THE EFFECT OF ELECTRIC POTENTIAL ON FIBROUS DEBRIS BYPASS THROUGH A CONTAINMENT SUMP STRAINER

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ABSTRACT

Fiberglass is an efficient thermal insulation material in Pressurized Water Reactors (PWRs). However, fibrous debris generated during a Loss-of-Coolant Accident (LOCA) from fiberglass insulation materials may cause a safety issue in the containment sump strainer. This safety issue addressed in the Generic Safety Issue (GSI) 191 by the U.S. Nuclear Regulatory Commission (U.S. NRC) can be categorized into upstream effects, which concern loss of Net Positive Suction Head (NPSH), and in-vessel effects which concern debris bypass through the strainer and transportation into the primary system. PWR power plants in the U.S. have increased the size of their sump strainers, in the attempt to decrease the head loss. However, the quantity of debris bypass through the strainer still remains an issue not fully resolved. It is known that filtration through a porous medium is affected by water chemistry, affecting the double-layer electric potential close to the surface of particles and filter media. In the present study, the effect of water chemistry (pH and ionic strength) and the effect of external electric potential (voltage applied to a strainer) were investigated. NUKON fiberglass was prepared using a high pressure (1800 psi) washer method. Two positive (+ 500 mV and +1000 mV) and two negative (-500 mV and -1000 mV) electric potentials were applied between the strainer and water in the tank. Total mass of debris penetrated through the strainer under different conditions was compared. It was found that debris bypass is influenced by water chemistry and that, an electric potential applied to the strainer may affect the mass of debris penetration.

KEYWORDS
GSI-191, fibrous debris, containment sump strainer, debris bypass, electric potential

1. INTRODUCTION

The reactor vessel and the pipelines of a Light Water Reactor (LWR) are thermally insulated to prevent heat losses and to protect the surrounding components from thermal effects. Low Density Fiberglass (LDFG), especially NUKON® (PCI Engineering Systems Group), is one of the most commonly used insulation materials in LWRs. However, it has been found that fibrous debris generated during a Loss of Coolant Accident (LOCA) from the LDFG causes a safety issue in the containment sump [1]. Once the fibrous debris reaches the containment sump strainer, it might accumulate on the strainer causing loss of NPSH (upstream effects) or penetrate through the strainer and transport into the primary system, potentially affecting the core cooling (in-vessel or downstream effects). This is the main subject of the Generic Safety Issue (GSI)-191 “Assessment of Debris Accumulation on PWR Sump Performance” [2] addressed by the U.S. NRC in response to several Emergency Core Cooling System (ECCS) failures [3]. For Pressurized Water Reactors (PWRs), the Generic Letter 2004-02 [4] described a mechanistic evaluation of the recirculation functions and additional actions to ensure system functionality. PWR power plants in the U.S. have increased the size of their sump screens, in the attempt to decrease the pressure drop through the strainer. However, the quantity of debris penetration still remains an open issue. Debris penetration through a fibrous bed deposited on a strainer can be studied using the theory of particle filtration through a fibrous filter. Hutten [5] summarized four filtration mechanisms such as surface straining, depth straining, depth filtration, and cake filtration. Surface straining and depth straining occur when a particle of a given size approaches a medium with pore size smaller than the particle. Depth filtration is a mechanism that removes particles from a fluid even though the particle is smaller than the size of the pore in the filter medium. Cake filtration is another important liquid filtration mechanism in which the capture of solid particles on the surface of a filter medium results in the build-up of particulate layers (filter cake). Though the cake filtration removes the largest fraction of debris, in case of NUKON fiber produced during a LOCA scenario, the depth filtration would be the main mechanism in the transport of debris through the fibrous bed and the strainer, because most of this debris penetrating the filter medium is smaller than millimeters. Effects of water chemistry, including pH and electrical conductivity (EC), on the mass of debris penetration (bypass) through the strainer were observed in the previous researches [6 - 8]. There are several research activities and theoretical explanations showing the effect of pH and EC on the filtering efficiency, by altering the double layer repulsion [9 - 11]. Based on these observations, the authors proposed to study the effect of electric potential applied on the strainer. Five different voltages were used in this study: 0, +500, +1000, -500, and -1000 mV. Local tap water was used to perform all the tests, which was showed to have similar effects on debris bypass than typical Boric-Acid (16 g/l) and Trisodium-Phosphate (TSP) (3 g/l) water (deionized water) solutions [6, 7].

