

Bench Top Screen Penetration Test (Water Type Sensitivity Analysis)



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A report submitted by

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REVISION HISTORY

August 2012: 1.0 First Release.

October 2012: 1.1. Added Conductivity of tap water and DI-Water (section 3.1)

PURPOSE

This document is intended to provide an overview of the tests performed, a detailed description of the test facility used, the methodology applied and the results obtained.

The purpose of the experiment is to study the sensitivity of water type on debris bypass fraction (weight). Two different types of water were used to conduct the experiments:

- Tap water
- Buffered/Borated water

For each type of water, the test was repeated four times in order to have a representative statistical sample to be used for the comparison of the results.

1. EXPERIMENTAL FACILITY DESCRIPTION

Figure 1 shows an overview of the experimental facility with a detailed view of the main components.

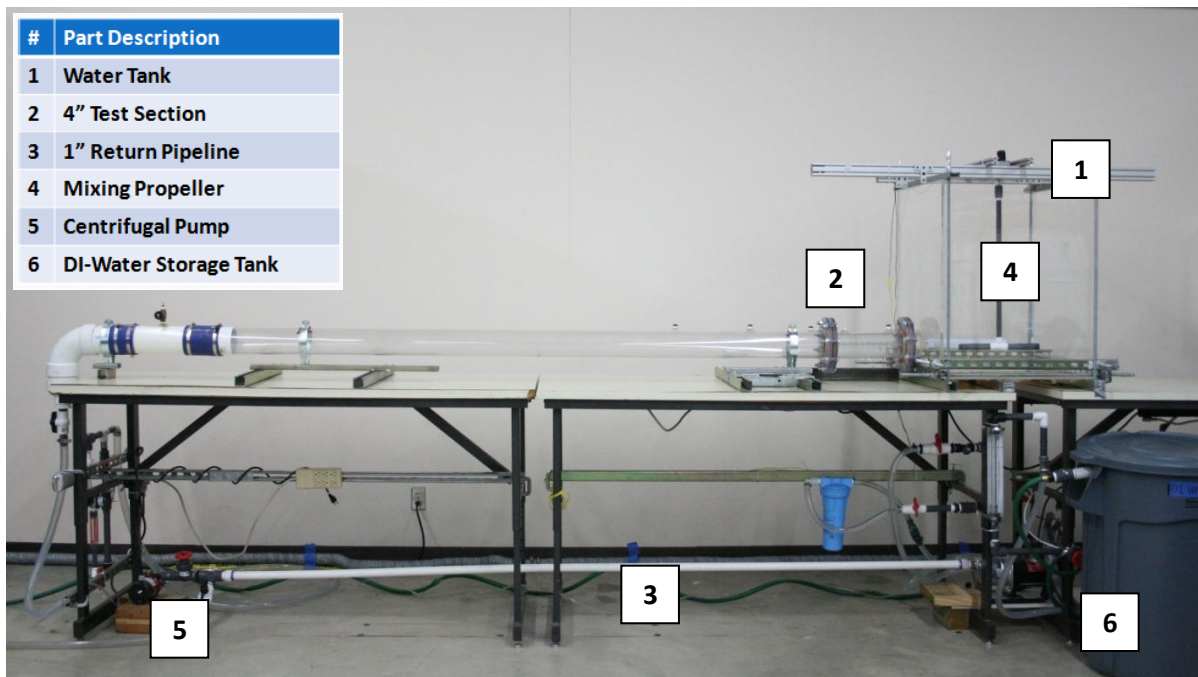


Figure 1. Experimental Facility Overview

The facility is semi-closed loop, consisting of (1) an open water tank (24" length, 24" width, and 30" height), (2) a horizontal 4" ID pipe (test section) connected to the side of the tank, and (3) a 1" ID return pipeline connected to the bottom of the tank. The water tank is made by acrylic panel of 0.5" thickness to allow visualization of the debris. To keep a uniform concentration of the debris in the water inside the

tank, (4) a rotating propeller mixes the debris. The water exits the tank through a 4" ID hole located on the side where the horizontal test section is attached. A detailed view of the water tank, the propeller and the water exit is shown in Figure 2.

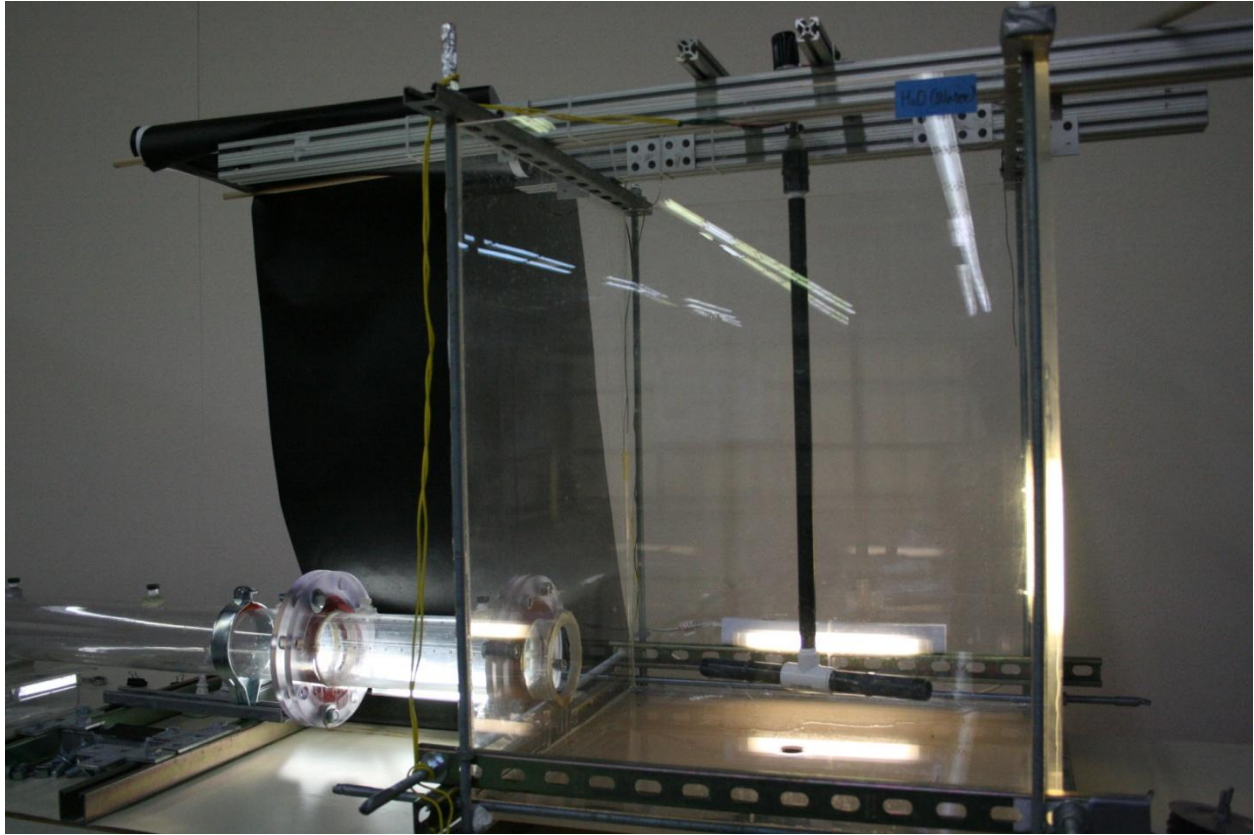


Figure 2. Water Tank Overview

The 4" ID, 4.25" OD polycarbonate pipe makes the test section. This section is subdivided in different parts connected with flanges. A perforated stainless steel plate was manufactured to simulate the sump strainer following the given specifications of:

- Hole Diameter
- Hole x and y pitch
- Plate Thickness and Material

The plate has a perforated section of 4" in diameter which fits the flow section of the polycarbonate pipe. Eight holes were machined at the edge of the plate to allow its connection between the flanges. A detailed view of the perforated plate and its connection at the test section are presented in Figure 3.



Figure 3. Strainer Plate (left) and its Location in the Test Section (right)

A centrifugal pump (5, in Figure 1) provides the required volumetric flow rate in the test section to reach the desired approaching velocity. A rotameter is installed upstream of the mentioned pump to read the volumetric flow rate. The flow rate is set up by changing the opening position of a PVC gate valve. Figure 4 shows the centrifugal pump and the mentioned devices used to setup the desired approaching velocity.

