Conventional and Chemical Head Loss Modeling of Multi-Constituent Debris Beds in Resolution of GSI-191

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ABSTRACT

Generic Safety Issue 191 (GSI-191) for the Vogtle nuclear power plant has been investigated at the University of New Mexico (UNM). A series of experiments on vertical head loss modules or columns to measure conventional and chemical head loss were carried out. The conventional and chemical head loss was measured on multi constituent debris beds of different particulates to fiber ratios. These beds are generated on horizontal screens following a newly developed procedure at UNM and presented herein. The procedure resulted in repeatable formation of debris beds that provided reproducible and stable conventional head loss for a few days of testing. These attributes are confirmed by series of experiments and the primary results showed a reproducible conventional head loss within ±7%. The conventional head loss was highly stable for 5 days of testing under stable column approach velocity.

A second series of experiments was carried out using prototypical Vogtle debris materials to measure both conventional and chemical head loss on three debris beds of different particulates to fiber ratios, η, of 6.89 , 2 , and 1.15. The particulates are presented by mass as 90% epoxy paint, 5% inorganic zinc and 5% latent debris dirt. The results show that the measured conventional head increased with increased particulate mass in the debris beds. The average measured conventional head loss values are 9.37, 6.4, and 5.66 $H_2O''$for particulate to fiber ratio of 1.15, 2, and 6.89 respectively. Debris beds with η of 2, and 1.15 were selected for chemical head loss experiments. A standard aluminum chemical precipitates were prepared and specific batches were introduced to these beds and the chemical head loss was measured. The results showed that the thin debris beds (~ 25mm) is more sensitive to the chemical precipitated compared to the thick debris bed (~ 55mm).The debris bed of η = 1.15 (~55 mm) was able to filter out 2.34 grams of aluminum precipitates to reach total head loss (conventional and chemical) of 42 H_2O''. The debris bed of η = 2 (~25 mm) filtered only 0.91 grams of aluminum precipitates to reach total head loss of 45 H_2O''.

KEYWORDS

GSI-191, Conventional and Chemical head loss, Debris beds, Fiber/ Particulates

1. INTRODUCTION

The Generic Safety Issue 191 (GSI-191) has attracted a lot of focus and efforts since it was issued by USA nuclear regulatory commission (NRC) in the late of 1990s. GSI-191 was issued after a series of revealing events at Barseback boiling water reactor (BWR) unit 2 in Sweden, Perry-1 (1992), Perry-2 (1993), and Limerick-1 (1995) [1]. These events showed the potential of debris such as insulation material or corrosion products that could be generated and dislodged by steam jet from pilot relief valve (Barseback) or inadvertently dropped materials into the suppression pool (Perry – 1and 2) to accumulate on containment strainers and compromise the emergency core cooling system (ECCS). During loss of coolant accident (LOCA), the high energetic water or steam jet from the pipe break destroys the pipe insulation material in the vicinity of the break. In addition, the water or steam jet could hit the containment walls and floor, generating concrete debris and cause failure to some qualified and unqualified wall paints. The paint, concrete and the thermal insulation debris washed by the water leak from the pipe break to the containment pool and accumulate on the emergency core cooling system (ECCS) sump screen. A simplified schematic for the containment including ECCS response during a LOCA is shown in Fig. 1. A few years after the GSI-191 safety issue was initiated, the Advisory Committee on Reactor Safeguards (ACRS) raised the concern of the chemically-induced corrosion products that could be generated in the containment, transported, and filtered by the accumulated fiber debris on the ECCS sump screen [2]. These chemicals have shown the potential to increase the head loss and impede the net positive suction head (NPSH) which is a safety pressure margin required to assure successful operation of ECCS pumps.

The primary reactor cooling system (RCS) water has a specific concentration of boron during regular operation as a chemical shim to reduce the effect of reactivity and airborne radioactive materials. The combined high boric acid concentration and high temperature environment inside the containment create highly corrosive conditions. Under these conditions, various metal surfaces inside containment could generate different types of ions such as aluminum ions. These ions are transported by coolant to the containment pool and have the potential to form precipitates under saturation conditions as shown in Fig.1.

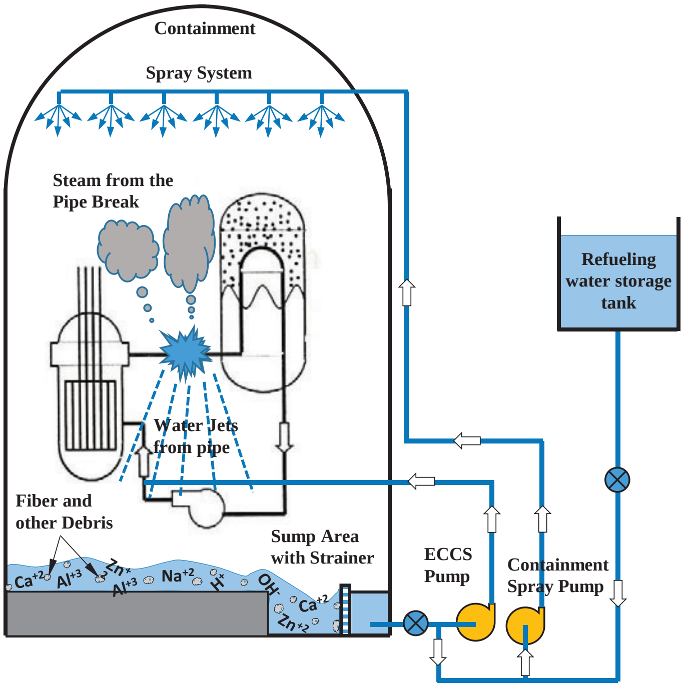

Figure 1: Simplified arrangement of the hypothesized LOCA inside the containment.