2. EXPERIMENT

The experimental facility used to conduct the experiments is the one described in details in [7]. A schematic representation of the experimental facility is shown in Figure 1.

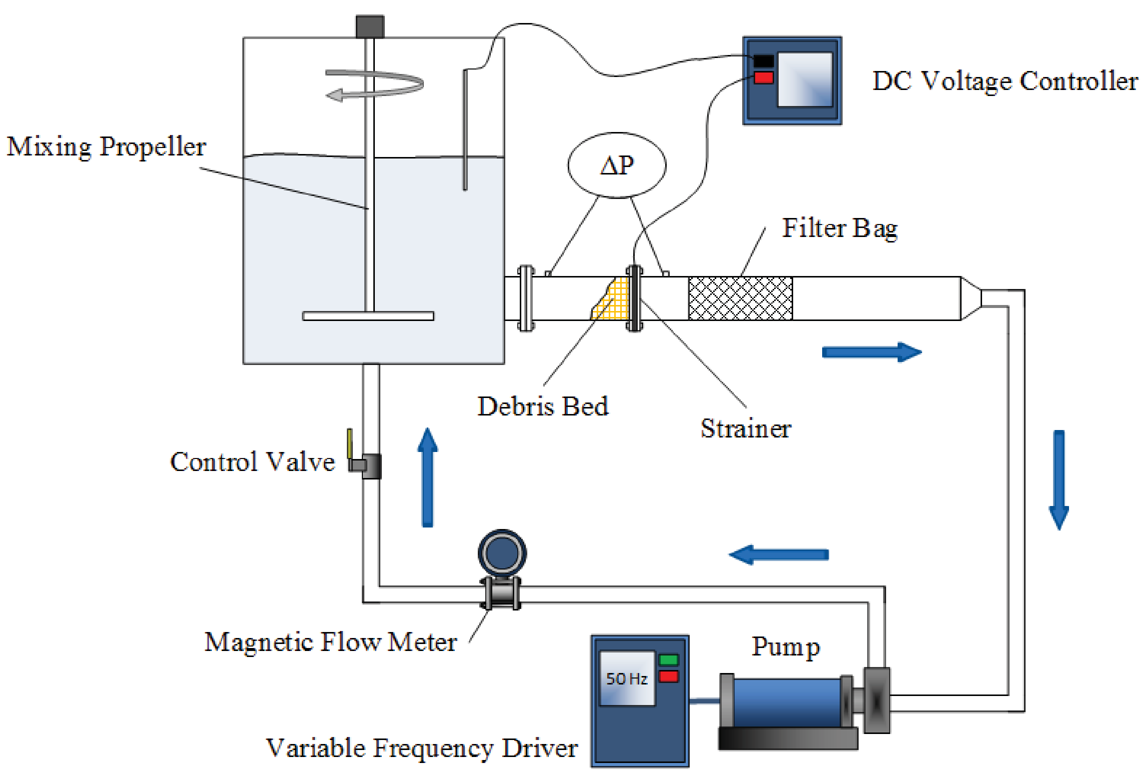

Figure 1. TAMU debris bypass experimental facility

The test facility is a semi-closed loop made of polycarbonate and stainless steel. It consists of a transparent water tank (where the NUKON debris is injected), a 10.16 cm in inner diameter outlet pipe on the side of the tank, and a return pipeline at the bottom of the tank. The volume of water in the tank and the test section upstream of the strainer for each test was 181 liters. The test section is made of two 30 cm long polycarbonate tubes. A perforated plate was manufactured following the size of holes obtained from the South Texas Project (STP) power plant sump strainer design [12]. The plate has a perforated section of 10.16 cm in diameter which fits the flow section of the polycarbonate pipe, allowing its installation between two flanges in the middle of the test section.