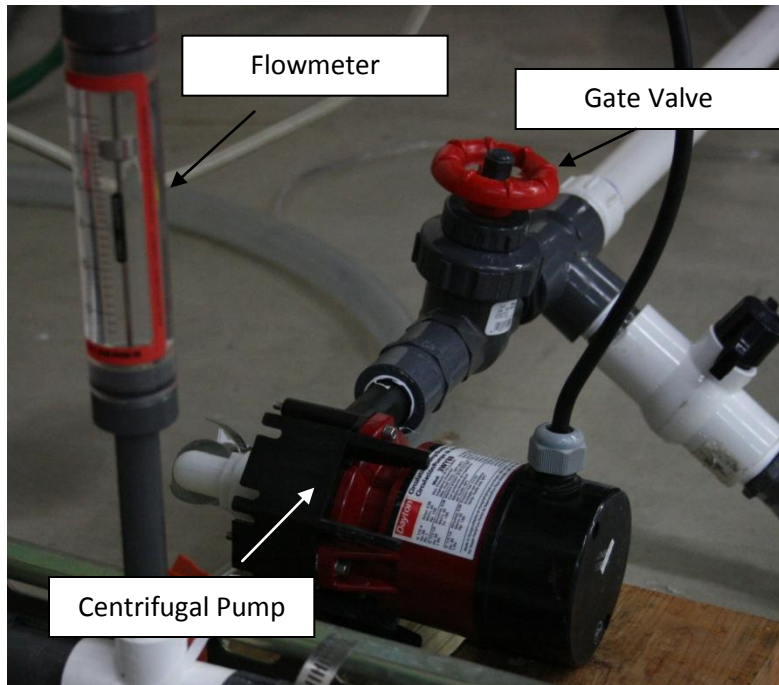


Figure 4. Centrifugal Pump and Flow Control

An additional pump was installed and is in use only during the cleaning operations between tests; it allows recirculation of the water within a battery of filters with high volumetric flow rates. There are other PVC valves that facilitate the drainage and filling operations. All of the components installed in the facility, including the pumps and valves, are made with plastic materials or stainless steel to avoid any reaction with the buffered and borated water used during the tests.

The total volume of the facility, including tank, pipelines and other components is 83.29 gallons.

The buffered and borated water used in the tests, which will be described in details in the next sections, was produced with a Reversed Osmosis / De-Ionized (RO/DI) water purifying system (Vertex[®] Deluxe PuraTek) which provided treated water at 100 gallons per day (gpd).

2. TEST PROCEDURE

This section provides a detailed description of the procedure adopted to run the experiments. Some of these procedures are of common use for both the tap water and buffered/borated water tests and will be described in section 2.1. Section 2.2 will provide a description of the specific methodology applied for the buffered/borated water preparation. Section 2.3 describes the procedure adopted to measure the debris bypass quantity for each test.

2.1 General Procedure

Once the facility is cleaned from the previous experiment (see section 2.1.2 for description of the cleaning procedure), the strainer bypass filter is installed downstream of the strainer. The filter selected for these experiments is a 1 μ m heat-welded polyester felt bag with a plastic ring head of 4" which fits in the polycarbonate pipe inner surface. The filter bag plastic head was lined with vinyl tape and inserted into the polycarbonate pipe. Figure 5 shows the filter preparation steps which include tape lining (Figure 5a), filter insertion (Figure 5b), and final configuration (Figure 5c).

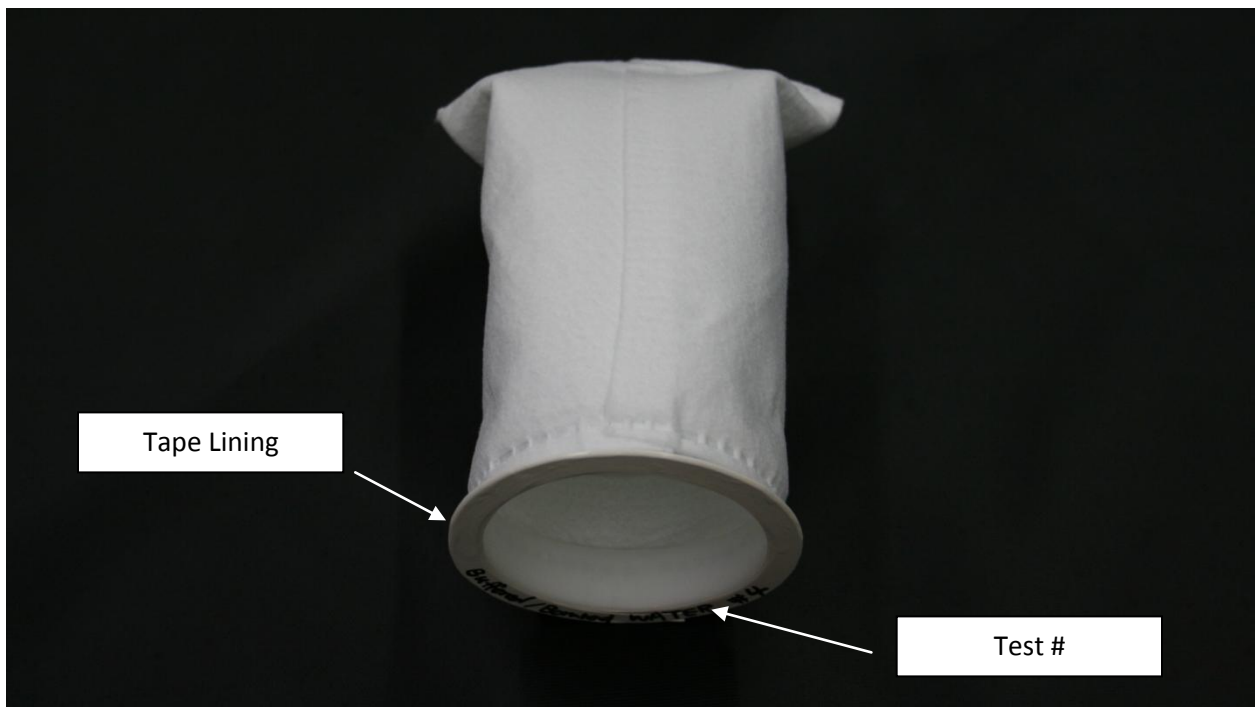


Figure 5a. Filter Bag (Before Test)