Zinc (galvanized pipes) exposed to the high temperature and highly acidic spray water especially during the early stage of LOCA event could produce corrosion products such as zinc phosphate. The phosphate is introduced to the containment water after pipe break as a chemical buffer in the form of trisodium phosphate (TSP) to normalize its pH and reduce the corrosive condition in the containment. These chemical products (precipitates and corrosion products) are expected to be transported to the ECCS sump and potentially filtered by the accumulated debris beds on the sump screen during the circulation of containment pool water through the ECCS [3]. The initial pressure drop or head loss resulting from the accumulated fiber and debris particulate is known as conventional head loss (CHL). The increased head loss due to the resultant filtration of chemical products is referred to as chemical head loss. Both conventional and chemical head loss can negatively impact the ECCS NPSH margin and compromise the overall reactor safety response.

An assessment of debris-induced head loss with the effect of chemicals in pressurized water reactor (PWR) has been experimentally investigated across a number of laboratories. Experiments in the form of horizontal strainer, vertical head loss columns, and integrated tank tests have been carried out at UNM and reported in the literature. Several small scale experiments were conducted to explore the effect of induced corrosion products on the ECCS pump head loss [4-6]. These studies focused on the interaction between the ECCS circulation water and exposed metal surfaces in the containment under different conditions (pH and temperature). Among those metals are aluminum, zinc, calcium, iron. The principle conclusion confirmed that it is possible for the material corrosion products and chemical precipitates, if formed, to be transported to the sump screen, filtered by the insulation debris on the sump screen and increase the head loss. A similar vertical loop head loss testing was performed using aluminum corrosion products created in situ using borated solution at different pH and temperature using different types of aluminum alloys [7]. The head loss measurements were compared for chemicals surrogates obtained previously from a series of integrated tank test (ICET) and other participates as described in WCAP-16530 [8,9]. The reported results concluded that the WCAP-16530 aluminum precipitate seems to be more effective in increasing head loss than the in situ precipitation similar to those generated in the ICET tests. The reported investigations of the small scale head loss work in vertical loops with chemical effects were limited only on separate for each material of interest that was added in gradual batches to the loop.

This paper presents obtained results on a set of currently ongoing head loss experiments at UNM towards a risk-informed resolution of GSI-191 for Vogtle. Among different objectives, two sets of experiments were carried out to quantify the conventional and chemical head loss on a prototypical multi-constituents debris beds. A first set of experiments was carried out to ensure the repeatability and stability of the measured conventional head loss on debris beds prepared following a new proposed procedure introduced herein. The procedure was developed in our thermal hydraulic lab at UNM and reported in the literature [10-12]. In these experiments, NUKON fiber, acrylic paint particulate were used to construct the debris beds. A second set of experiments was carried out using debris beds composed of 90% epoxy paint particulates, 5% In-organic Zinc (IOZ), and 5% latent dirt by mass to measure both conventional and chemical head loss. These materials and debris bed compositions are prototypical to those predicted in Vogtle nuclear power plant containment during and post-LOCA as provided by industrial consultant co-operative teams. The next section provides more information on the testing facility and the experimental condition and procedure.

2. EXPERIMENNTAL FACILITY and PROCEDURE

2.1. Vertical loop Description

The testing facility has three identical vertical head loss modules that are designed to operate in parallel or in isolation. Each loop consists of a circulation pump, vertical testing column, control valves and measuring instrumentations (flow, temperature and pressure). A schematic of a representative loop is shown in Fig. 2. The upper and lower portions of the 6-in diameter vertical columns are constructed of stainless steel and are sealed at the top with a blind flange. The blind flanges can be removed to introduce debris into the head loss assembly. The middle section of the assembly is constructed of 1/4-in thick polycarbonate to visualize of the debris beds. A perforated plate or screen supported by a ring is located 6-in from the lower edge of the section where the debris beds are generated. The screen is constructed of stainless steel and contains 0.094-inch holes. A differential pressure (ΔP) transducer is connected to ports above and below the screen support to measure the pressure loss through the debris bed with a maximum measuring value of 5 ± 0.05% psi. Each module has a flow meter (up to 10 gallons per minutes, gpm) and control valves to monitor column flow rate and adjust the approach velocity in each column (Fig. 2). The debris are added manually to the columns by pouring pre-prepared beds with a particulate mixture from the open lid of each column.

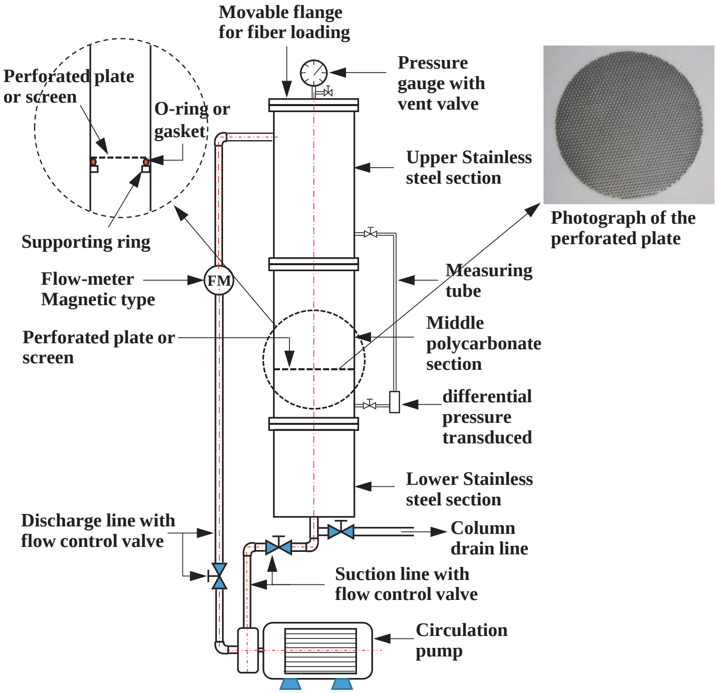

Figure 2: Schematic of typical vertical head loss module.