The approach velocity was determined to be 0.3 cm/s based on the STP strainer surface area, 168.9 m^2 (1818.5 ft^2), and nominal flow rate per Safety Injection (SI) train, 26.6 m^3/min (7020 gallons/min) [12].

The debris was prepared starting from a one-side baked NUKON® mat. The concentration of debris in the water tank at the beginning of each experiment was set to 0.09 volume percent (vol. %) corresponding to 0.0034 weight percent (wt. %). All tests were conducted at 25 ± 3 ˚C. Sodium carbonate (CNa_2O_3) and boric acid (H_3BO_3) were used to change the solution pH. Sodium Chloride (NaCl) was used to change the solution ionic strength (electric conductivity). Five electric potential values (0, +500, +1000, -500, and -1000 mV) were applied to the strainer. Local tap water was used for these electric potential effect tests. Tap water showed similar trend with a typical buffered borated water (16 g/l of boric acid and 3 g/l of TSP dissolved in deionized water, boron concentration: ~ 2500 ppm) [12].

A filter bag (1μm heat-welded polyester felt bag with plastic ring head) was installed downstream of the strainer to collect the debris penetrating through the strainer. The filter bag was installed inside the polycarbonate pipe with a silicone gasket lining. The final configuration of the filter bag installed in the test section is shown in Figure 2.

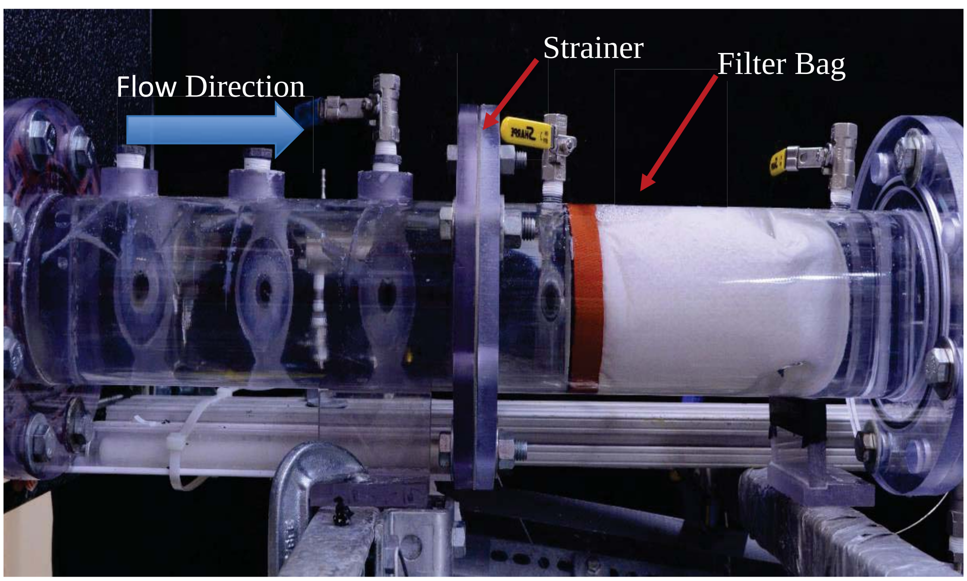

Figure 2. 1μm filter bag installed downstream of the perforate plate in the test section

Once the facility was filled with water, the flow rate was adjusted using a control valve and a frequency inverter until the desired velocity (0.3 cm/s) in the test section was achieved. Debris sample (6.60 g) was prepared using a method described in previous work [6 - 8], based on the Nuclear Energy Institute (NEI) fine debris preparation procedure [13]. Figure 3 shows three pictures taken during a debris sample preparation.