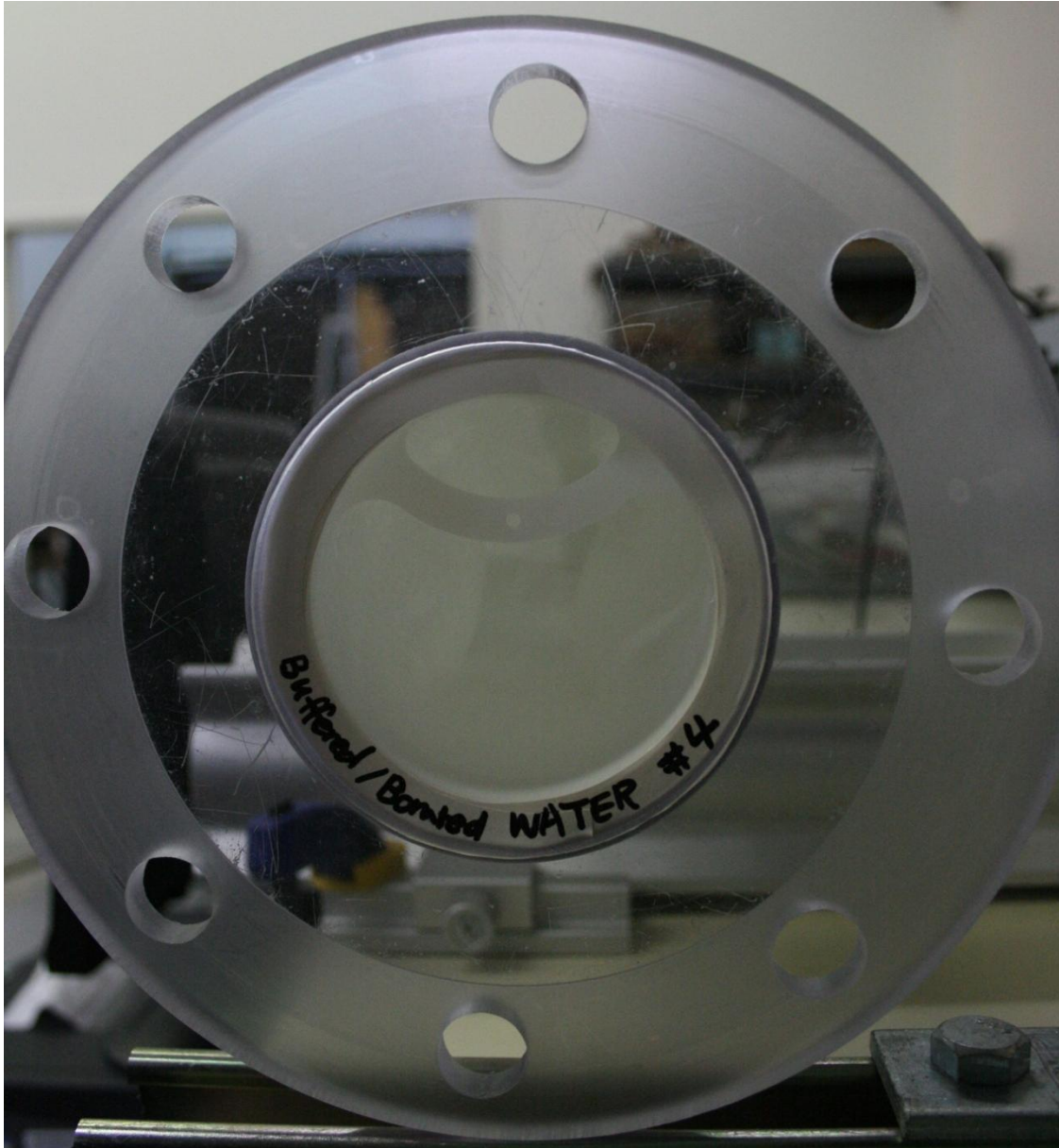


Figure 5b. Test Section Filter Bag Insertion

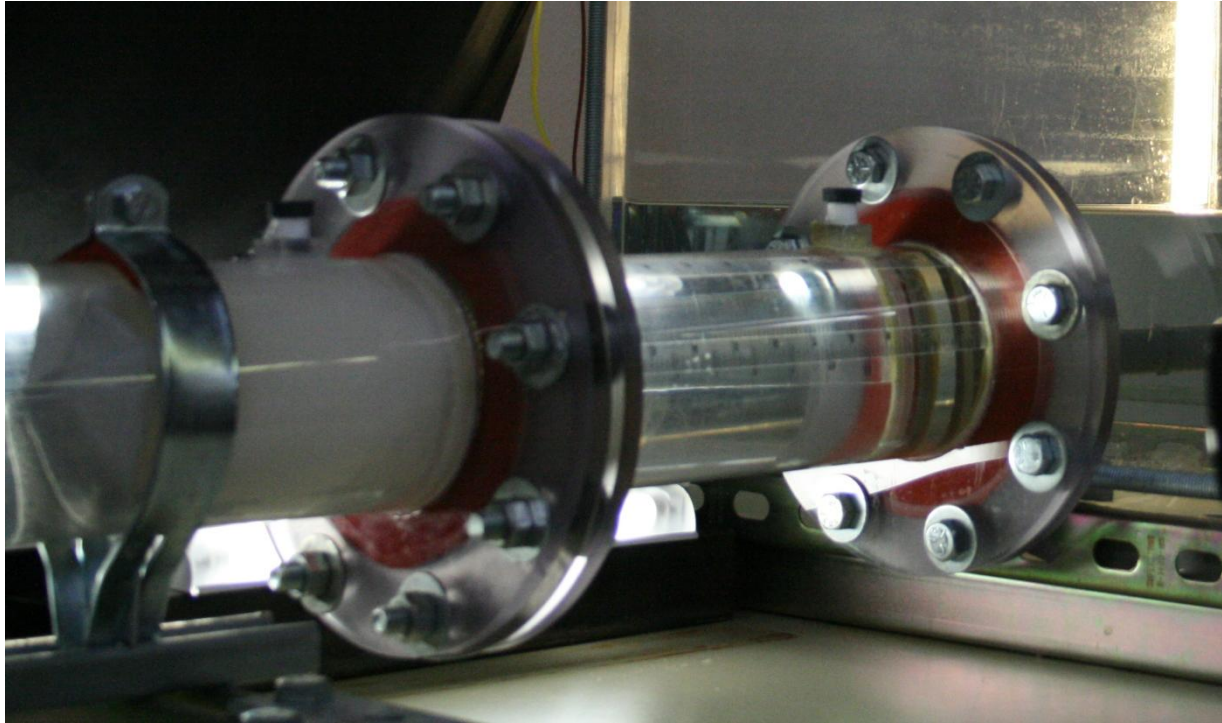


Figure 5c. Final Configuration

The facility was then filled with water (tap or buffered/borated depending on the test type). The final water level in the tank was selected to be 18.4 inches. This allowed the final level of the water (including the water injected with the debris) to reach 20 inches, corresponding to a total volume of water in the facility of 58.36 gallons. Six venting valves were installed on the top side of the horizontal pipe section to allow air trapped in the pipeline to be vented out during the filling phase. Figure 6 shows one of these venting valves used during this phase.

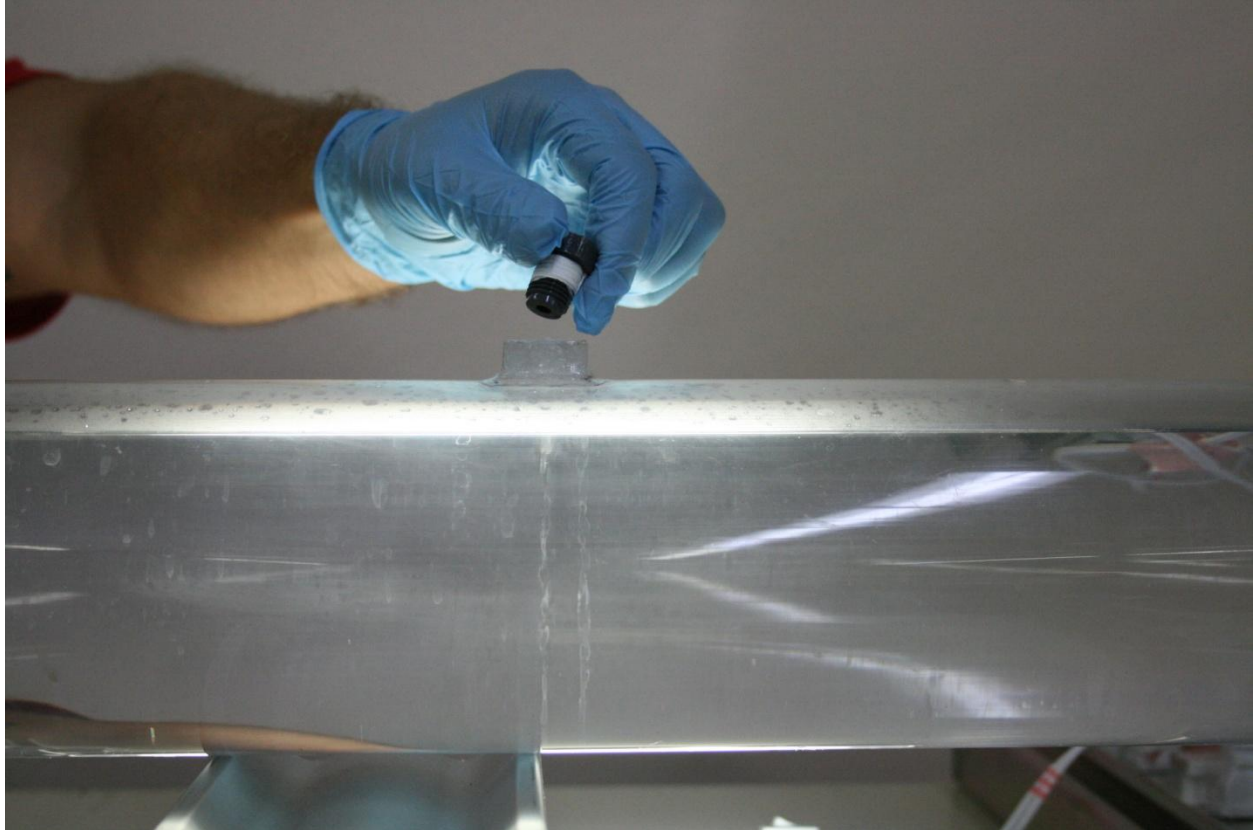


Figure 6. Venting Valve

The circulation centrifugal pump was turned on and the PVC gate valve aperture was increased gradually until the nominal volumetric flow rate of 24 g/h was achieved. This flow rate was selected in order to reach the desired water approaching velocity in the test section (0.01 ft/s).