2.2. Debris Bed Preparation Procedure

A high pressure jet in the vicinity of pipe break destroys the insulation fiber glass during and post postulated LOCA conditions. The resulted broken fiber can be classified within 6 categories as reported in the literature [13]. The fiber class start at Class 1 for very small pieces of fiberglass which appear to be cylinders of different length/diameter ratios, to class 2 for very loose individual fiber debris and increase as the agglomeration of this fiber debris occurs up to Class 6. The generated debris beds presented in the work (Fig. 3a – h) are prepared partially following the Nuclear Energy Institute (NEI) [14] procedure by breaking NUKON fiber with a pressure washer and formed mostly from Class 1 and Class 2 fiber debris.

A large piece of NUKON fiber (Fig. 3a) is separated by hand into a few layers and placed in five gallons bucket (Fig. 3b) with1 liter of reverse osmosis (RO) water. Fiber layers are separated using RO water run through 1800-psi 1.5 gpm electric pressure washer with a 40 degree small diameter fan type tip. The nozzle is maintained slightly below the water surface for 2.5-3 minutes (Fig. 3c). The pressure washer tube is kept in rotational motion to provide disturbance energy in the water to break the fiber. The degree of fiber separation is confirmed via visual inspection, by taking a mixture sample using a clean ladle from the 5-gallon bucket and pouring into a clear glass baking dish and placing the baking dish on the light table (Fig. 3e). Using a small diameter glass stir rod, the fiber solution is swirled gently to reveal any clumps. Confirm that the fiber debris are mostly class 1 to 3 debris (Fig. 3e).

The resulting solution from the pressure washer process (5 gallons bucket) is filtered through ultra-fine mesh (40 μm x 10 μm, hole size) to collect mostly class 2 and class 3 fiber debris for the next preparation step (Fig. 3d). The water with fiber shards in transferred to the column to preserve the total fiber mass and treated chemically by boric acid and trisodium phosphate. The filtered fiber debris then collected into a glass beaker with 3 liter RO water (Fig. 3f) to be mixed with the other particulates such as paint and latent dust debris. Using a glass rod, fiber water solution is shacked a few seconds to break any agglomerated fibers (Fig. 3g). The beaker content solution is circulated for about 20 minutes on a magnetic stirrer (Fig.

3h). A 1 liter solution of RO with particulate prepared previously is mixed by with the 3 liters water with fiber mixture (Fig. 3i). The final debris mixture is remixed for another 10-15 minutes on the magnetic stirrer. The debris mixture is then ready to be loaded to the vertical column and generate the debris beds.

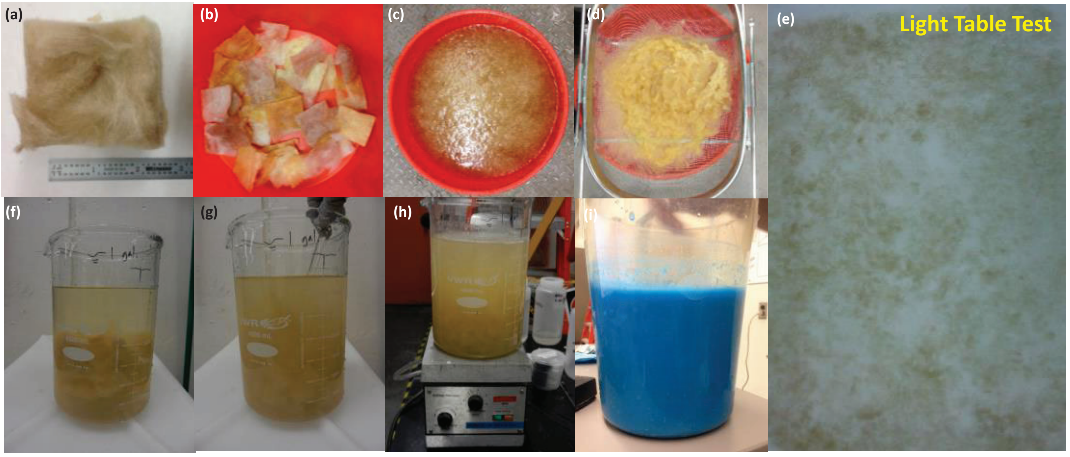

Figure 3: Photographs for the debris mixture preparation process.

2.3. Experimental Condition and Procedure

The primary set of experiments was carried out to ensure that the debris preparation and experimental procedure is generating reproducible and stable conventional head loss for different fiber to particulates ratio in single of multiple vertical head loss modules under the same flow conditions. Two different debris beds were used in this series of experiments, a relatively thick bed (20-25 mm) and relatively thin bed (8-10 mm). The particulate to fiber mass ratios (P/F),η, were 2 (40 g of paint particulates / 20 g of fiber) and 13.8 (50 g of paint particulates / 3.63 g of fiber) for the relatively thick and thin beds respectively. Both debris beds are composed of NUKON fiber debris mixed with acrylic paint particulates. The acrylic particulates has been used and reported in the literature to be representative to the paint particulates in the containment. These particulates are commercially available and have a wide range of size distribution [6].

