratory Testing Procedure

1. Particle size distribution
2. Full scale laboratory testing requirements
3. Measuring treatment efficiency

1. Particle size distribution

The following particle size distribution will be utilized to evaluate a manufactured treatment system. A natural/commercial soil representing U.S.D.A. definition of a sandy loam material. This hypothetical distribution was selected as it represents the various particles that would be associated with typical stormwater runoff from a post construction site.

Specifically, the following distribution can be utilized:

Particle Size (microns)	Sandy loam (percent by mass)
500-1000 (coarse sand)	5.0
250-500 (medium sand)	5.0
100-250 (fine sand)	30.0
50-100 (very fine sand)	15.0
2-50 (silt)	(8-50 um, 25%) (2-8 um, 15%)*
1-2 (clay)	5.0

Notes:

1. Recommended density of particles ≤2.65 g/cm3

*The 8 um diameter is the boundary between very fine silt and fine silt according to the definition of American Geophysical Union. The reference for this division/classification is: Lane, E. W., et al. (1947). "Report of the Subcommittee on Sediment Terminology," Transactions of the American Geophysical Union, Vol. 28, No. 6, pp. 936-938.

2. Full Scale lab test requirements
   A. At a minimum, complete a total of 15 test runs. 3 tests each at a constant flow rate of 25, 50, 75, 100, and 125 percent of the treatment flow rate. These tests should be operated with initial sediment loading of 50% of the unit's capture capacity.
   B. The 3 tests for each treatment flow rate will be conducted for influent concentrations of 100, 200, and 300 mg/l.
   C. For an online system, complete 2 tests at the maximum hydraulic operating rate. Utilizing clean water, the tests will be operated with initial sediment

loading at 50% and 100% of the unit's capture capacity. These tests will be utilized to check the potential for TSS resuspension and washout.

D. The test runs should be conducted at a temperature between 73-79 degrees Fahrenheit or colder.

3. Measuring treatment efficiency
   A. Calculate the individual removal efficiency for the 15 test runs.
   B. Average the three test runs for each operating rate.
   C. The average percent removal efficiency will then be multiplied by a specified weight factor (see table below) for that particular operating rate.
   D. The results of the 5 numbers will then be summed to obtain the theoretical annual TSS load removal efficiency of the system.

Treatment operating rate	Weight factor	
25%	.25	
50%	.30	
75%	.20	
100%	.15	
125%	.10	

Notes:

Weight factors were based upon the average annual distribution of runoff volumes in New Jersey and the assumed similarity with the distribution of runoff peaks. This runoff volume distribution was based upon accepted computation methods for small storm hydrology and a statistical analysis of 52 years of daily rainfall data at 92 rainfall gages.

A vendor shall submit for review and approval a quality assurance project plan supporting the above TSS Lab Test Procedure to the NJDEP and NJCAT prior to commencement of the full-scale lab tests. The plan shall provide procedures and methods to be followed in conducting the lab test (i.e. sampling design and methods, laboratory procedures, analytical methods, quality control, schematic of testing apparatus).