The debris previously prepared using the NEI protocol described in section 2.1.1 (total water volume with debris was 4 gallons) was poured into the water tank while the mixing propeller spun. The selected debris concentration in the water tank at the beginning of each experiment was 0.09 volume percent (vol.%), corresponding to 0.0034 weight percent (wt.%). The total weight of debris used for each experiment was 6.6 g.

Each experiment was terminated at $t_{end} = 125$ min which corresponds to one turnover of the water in the tank at the selected volumetric flow rate.

During the experiment a camera, installed in front of the test section, recorded the flow and the debris bed generation. The movie recorded during each experiment was also used to estimate the final debris bed thickness (at $t = t_{end}$).

The water tank and the system was drained and cleaned at the end of the test in preparation for the next run. A detailed description of the procedure followed during this phase is reported in 2.1.2.

2.1.1 Debris Preparation Procedure

The NUKON debris was prepared using the NEI protocol reported in [1]. In particular, the procedure adopted aimed to produce fine debris defined in the NEI protocol. A brief description of the steps followed to produce the debris used for each test is reported in this section.

STEP 1: NUKON Debris Sampling and Weighting

The desired quantity of NUKON (6.6g) was sampled from a NUKON heat treated mat (PCI 2.5" x 24" x 48", Lot #10958HT). The NUKON mat where the samples were taken is shown in Figure 7.



Figure 7. NUKON® Mat

The sample cut from the mat was approximately 2.5" x 1.5" x 3" and was repeatedly trimmed on the edges in order to achieve the target weight. All the cuts on the samples were performed in a way that the full thickness of the sample was preserved in order to conserve the original characteristics of the heat treated mat. Once the weight displayed on the scale was steady, the sample was moved to the next step. The technical information of the scale used during the experiment preparation is reported in section 3.

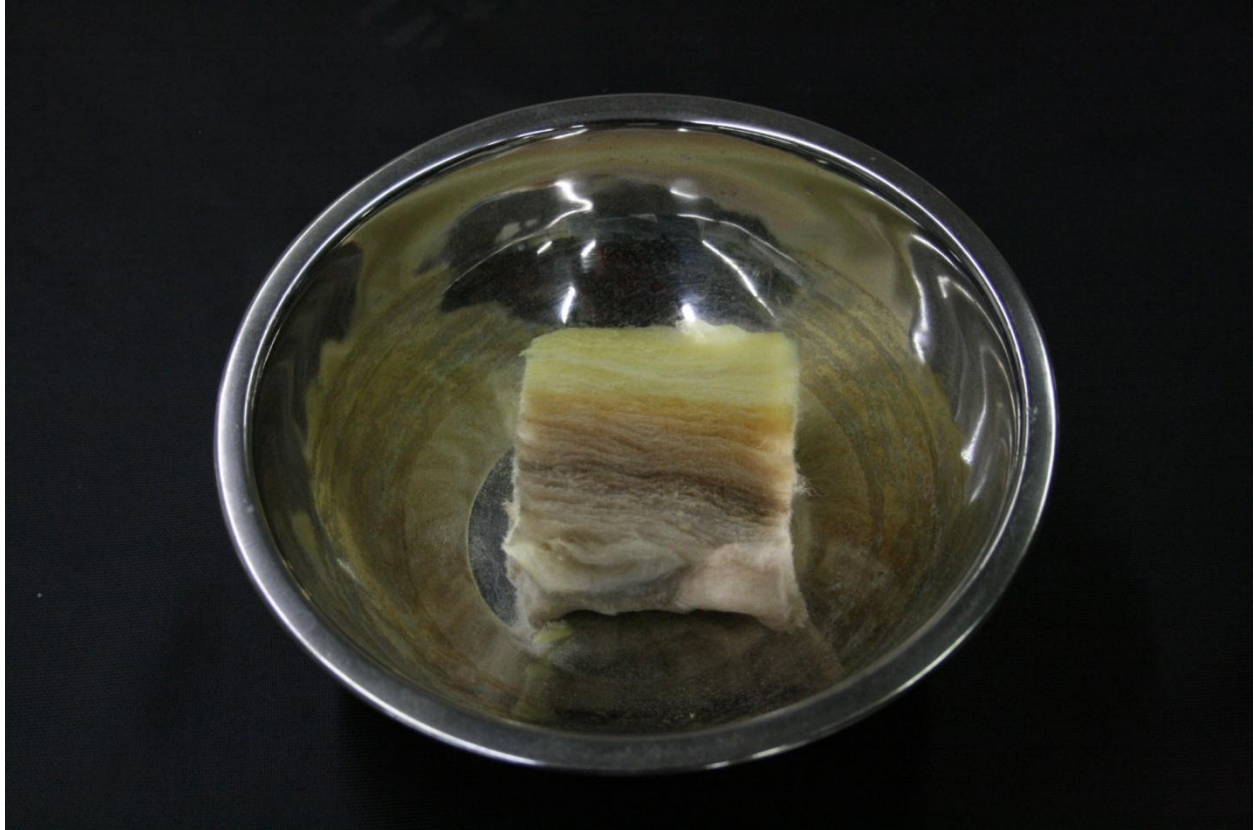


Figure 8. Debris Portion Selected from the NUKON® Mat



Figure 9. Debris Final Quantity

STEP 2: Sample Size Reduction

The sample was initially separated in four layers of approximately same thickness: two dark layers, corresponding to the side of the mat in contact with the hot surface used during the heat treatment, and two light layers, the opposite side of the mat (Figure 10a).



Figure 10a. Layers Separation

These layers were then cut in small pieces of approximately 1" x 1". The pieces originating from the light layers were additionally torn and all pieces were put in a plastic bucket (total capacity = 5 gallons) (Figure 10b).



Figure 10b. Debris Size Reduction

Approximately 0.5 gallons of water (tap water or DI-water depending on the test) were poured into the bucket to slightly cover the debris pieces (Figure 10c).



Figure 10c. Debris before High Pressure Jet Mixing

STEP 3: High Pressure Washer Jet Mixing

A high pressure (1800 psi) washer was used to break down and mix the debris previously stored in the plastic bucket (Figure 10d). The jet was kept submerged into the water in the bucket while it was turned on. The jet gun was moved randomly inside the bucket to allow uniform breaking and mixing. A 40° angle nozzle was used during this phase. Spraying ceased when the final amount of water in the bucket was approximately 4 gallons. This allowed uniform debris tearing and mixing.



Figure 10d. Pressure Washer Debris Mixing (left). Final Debris (right)

2.1.2 Cleaning Procedure

At the end of each experiment the system was carefully cleaned in order to remove debris from the previous experiment. After the recirculation pump was turned off, the test section was isolated from the water tank using a 4" end cap as shown in Figure 11.