After confirming the repeatability of the debris bed formation and reproducibility and stability of the measured conventional head loss, a second series of experiments was executed to measure the conventional and chemical head loss on prototypical mutli-constituents debris beds. The investigated beds are composed of specific debris presenting Vogtle power plant. Three different beds were investigated, thin (~10 mm) intermediate (~25 mm) and thick (~55 mm) with particulate to fiber ratios, η of 6.89 (25 g of particulates / 3.63 g of fiber), 2 (40 g of particulates / 20 g of fiber), and 1.15 (50 g of particulates / 43.53 g of fiber). The particulates are presented by mass as 90% epoxy paint, 5% inorganic zinc (Carbozinc 11, Zinc Filler Type II) and 5% latent dirt (PWR MIX Dirt, PCI Inc.). The debris material types and composition was determined based on different LOCA scenarios analysis carried out and provided by other teams.

All experiments in the three vertical columns presented in the work were carried out at ambient temperature under atmospheric pressure. The water volume per column was 8.32 gallons with chemical conditions similar to those present in the containment pool during LOCA conditions at Vogtle. The water was borated (221.3 mM) and buffered with TSP (5.83 mM) before the debris mixture was loaded from the top of the column and distributed to generate relatively uniform bed on the horizontal screen. The bed mixture was loaded at column approach velocity of 0.05 ft/s. Upon head loss reaches the stability criteria, the column approach velocity was reduced to a lower value representative to the water velocity in the containment pool approaching the sump screen in Vogtle power plant of 0.013 ft/s. The head loss is considered stable when the root mean square (RMS) of the five minutes head loss data recorded at the beginning of two consecutive testing hours is changing by less than 1% [10-12]. After satisfying the stability criteria, the column approach velocity and measured head loss on the debris beds were recorded using Labview software for enough time of testing.

3. RESULTS and DISCUSSION

The first set of experiments was design to ensure reproducible formation of different fiber to particulates ratio debris beds (fiber and acrylic particulates) in multiple columns following the proposed technique explained above. The reproducibility is quantified by the measured conventional head loss on these debris under the same flow conditions. A second objective of this series of experiments is to ensure that the formed debris beds are stable for long period of testing with no adjustment or motion that because the conventional head loss to change during the experiment. The following sections present the obtained results of series of experiments investigated these attributes on debris beds prepared following the newly proposed procedure discussed above.

3.1. Conventional Head Loss Stability and Repeatability on fiber/acrylic particulate debris beds

3.1.1. Conventional heat loss reproducibility

Three consecutive tests were carried out to measure the conventional head loss on debris bed with η of 2 in a selected column (column 1). Figure 4 shows the measured conventional head loss of the three consecutive experiments (Tests 1-3). Each data point in this figure presents the 5 minutes RMS value at the beginning of each testing hour. The results in the figure shows that at the debris loading approach velocity 0.05 ft/s, the data was recorded for for a few hours before the approach velocity was reduced to 0.013 ft/s. Although the measured head loss for the three experiments showed some degree of variability at the loading velocity (0.05 ft/s) but the measured head loss for the three generated beds are almost identical at the prototypical approach velocity (0.013 ft/s).

The presented results in Fig. 4 show that the measured head loss varies between 44 to 56 inch water at 0.05 ft/s approach velocity for the three tests. At low approach velocity, the average head loss values recorded over 9 hours of testing are 5.71, 5.69, and 5.97 inch water for tests 1, 2 and 3 respectively. The measured conventional head loss in single column (column 1) is reproducible within ± 3% from the mean value of the measured head loss for the three experiments (5.79 inch water).

These results confirm the consistency of the proposed procedure to generate repeatable debris beds of the same η in a single column under the same prototypical flow conditions (0.013 ft/s). The reproducibility of the debris bed formation and the repeatability of the measured conventional head loss in multiple column and different fiber to particulate ratio under the same flow condition were addressed in separate experiments. Three simultaneous tests using relatively thin beds (η = 13.8) with three independent identical vertical columns were performed to measure the conventional head loss. Similar to the previous experiments, the three beds were loaded at 0.05 ft/s and a few hours later (5 hours) the velocity was swept down to 0.013 ft/s. The conventional head loss was recorded at each column for at least 10-15 hours at the low velocity. The obtained results of the measured head loss for the three independent simultaneous tests are presented in Figures 5 (lower set of curves). The calculated mean head loss values at 0.013 ft/s velocity are 4.79, 4.40, and 4.28 inch water for columns 1, 2, and 3 respectively.

In a second step, prototypical latent debris dirt was added to the columns to investigate the ability of the three debris beds to filter out equal mass of added debris and quantify their response on the measured conventional head loss. The latent dirt is an industry standard testing particulate simulating the concrete debris generated in the containment and could accumulate on the sump screen. At each column 1.8 grams of latent debris dirt was added directly from the open top of each column at 0.013 ft/s. The introduced latent dirt increased the measured head loss by being filtered through the debris beds. After reaching stability condition, the measured head loss values for the debris beds with Acrylic particulate and latent dirt are 7.42, 7.95, and 7.72 H_2O" for columns 1, 2 and 3 respectively (Fig. 5, Upper set of curves). These results show that the measured conventional head loss is reproducible for the three different debris beds within ± 7% and ± 5% from the mean value before and after the addition of the latent dirt, respectively.