(a) (b) (c)

Figure 3. NUKON debris sample preparation - (a) pre-cut one-side baked NUKON pieces, (b) the NUKON sample after applying high pressure washer, and (c) the final shape of samples in a visualization tray

The debris sample prepared was poured into the water tank over a short (~5 sec) time period while the mixing propeller spun. Each experiment was terminated at 125 minutes, corresponding to one turnover time of the water in the tank. The final fibrous bed observed on the strainer was approximately 4cm thick. At the end of each experiment, the test section was isolated to remove the filter bag following a special procedure to avoid any impact on the mass collected. Each filter bag was weighed at the beginning of each experiment before insertion into the test section. The filter bag removed from the test section at the end of each test was placed on a heated plate at 50 °C for approximately 15 hours. This drying time was verified to be enough to remove moisture from the filter bag with preliminary tests. The difference between the weight of the filter bag before the test, $M_{filter\_initial}$, and the weight of the filter bag after the test, M_{filter_final}, was associated with the weight of total debris bypass, M_{debris}, deposited in the filter during the test, as shown in Equation (1).

$$M_{debris} = M_{filter\_final} - M_{filter\_initial} \tag{1}$$

Table I summarizes instruments used in the present experiments.

Table I. Instruments Specifications

Parameter	Instrument	Accuracy
Flow Rate	Electro-magnetic flow meter (Optiflux-1300, Krohne®)	± 1.7 %
Temperature	T-type thermocouple (Omega® EN60584-2)	± 0.5 °C
Weight	Acculab® VI-350 Acculab® VI-2400	± 0.01 g ± 0.1 g
pH	SevenCompact™ S220 (METTLER TOLEDO®)	±0.002
EC	PCSTestr™35 (Eutech Instruments OAKTON®)	± 1 % of full scale (200 ~ 1999 μS/cm, 2.00 ~ 20.00 mS/cm)

3. RESULTS AND DISCUSSIONS

Table II summarizes the test results in terms of debris mass for the case where no voltage was applied at the strainer. The table shows the pH and electrical conductivity (EC) of the solutions used for the tests (deionized water, Tap water, and chemical solutions).

Table II. Water chemistry effect on debris bypass

Water Type	pH	EC* (μS/cm)	Bypass (g)
Deionized water [7]	5.6 ~ 6.4	1	0.32 ± 0.06
**Buffered borated water Typical concentration (16 g/l of H_3BO_3, 3 g/l of TSP) [7]	7.2	2030	0.44 ± 0.03
**Buffered borated water Double concentration (32 g/l of H_3BO_3, 6 g/l of TSP)	6.7	3540	0.45± 0.02
**Buffered borated water Triple concentration (48 g/l of H_3BO_3, 9 g/l of TSP)	6.3	4760	0.41
Tap water [7]	8.6	840	0.46 ± 0.02
**CNa_2O_3 1 g/l	11.2	1703	0.55
**NaCl 1 g/l	6.7	1752	0.37
**NaCl 5 g/l	6.5	7290	0.28
**NaCl 10 g/l	6.6	15500	0.20
**H_3BO_3 1g/l	4.4	10	0.17

* Electrical Conductivity, S = Ω^{-1}
** Chemicals dissolved in deionized water

For Tap water tests, 7 values were obtained from the previous work [7] and an additional value was obtained from the present experiment, to confirm repeatability. For buffered borated solutions, three tests with double concentration and one test with triple concentration were conducted in this study and added to the results acquired from [7]. Table III presents the results of tests with electric potential applied to the strainer.

Table III. Effect of electric potential applied to the strainer on debris bypass

Water Type	pH	EC (μS/cm)	Electric potential (mV)	Bypass (g)
Tap water	8.6	840	-1000	0.80
			-500	0.52
			0	0.46
			500	0.43
			1000	0.27

Figure 4 shows the mass of the debris bypass at different pH values in Table II. The effect of pH can be explained in terms of electrical double layer repulsion in the depth filtration with the interaction energy. The electrical double layers overlapping debris and fibrous bed give rise to repulsive energy of interactions. Khilar and Fogler [9] summarized equations for double layer repulsion energy, V_{DLR}, of a sphere-plate system for a case of constant potential (Hogg et al. [14]) and for a case of constant charge (Wiese and Healy [15]). Since both debris and fibrous bed were generated from NUKON® fiberglass, Khilar and Fogler's equations can be simplified as shown in Equations (2) and (3) [7].