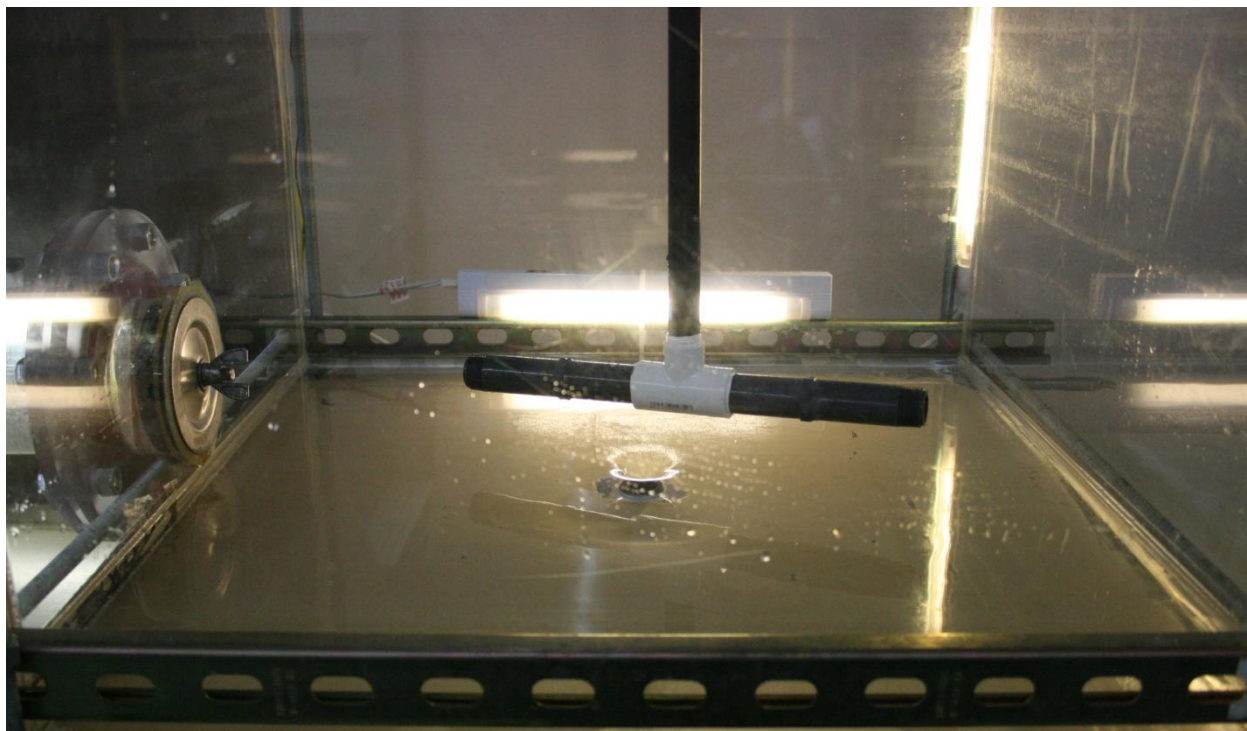


Figure 11. Water Tank Isolation Cap

End cap placement avoided any undesired flow through the filter that may cause a perturbation in the debris bypass quantity captured during the experiment. The water from the tank was slowly drained. When the water tank was completely emptied, the test section drainage valve was gradually opened to allow a very slow drainage of the water of the section. Once the entire facility was emptied, the test section was opened by removing the bolts at the flanged connection, and the filter was carefully removed from the test section. The flanged connection was re-established, and the facility was filled with tap water which was recirculated through the pipelines, pumps and other components for approximately 30 min at maximum flow rate (10 g/min) to remove the remaining debris. The water was completely drained and the procedure was repeated with clean tap water. During both cleaning steps, the water was forced to flow through a 1 μ m filter cartridge. For the test with buffered/borated water, an additional cleaning step was run using DI-water.

2.2 Buffered and Borated Water Preparation

The buffered and borated water was prepared mixing DI-water with 16g of Boric Acid (Optibor® Orthoboric Acid, H_3BO_3) and 3g of Trisodium Phosphate (SONI-LOK® TSP) per liter of water. For the given volume of the tank with the final liquid level of 20" (see section 2.1), the total amount of boric acid and TSP was (Figure 12a):

- Boric Acid: 3535 g
- TSP: 663 g



Figure 12a. Boric Acid (left) and TSP (right) Final Quantities

The mentioned quantities were poured into the water tank where approximately 10 gallons of DI-water were previously added (Figure 12b).

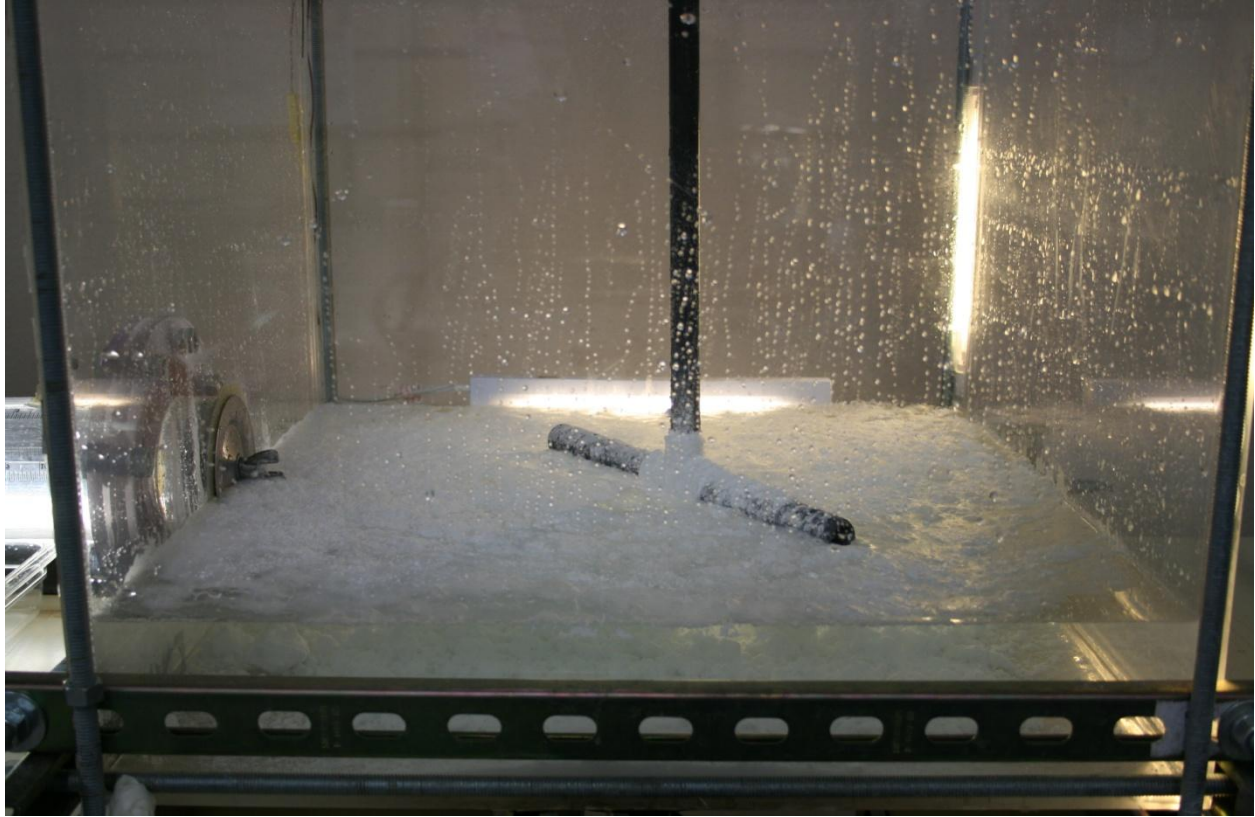


Figure 12b. Chemicals in the Tank before Mixing

The tank was also isolated from the test section using the end cap mentioned in section 2.1.2. Additional DI-water was injected into the tank using the high pressure washer gun to allow a fast and uniform dissolving of the chemicals into water (Figure 12c).