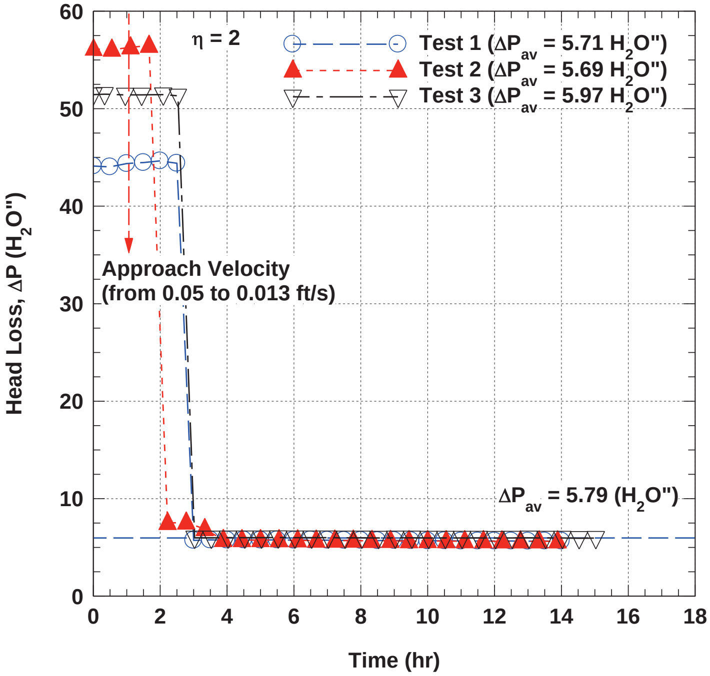

Figure 4: Conventional head loss in column #1 for three consecutive tests.

In a second step, prototypical latent debris dirt was added to the columns to investigate the ability of the three debris beds to filter out equal mass of added debris and quantify their response on the measured conventional head loss. The latent dirt is an industry standard testing particulate simulating the concrete debris generated in the containment and could accumulate on the sump screen. At each column 1.8 grams of latent debris dirt was added directly from the open top of each column at 0.013 ft/s. The introduced latent dirt increased the measured head loss by being filtered through the debris beds. After reaching stability condition, the measured head loss values for the debris beds with Acrylic particulate and latent dirt are 7.42, 7.95, and 7.72 H_2O" for columns 1, 2 and 3 respectively (Figures 5, Upper set of curves). These results show that the measured conventional head loss is reproducible for the three different debris beds (η = 13.8) within ± 7% and ± 5% from the mean value before and after the addition of the latent dirt to the columns, respectively.

The results in Figs 4 and 5 indicate that the generated prototypical debris beds following the proposed procedure are reproducible for different particulate to fiber ratio generated in single or multiple vertical head loss modules. In addition these debris bed are able to filter out other debris from the flow and response with conventional head loss increase within very small variability. Another attribute of the debris beds used for these types of experiments is to provide stable conventional head loss for long period of time.

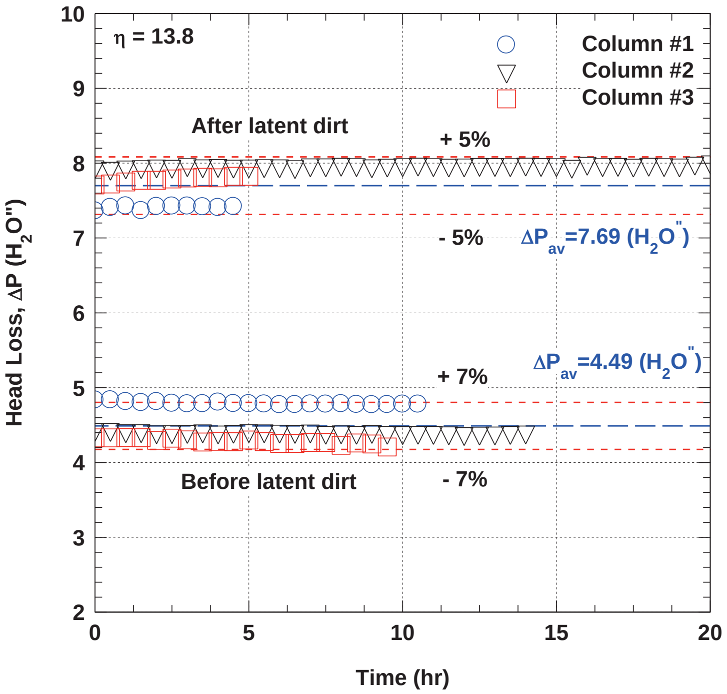

Figure 5: Conventional head loss in three vertical head loss modules.

3.1.2. Conventional Head Loss Stability and Hysteresis

The LOCA scenario for different types of pipe breaks (small, medium, and large breaks) could last for up to 30 days. The stability of the measured conventional head loss was addressed and presented in Fig. 6. Test 3 (Fig. 4) was extended for longer time and the measured head loss on debris bed of η=2 at 0.013 ft/s approach velocity was recorded. During the test, the approach velocity was also monitored for a few days. Figures 6 shows the results of the measured head loss and column approach velocity for 5 days testing in column 1. The mean value of the measured conventional head in a few hours (5.97 H_2O”) and over few days (5.98 H_2O”) are almost identical. The recorded approach velocity result shows very stable value during the 5 days test as shown in Fig. 6.

The stability of the measured head loss and the corresponding approach velocity (fig. 6) indicate that the geometrical characteristics such as thickness and porosity of the debris bed mixed with the particulate are highly stable under steady flow conditions. A slight change in the flow conditions (approach velocity) could results in a change in the debris bed thickness (compaction or expansion). As a consequence, the bed porosity could change and the conventional head loss is also changes. This concern could be addressed by performing a sweep test on stable debris beds.

The purpose of the sweep test is to examine the sensitivity of the debris bed (compaction and expansion) to the flow conditions in the vertical column. For test #3 (Fig. 4), a sweep test was carried out on the same debris bed (η = 2). The column approached velocity started from 0.013 ft/s decreased gradually to 0.009 ft/s followed by increase to 0.014 ft/s before set back to the original velocity (0.013 ft/s). Figure 9 presents the measured conventional head loss and the corresponding column approach velocity. The measured head loss at 0.013 ft/s before and after the sweep was 5.98 and 6.12 inch water. This slight increase in the measured head loss (2.3%) during 11 days of testing under different flow velocity showed almost no hysteresis on the measured conventional head loss on the debris bed.