$$V_{DLR} = (\varepsilon a_p / 4)\psi^2 \left[\ln \frac{(1+\exp(-\kappa h))^3}{1-\exp(-\kappa h)} \right] \tag{2}$$

$$V_{DLR} = (\varepsilon a_p / 4)\psi^2 \left[\ln \frac{1+\exp(-\kappa h)}{(1-\exp(-\kappa h))^3} \right] \tag{3}$$

where ψ is the electric potential, a_p is the particle radius, h is the distance of separation, ε is the dielectric constant, and κ is the Debye-Hückel parameter. The electric potential ψ of the double layer can be replaced by zeta potential measured. Then Equations (2) and (3) clearly show that when zeta potential increases, the repulsion energy increases, which lower the filtering efficiency. Eventually, the increased repulsion energy results in greater debris bypass by decreasing probability for the debris to agglomerate or deposit on the debris bed. Several experimental data showed that higher pH values increased zeta potential of glass materials [16 - 19]. The present experimental results showed the effect of pH on debris bypass in accordance with the zeta potential data and Equations (2) and (3). The zeta potential data [16 - 19] showed that some types of glass exhibited a well-established plateau in the range of $7 < pH < 10$. This plateau is similar to bypass quantities between pH 7 and pH 9 that are not significantly different in Figure 4.

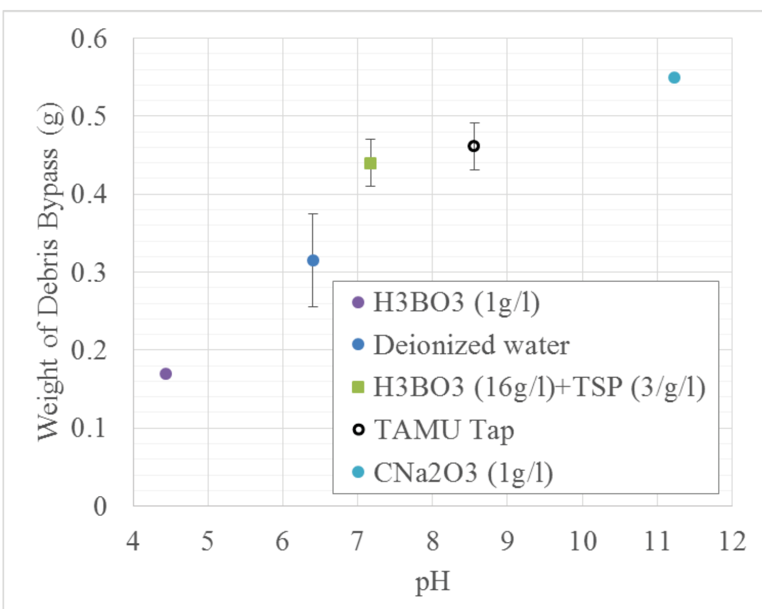

Figure 4. pH effect on debris bypass in terms of weight

Since EC is one of the indicators of ionic strength in a chemical solution, EC was used to observe the effect of ionic strength on debris bypass. There are several methods available to calculate ionic strength based on EC proposed by [20 - 24]. Kolakowski and Matijevic [10] and Kia and Fogler [11] showed that zeta potential decreased as electrolyte concentration increased. This can be explained by that higher ionic strength compresses the thickness of the electric double layer resulting in decrease of double layer potential. Figure 5 presents the quantity of debris bypass against EC obtained from deionized water tests and buffered borated water tests with different concentrations of boric acid and TSP.