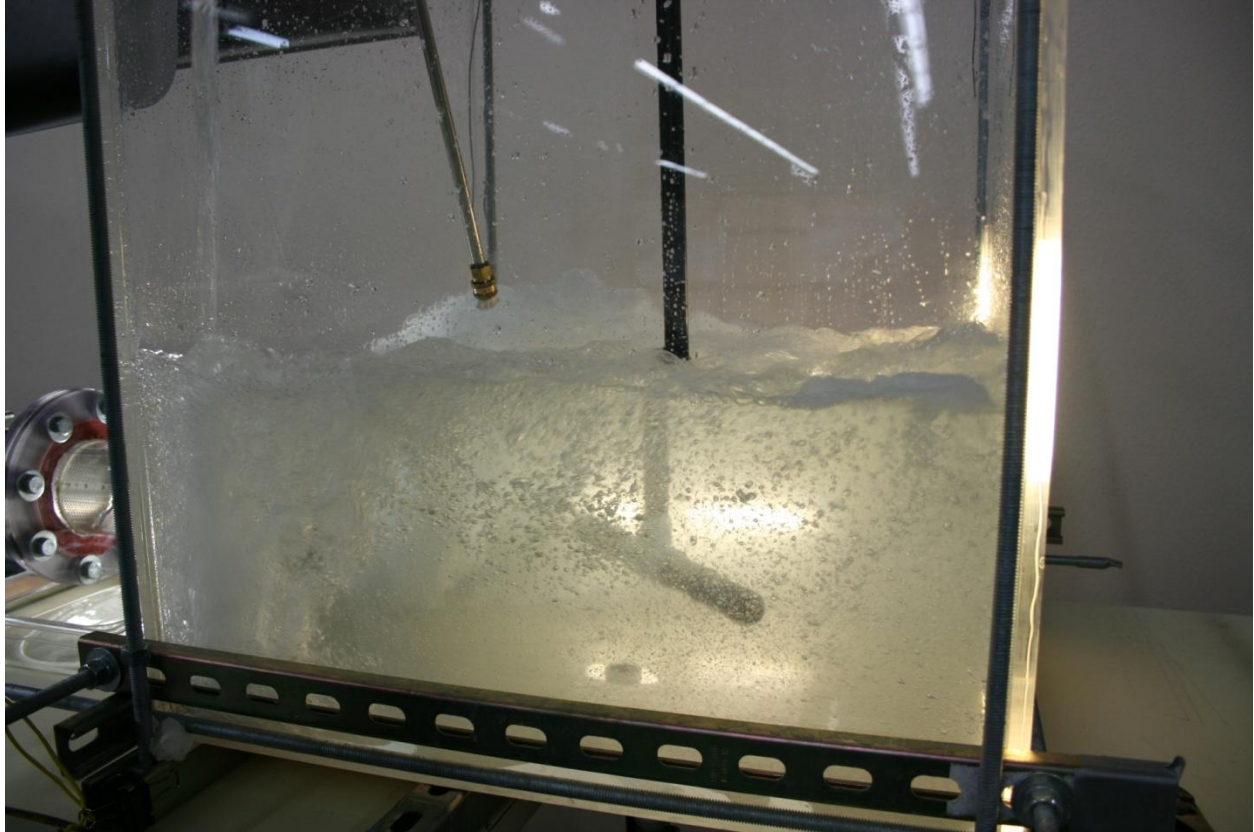


Figure 12c. Water Jet and Chemical Dissolution

The mixing was continued using propeller installed in the water tank until the water appeared clear and all the small chemical particles were totally dissolved (Figure 12d).

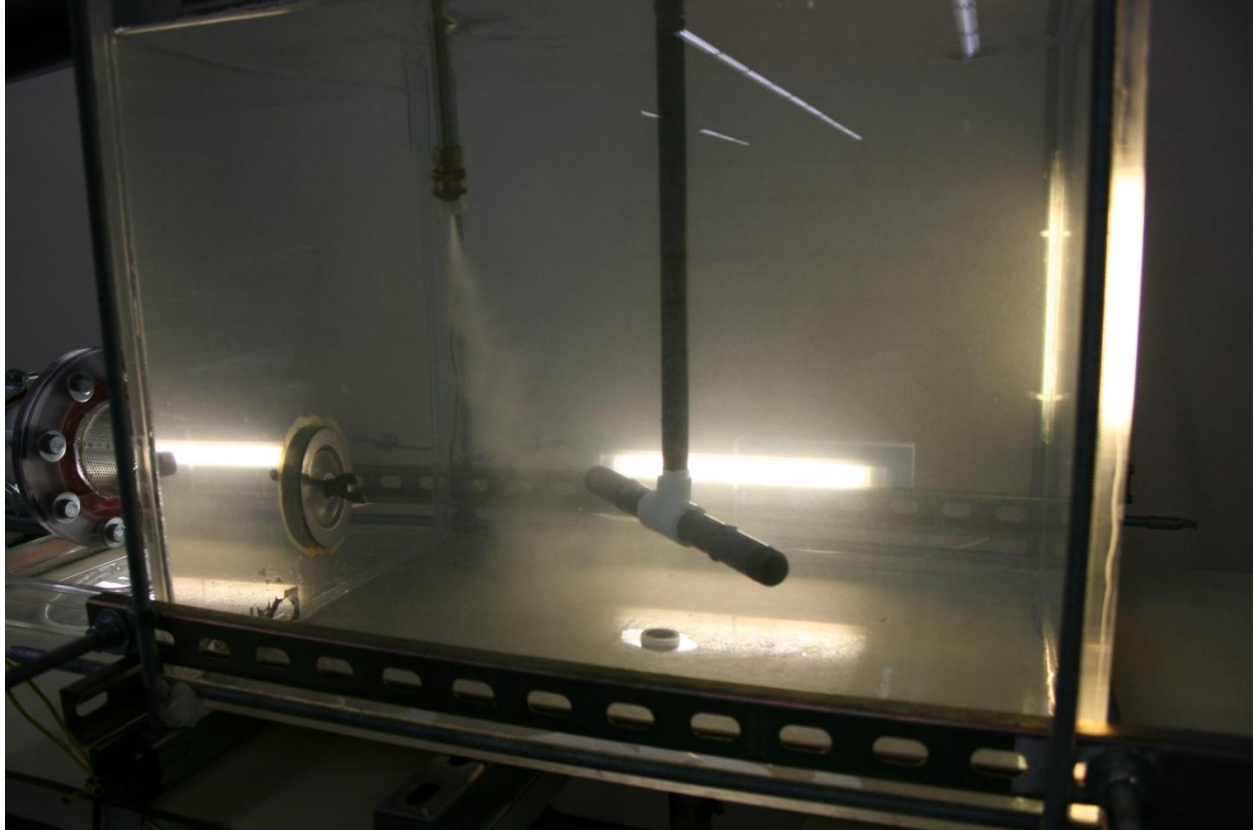


Figure 12d. Chemicals Dissolved in the Water Tank before Test Start

The end cap was then removed and the facility was filled with additional DI-water. The recirculation pump was turned on at high flow rate for approximately 10 minutes to allow the mixing of the water in the tank with the water in the remaining sections of the facility. The final pH of the solution prepared was measured at the beginning of each test. The flow rate was then adjusted to the nominal flow rate for the experiment and debris was injected into the water tank.

2.3 Debris Quantity Measurement

Each filter bag used during the experiments was labeled with a letter and a number identifying the type of water and the test number respectively. The filter was weighed at the beginning of each experiment. During this phase, the time of measurement, the relative humidity of the laboratory where the experiments were carried out and the ambient temperature were also recorded. The filter bag removed from the test section at the end of each test were hung vertically for a few minutes, to remove the excess of water, and then placed on a horizontal heated plate ($T_{surface} = 120$ °F) for approximately 12 hours. The drying time was estimated using a preliminary test described in 2.3.1. At the end of the drying period the filter was removed from the heated plate and left under the room conditions for approximately one hour. This allowed the filter to absorb the moisture of the air and reach the equilibrium with the environment under which the weight of the clean filter was taken. Relative humidity and ambient temperature were also recorded at this time. The difference of the two weights recorded for each test was associated with the total debris bypass deposited in the filter during the experiment:

$$M_{debris} = M_{filter,final} - M_{filter,initial} \quad (1)$$

2.3.1 Preliminary Verification

Preliminary verifications were required in order to assess:

1. The drying time (t_{dry}) required to completely remove the water from the filter after each test.
2. The equilibrium time (t_{eq}) necessary for the dry filter to reach the equilibrium (humidity and temperature) of the environment after each test.
3. The washout methodology to remove the chemicals collected in the filter after each of the buffered/borated water experiment.

1. Drying Time Estimation

A clean filter was used for preliminary verification. The clean filter bag was weighed at the beginning of the verification and then immersed in tap water for a few minutes. The excess water was removed by hanging the filter bag vertically for a few minutes. The bag was then moved on the heated plate and consecutive measurements of the sample weight were taken until the value reached a steady-state. The dry weight of the sample was found to be lower than the original weight (including the air moisture) which confirmed the total sample dry out.

The drying time estimated with this procedure was:

$$t_{dry} \cong 15 \text{ hours}$$

2. Equilibrium Time Estimation

The sample was then left in the environment, and its weight was continuously monitored until the filter bag reached its previously recorded weight. The time estimated with this method was:

$$t_{eq} \cong 1 \text{ hour}$$

To account for uncertainty and changes in the filter bags' properties, the times estimated were assumed to be approximate and used as reference values. During the evaluation of the filter bags during each test the same methodology was applied in order to confirm drying period completion and equilibrium achievement.