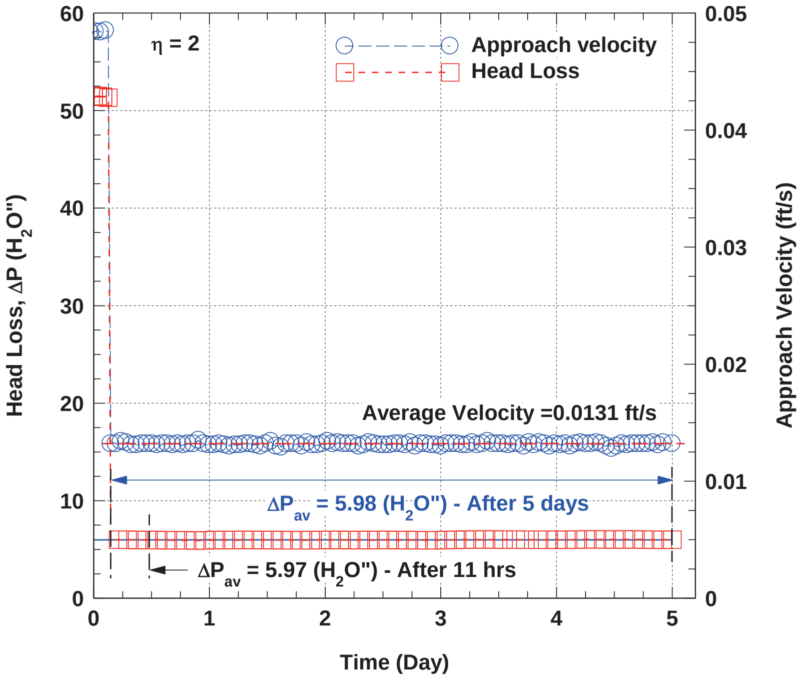

Figure 6: Long term testing of conventional head loss and approach velocity.

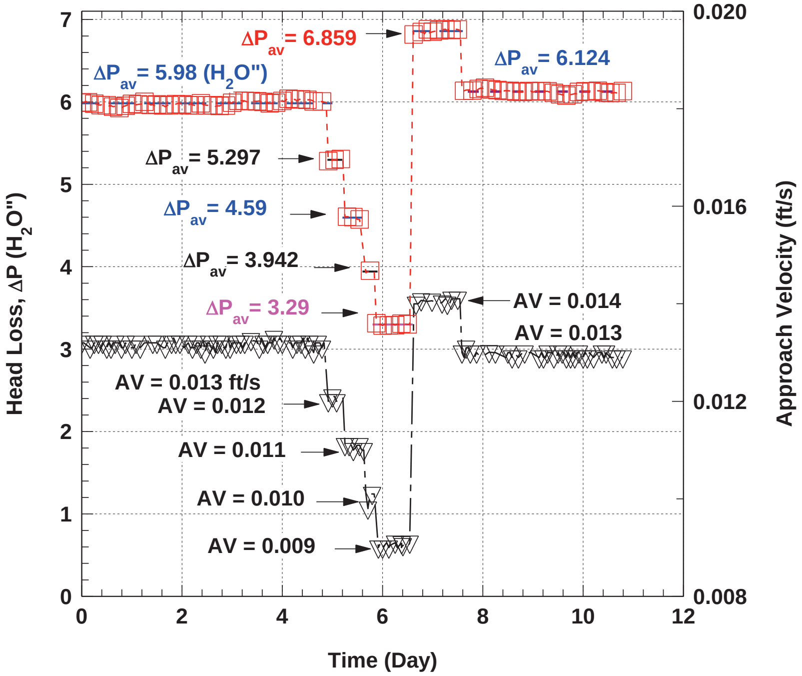

Figure 7: Sweep test and conventional head loss no hysteresis.

In the second set of experiments, the developed procedure was used to generate fibrous beds with more prototypical particulates that are present in Vogtle containment. Debris beds with different particulate to fiber ratios were investigated and both conventional and chemical head loss were measured and presented in the next section.

3.2. Conventional and Chemical Head Loss on Mutli-Constituents Debris Beds

3.2.1. Conventional Head Loss

Three multi-constituents debris beds were investigated for conventional heal loss prior to adding chemical surrogates and measuring the chemical head loss. The three beds have particulates to fiber ratio of 1.15 (50 g particulates/43.53 g fiber), 2 (40g particulates/20 g fiber), and 6.89 (25 g particulates/3.63 g fiber). The particulates in each bed is a combination of 90% epoxy paint, 5% IOZ, and 5% latent dirt by mass. The three beds were prepared by the procedure developed and presented in this paper and loaded to three different vertical head loss module or column filled with borated buffered solution at ambient temperature. The debris mixture was add to each column at 0.05 ft/s and few hours later the approach velocity was reduced to 0.013 ft/s which is the velocity of interest to measure the head loss. Figure 8a and 8b show the three column approach velocities and the corresponding measured conventional head loss. The approach velocity was stable for more than 15 hours in each experiment and the average velocity was 0.013 ft/s for the three columns individually (Fig. 8a). Reducing the approach velocity from 0.05 ft/s to 0.013 ft/s resulted in decrease in the conventional head loss (Fig. 8b). As the particulate to fiber ration decreases, the conventional head loss increases at low approach velocity. The average conventional head loss is 9.37, 6.4, and 5.66 H_2O"for particulate to fiber ratio of 1.15, 2, and 6.89 respectively.