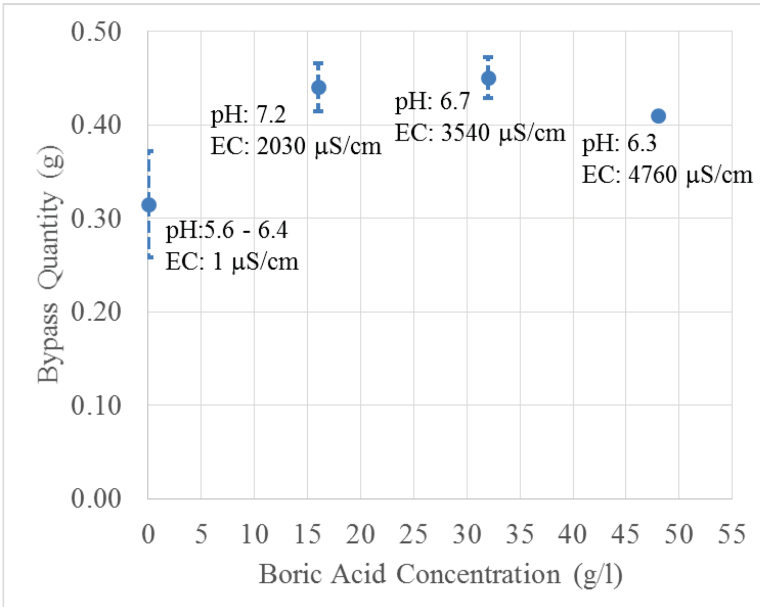

Figure 5. Ionic strength effect on debris bypass in buffered borated water (H_3BO_3 : TSP = 16 : 3)

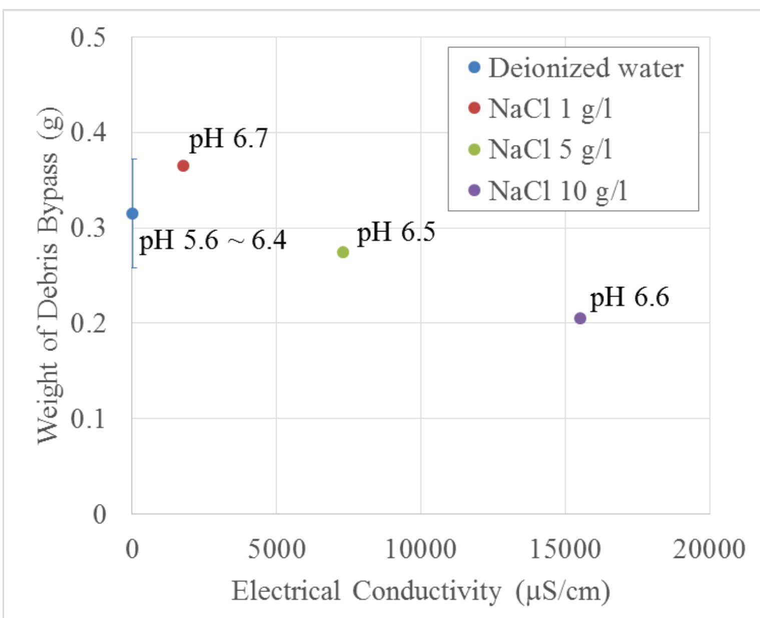

Figure 6. Ionic strength effect on debris bypass in NaCl solutions

Although the test with triple-concentration buffered borated water resulted in less debris bypass, the difference among buffered borated water tests was not clear. Carneiro-da-Cunha et al. [25] reported that the effect of pH is much stronger than the effect of ionic strength and other factors on an electrostatic self-assembly process. Figure 5 shows good agreement with that the quantity of debris bypass in deionized water was significantly smaller than buffered borated solutions, even though deionized water has much lower EC. In order to clearly separate the effects of ionic strength and pH, additional experiments with different NaCl concentrations were conducted in this study as shown in Figure 6, which showed good agreement with Kolakowski and Matijevic's [10] and Kia and Fogler's [11] results.
Based on the results shown in Figures 4, 5, and 6, the authors concluded that applying a electric potential at the debris bed may had an effect on the behavior of the debris penetration.
Figure 7 presents the quantities of debris bypass of five tests with different voltages applied to the strainer: 0, +500, +1000, -500, and -1000 mV. When negative electric potential was applied to the strainer, debris bypass increased. As electric potential between the strainer and water in the tank increased, total amount of debris bypass decreased.