3. Washout Methodology (for buffered/borated water experiments only)

Due to the amount of chemicals dissolved in the water during these experiments, a non-negligible quantity of these chemicals was expected to deposit in the filter bags with the water absorbed by the filter. A preliminary measurement on clean filter revealed that the approximate amount of water absorbed by the filters was 110 grams. This was done by weighing a clean and dry filter and comparing the value with the one obtained after immersion in tap water. Given the total concentration of chemicals in water used for the buffered/borated water experiments (16 + 3 = 19 g/l), the amount of chemicals stored in the filter bag was found to be approximately:

$$m_{chem} = \frac{110}{998} \times 19 = 2.09 \text{ g} \quad (2)$$

In order to remove this additional weight which may cause errors in the debris weight estimation, washing of the filter bags with DI-water was required after each experiment, before the drying period. To verify the methodology and confirm that no impact was made on the debris quantity accumulation in the filter bag, two preliminary tests were executed. The first test used a clean dry filter (weight recorded at the beginning of the test). The bag was immersed in buffered/borated water until the filter was fully wet. The filter bag was then immersed in clean DI-water several times and then dried out using the standard drying procedure previously described. The weight measured at the end of the test was found to be the same as the mass recorded at the beginning. This confirmed that the method removed the chemicals stored in the filter bag. The second test used a filter bag where a given amount of debris was previously collected to verify that the defined methodology would not impact the debris bypass quantity collected in the filter. The bag was immersed in buffered/borated water until the filter was fully wet and then immersed in clean DI-water with extreme care to avoid collected debris from being removed from the bag. The filter was then dried out using the standard drying procedure previously described, and its weight was recorded at the end. Also in this case the final weight was found to be the same of the initial weight which confirmed that the methodology adopted did not impact the debris quantity collected by the filter. The methodology described was applied for all the filters used for the buffered/borated water tests.

3. INSTRUMENTATION

This section provides a description of the instrumentation installed in the facility and used during the experiments. This includes instruments for the analysis of the debris bypass quantity such as scale, hygrometer and thermometer.

3.1 Facility Instrumentation

The following devices were installed and used during the experiments:

1.1 Flowmeter. As previously mentioned (section 1), a rotameter (King Instruments K71) was installed to measure the flow rate of the water through the test facility. The rotameter has a working range of 0.6 – 60 gph and its accuracy is approximately 3% within the specified range.

1.2 K-Type Thermocouple and Thermocouple Reader. A Fluke® 52II thermocouple reader was used with a k-type thermocouple probe (Omega® EN60584-2, Class 1) to read the temperature of the water in the water tank at the beginning of each test. The accuracy of the system is ± 0.3 °C.

1.3 pH/Conductivity Meter. The pH meter (Eutech Multi-Parameter PCSTestr™ 35) was used to measure the pH of the buffered/borated water at the beginning of the experiments. The desired range of the value of the solution pH for the concentration selected was 7.2 – 7.9. The accuracy of the meter is 0.01. The accuracy was also confirmed with a reference solution of 7.0 pH. The same device was used to measure the conductivity of tap water and di-water. The following vales were measured:

- Tap Water: 840 μ S
- DI-Water: 4.0 μ S

1.4 Scale. A Acculab® VI-2400 was used to weigh the TSP and boric acid to be added to the DI-water during the buffered/borated water experiments. Due to the limited measuring range (0 – 2400g) of the scale in use, the boric acid quantity used on each test (3535g) was prepared in two batches. The readability of this scale is 0.1g.

3.2 Debris Analysis Instrumentation

The following devices were used to support the analysis of the debris collected in the filter bags after each experiment.

2.1 Scale. A Acculab® VI-350 was used to weight the debris to be added to each experiment. The range of this scale is 0 – 350g with a readability of 0.01g. The same scale was used to measure the weight of the filter bags during the phases of the analysis (see section 2.3).

2.2 Digital Hygrometer/Thermometer. This device (Dwyer® 485-2) supported the measurements of the relative humidity and temperature of the air in the laboratory where the experiments were conducted. The accuracy and resolution for the relative humidity are $\pm 2\%$ and 0.1% respectively. Temperature measurements have a $\pm 1^\circ$ F accuracy and 0.1°F resolution.

4. RESULTS and ANALYSIS

The following sections will present the results obtained during the tap water tests (section 4.1) and the buffered/borated water tests (section 4.2). The results are reported in terms of the weight in grams of the filter bag before and after the test. The amount of debris bypass (weight) was also calculated using Eq. 1. As mentioned in section 2.3 the temperature and relative humidity of the air in the laboratory were recorded during the weight measurements of the filter bags performed before and after each test. The only purpose of such additional measurements was to verify the experimental environment conditions did not significantly change between tests or within the phase of a single test. A statistical analysis and comparison of the test results will be provided in section 4.3.

4.1 Tap Water Tests Results

Table 1 summarizes the results of the four tests performed with tap water. The temperature and relative humidity of the air in the laboratory is plotted in Figure 13 for the same tests.

Table 1. Tap Water Test Results

Test #	$M_{\text{filter, initial}}$	$M_{\text{filter, final}}$	M_{debris}
1	46.35	46.78	0.43
2	47.39	47.88	0.49
3	50.67	51.11	0.44
4	49.78	50.26	0.48

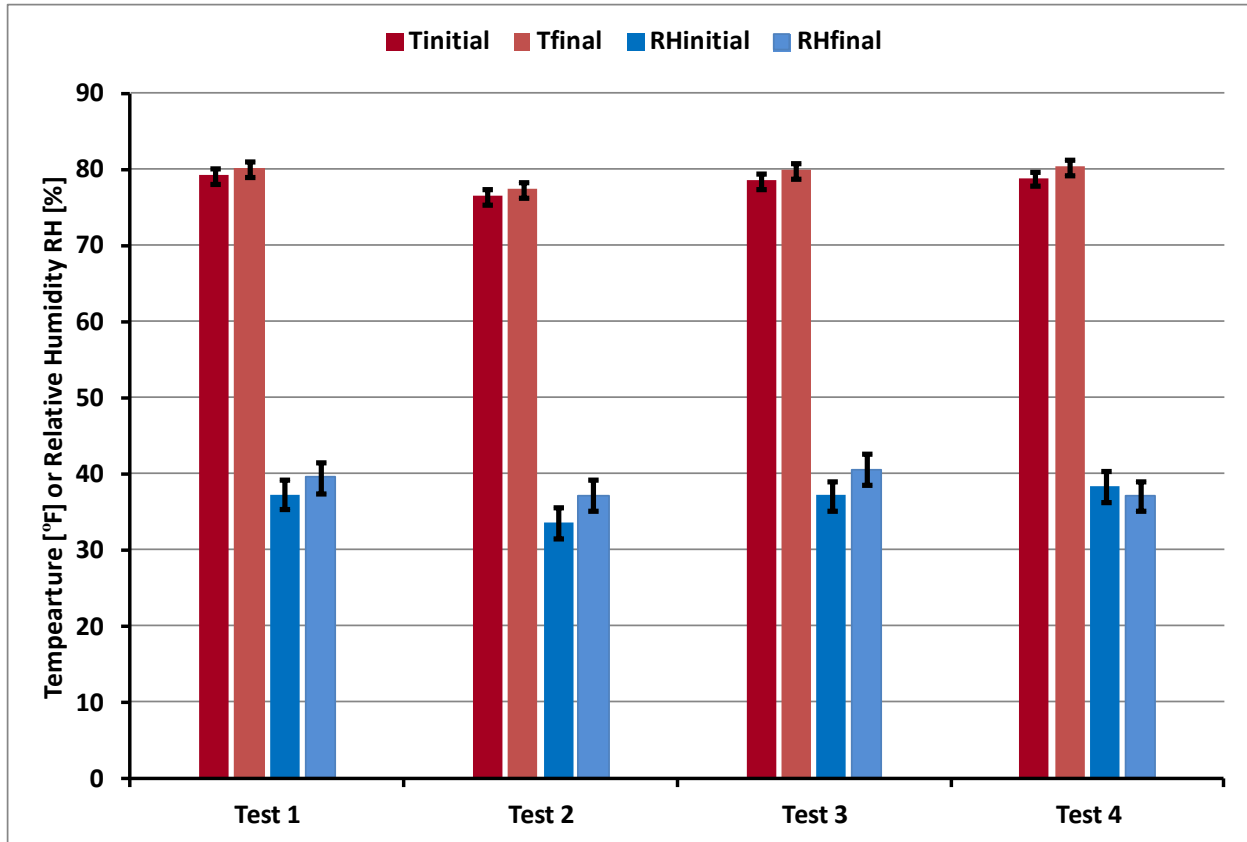


Figure 13. Ambient Conditions (Tap Water Tests)

The results, in terms of amount of debris bypass collected, showed a satisfactory repeatability. The average weight of the debris bypass is 0.46g and the standard deviation is 0.029g.