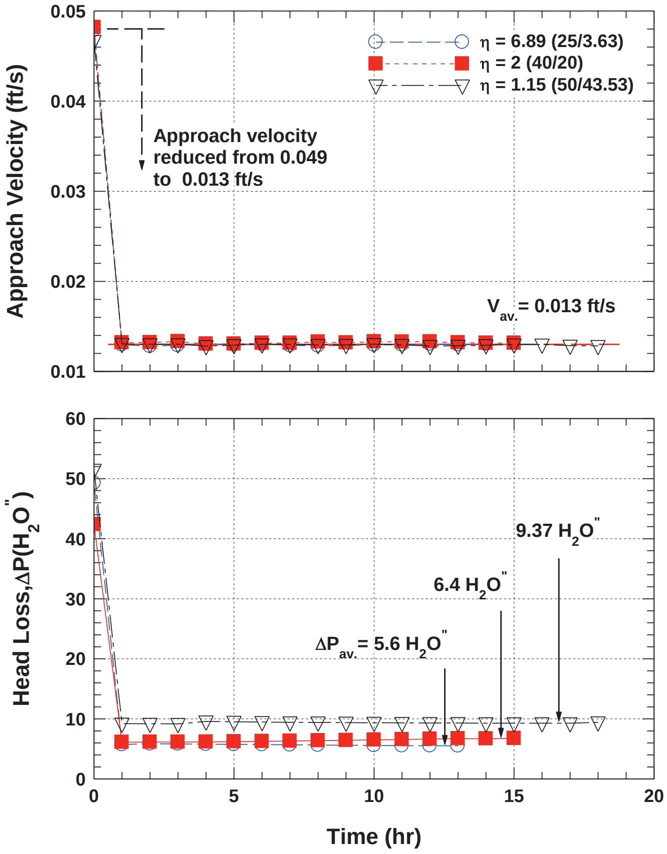

Figure 8: Conventional head loss on multi-constituents beds.

These results indicate that the conventional head loss increases as the particulates mass in the debris beds increases. The highest conventional head loss of 9.37 H_2O" is measured on debris bed with 50 grams of particulates (η = 1.15) while the lowest conventional head loss of 5.66 H_2O"is recorded on a debris bed has

25 grams of particulates (η = 2). These two debris beds were selected for chemical head loss investigation and the results are discussed in the next section.

3.2.2. Chemical Head Loss

A bench scale procedure to create different types of chemical precipitates was reported by Westinghouse in WCAP 16530 [8]. This report discussed how to make chemical surrogates including aluminum oxyhydroxide (AlOOH) and calcium phosphate ($Ca_3(PO_4)_2$) precipitates. A series of experiments with chemical addition of WCAP precipitates was carried out and confirmed that AlOOH WCAP surrogates is the most suitable for small scale head loss experiments [9,15-16]. Multiple samples of 50 ml each were prepared following the WCAP procedure for AlOOH (11 g/L) to be used in two different columns. These columns has two different particulates to fiber ratio debris beds, η (1.15 and 2). The surrogate concentration (11 mg/L) is the maximum recommended by the WCAP for this specific precipitates (AlOOH). All samples were successfully passed the settling tests as described in WCAP-16530 documents [8]. Table 1 shows the sequence and amount of batches added to each debris bed.

Table 1.Chemical batches added to the debris beds and their corresponding concentrations.

Batch #	Batch volume (mL) / Precipitate mass (g)	
	η = 2	η = 1.15
1	20 / 0.22	20 / 0.22
2	20 / 0.22	30 / 0.33
3	20 / 0.22	30 / 0.33
4	25 / 0.25	30 / 0.33
5	----	30 / 0.33
6	----	50 / 0.55
7	----	25 / 0.25
Total precipitates	**0.91 grams**	**2.34 grams**

The measured chemical head loss as a result of these additions of aluminum precipitates are presented in Figs 9 and 10 for η = 1.15 and 2 respectively. The chemical head loss measured on debris bed of η = 1.15 is shown in Fig. 9. The corresponding column approach velocity was also recorded and presented in the same figure. The conventional head loss prior adding batches of chemical surrogate was stable at 9.37 $H_2O^{"}$. Three consecutive batches of alumni surrogate of volume 20, 30 and 30 ml were added with no significant change in either head loss or column approach velocity. Adding two other batches of 30 ml each resulted in slight head loss increase from 9.37 to approximately 12 $H_2O^{"}$. A significant head loss increase was recorded after adding 50 ml of aluminum surrogate (batch # 6, table 1). A slight compaction was observed in the debris bed thickness. The debris bed height decreased from ~ 55 mm to about ~51 mm. This compaction resulted in change in the flow resistance by the debris bed and the column approach velocity decreased to 0.0124 ft/s as shown in Fig. 8. The velocity was increased using the pump frequency controller to recover the testing approach velocity of 0.013 ft/s and a slight increase in the measured head loss was observed. The largest head loss increase was recorded when the last chemical surrogates batch of 25 ml was added. The measured head loss started to increase with slight decrease in both bed height (~ 49 mm) and column approach velocity (0.0122 ft/s). Recovering the testing approach velocity by increasing pump frequency also increased the head loss to a final value of ~ 42 $H_2O^{"}$.

The chemical head loss measured on the debris bed of η = 2 is shown in Fig. 10. The corresponding column approach velocity was recorded and presented in the same figure. The conventional head loss prior adding batches of chemical surrogate was stable at 6.4 $H_2O^{"}$. Two consecutive batches of alumni surrogate of volume 20 and 20 ml were added with no significant change in either the head loss or column approach velocity. Adding a third batch of 30 ml (table 1) resulted in significant head loss increase from approximately 9 $H_2O^{"}$ to about 16 $H_2O^{"}$ without any observed change in the debris bed thickness (originally ~ 25mm) or column approach velocity as shown in Fig. 10. The largest head loss increase was recorded after adding 25 ml of aluminum surrogate (batch # 4, table 1). A slight compaction was observed in the debris bed thickness from ~ 25 mm to about ~21 mm and reduction in the column approach velocity from 0.013 ft/s to 0.012 ft/s. The velocity was increased using the pump frequency controller to recover the testing approach velocity of 0.013 ft/s and a slight increase in the measured head loss was recorded. The head loss increased from ~ 40 H_2O" to a final value of ~ 45 H_2O" at 0.013 ft/s column approach velocity as shown in Fig. 10.