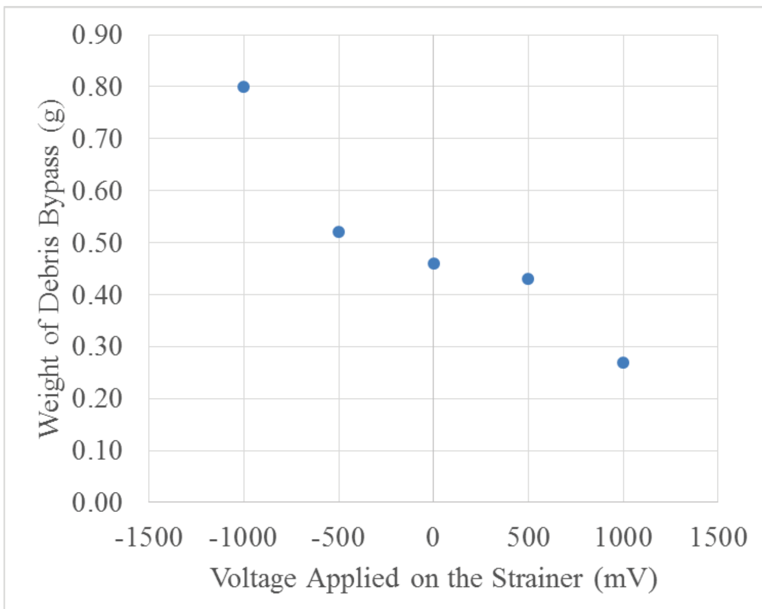

Figure 7. Electric potential effect on debris bypass in terms of weight (Tap water)

4. CONCLUSIONS

The effect of water chemistry (pH and ionic strength) on NUKON® debris bypass through debris bed on a sump strainer was investigated. In addition to previous researches, experiments were performed for wider range of pH values, and the effect of ionic strength was isolated from the pH effect by using NaCl solutions with three different concentrations. Higher pH and lower electrical conductivity resulted in greater quantity of debris bypass. This behavior was related to the electrical double layer repulsion of the debris. Based on this conclusion, a set of experiments was conducted to evaluate the effect of electric potential directly applied between the strainer and water in the tank. Two tests with positive electric potential (+ 500 mV and +1000 mV) resulted in less mass of debris bypass, and two tests with negative electric potentials (-500 mV and -1000 mV) resulted in larger mass of debris bypass. It was found that debris bypass is influenced by water chemistry and externally applied electric potential on the strainer in the present conditions. As electric potential between the strainer and water in the tank increased, total amount of debris bypass decreased. Several researchers reported negative zeta potential values of glass materials, thus, the effect of electric potential can be explained by the positive electric potential reducing the repulsive energy between NUKON® debris and debris bed. Although it is clear that electric potential affected debris filtration, additional tests are required to investigate physical root causes of the electric potential effect and the relation between electric potential and the behavior of NUKON® debris bed.

NOMENCLATURE

a_p: particle radius
h: distance of separation
$M_{filter\_initial}$: weight of the filter bag before test
M_{filter_final}: weight of the filter bag after test
M_{debris}: weight of total debris bypass
V_{DLR}: double layer repulsion energy
ε: dielectric constant
κ: Debye-Hückel parameter
ψ: electric potential
EC: Electrical Conductivity
ECCS: Emergency Core Cooling System
GSI: Generic Safety Issue
LDFG: Low Density Fiberglass
LOCA: Loss-of-Coolant Accident
LWR: Light Water Reactor
NEI: Nuclear Energy Institute
NPSH: Net Positive Suction Head
PWR: Pressurized Water Reactor
STP: South Texas Project
TAMU: Texas A&M University
TSP: Trisodium Phosphate

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