4.2 Buffered/Borated Water Tests Results

Table 2 summarizes the results of the four tests performed with buffered and borated water. The temperature and relative humidity of the air in the laboratory is plotted in Figure 14 for the same tests.

Table 2. Buffered/Borated Water Tests Results

Test #	$M_{\text{filter, initial}}$	$M_{\text{filter, final}}$	M_{debris}
1	50.44	50.89	0.45
2	55.44	55.91	0.47
3	45.96	46.37	0.41
4	47.78	48.21	0.43

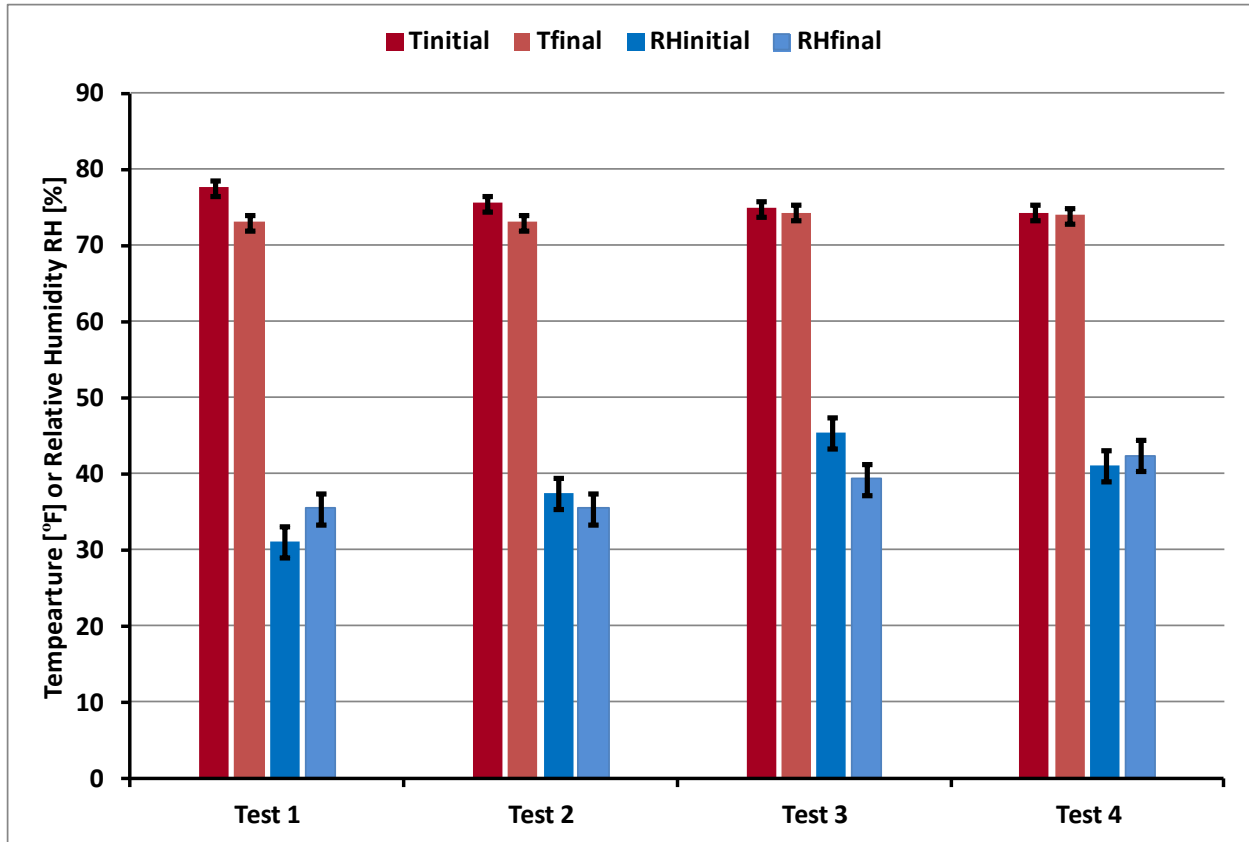


Figure 14. Ambient Conditions (Buffered/Borated Water Tests)

The average weight of the debris bypass is 0.44g and the standard deviation is 0.026g. Additional statistical information for both tests will be provided in section 4.3.

4.3 Statistical Analysis

The following analysis was meant to determine whether or not there is a statistically significant difference between the results from the two types of water (tap and buffered/borated) in terms of debris bypass quantity. The procedure is also known as Welch's t-test and is described in details in [2].

First the mean and the variance of the debris bypass weight for each water type tests were calculated:

$$\bar{W}_{tap} = \frac{1}{4} \sum_{i=1}^4 W_{tap,i} = 0.46g \quad (3a)$$

$$S_{tap}^2 = \frac{1}{3} \sum_{i=1}^4 (W_{tap,i} - \bar{W}_{tap})^2 = 0.00087g^2 \quad (3b)$$

$$\bar{W}_{b/b} = \frac{1}{4} \sum_{i=1}^4 W_{b/b,i} = 0.44g \quad (4a)$$

$$S_{b/b}^2 = \frac{1}{3} \sum_{i=1}^4 (W_{b/b,i} - \bar{W}_{b/b})^2 = 0.00067g^2 \quad (4b)$$

The t-statistic parameter was then calculated as follow:

$$t = \frac{\bar{W}_{tap} - \bar{W}_{b/b}}{\sqrt{\frac{S_{tap}^2}{4} + \frac{S_{b/b}^2}{4}}} = 1.02151 \quad (5)$$

The degree of freedom was calculated using the Welch-Satterthwaite equation:

$$\nu = \frac{\left(\frac{S_{tap}^2}{4} + \frac{S_{b/b}^2}{4} \right)^2}{\frac{S_{tap}^4}{48} + \frac{S_{b/b}^4}{48}} = 5.89963 \quad (6)$$

Assuming a level of confidence α equal to 0.05, the critical t-value, t_{crit} , can be found from the t-table. The value of t_{crit} for the calculated degree of freedom (Eq. 6) and the assumed level of confidence were found to be $t_{crit} \approx 2.45$.

Based on the calculated t-statistic parameter (Eq. 5) and the value of t_{crit} for the sets of tests performed, the following condition was found:

$$t = 1.02151 < t_{crit} \approx 2.45 \quad (7)$$

5. CONCLUSIONS

The Welch's t-test approach applied for the statistical analysis of the tests results suggest that, if $t > t_{crit}$, a statistical significant difference exists, whilst no statistically significance difference exists if $t < t_{crit}$.

For the selected boundary conditions of approaching velocity of 0.01 ft/s (0.305 cm/s), debris concentration (0.09 vol.%, 0.0034 wt.%), boric acid and TSP concentrations (16 g/l and 3g/l respectively, for buffered/borated water tests), and based on the results shown in Eq. 7, it was found that no statistical difference between the tap water and buffered/borated water debris bypass weight existed.

6. NOMENCLATURE

t_{end} – End time

$T_{surface}$ – Surface Temperature

M_{Debris} – Mass of Debris

$M_{filter,final}$ – Mass of Filter, final

$M_{filter,initial}$ – Mass of Filter, Initial

t_{dry} – Time to Dry

t_{eq} – Time to Equilibrium

m_{chem} – Mass of Chemicals

7. REFERENCES

1. J. C. BUTLER, "ZOI Fibrous Debris Preparation: Processing, Storage, and Handling," NEI, Rev. 1 (2012).
2. Jaremy Tejada, "Texas A&M Tap Water vs. Borated Water Statistical Analysis Procedure", (2012)

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