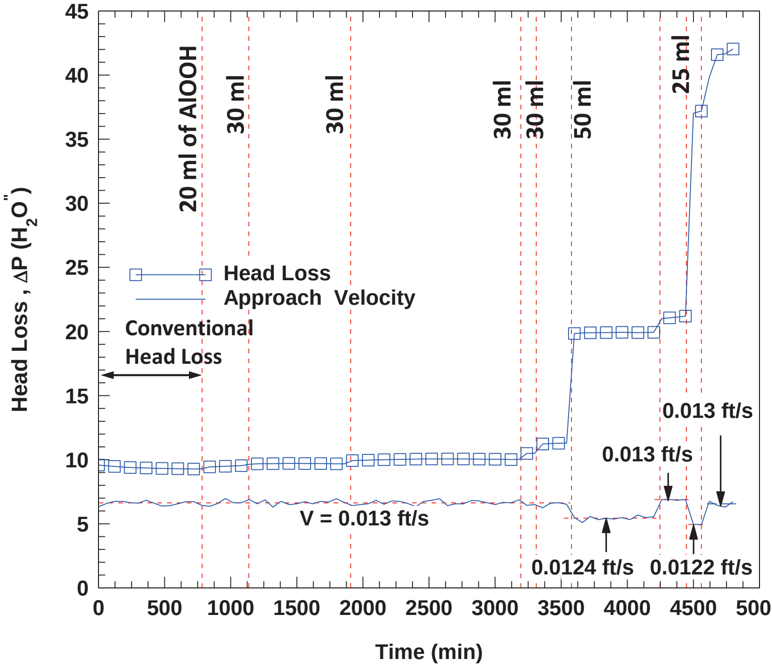

Figure 9: Chemical head loss on multi-constituents beds of η = 1.15.

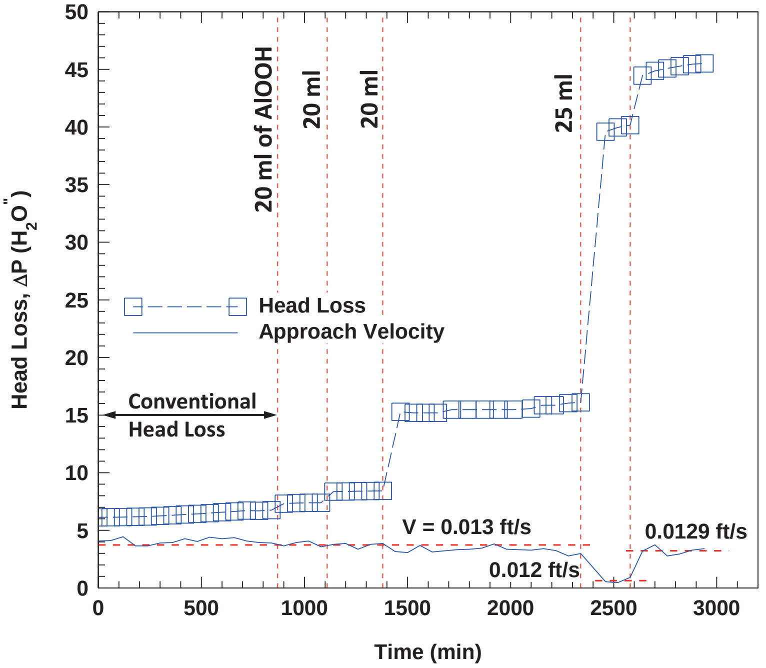

Figure 10: Chemical head loss on multi-constituents beds of η = 2.

4. SUMMARY and CONCLUSIONS

A series of head loss experimental studies was carried out to address GSI-191 for the Vogtle nuclear power plant at UNM. Conventional and chemical head loss was measured in a series of experiments on small scale vertical head loss modules or columns. The conventional and chemical head loss was measured on multi constituent debris beds of different particulates (acrylic) to fiber ratios ($\eta = 13.8$ and 2). These beds are generated on horizontal screens following a newly developed procedure developed at UNM and presented herein. The procedure resulted in repeatable formation debris beds that provided reproducible and stable conventional head loss for a few days of testing. The results showed a reproducible conventional head loss in the three vertical columns within ±7%. The conventional head loss was highly stable for 5 days of testing under stable column approach velocity.

Taking advantage of the reproducibility of the developed debris beds procedure, a second series of experiments was carried out using prototypical Vogtle debris materials to measure both conventional and chemical head loss. The conventional head loss was measured on three debris beds of different particulates to fiber ratios, η of 6.89, 2, and 1.15. The results showed that the measured conventional head loss increased with increased particulate mass in the debris beds. The average measured conventional head loss values are 9.37, 6.4, and 5.66 H2O"for particulate to fiber ratio of 1.15, 2, and 6.89 respectively.

The chemical head loss was quantified on two different debris beds using chemical surrogates. A standard aluminum chemical precipitates were prepared according to WCAP procedure and introduced to these beds. The results showed that the thin debris beds (~ 25mm) is more sensitive to the chemical precipitated compared to the thick debris bed (~ 55mm). The thick debris beds was able to filter larger mass of aluminum precipices compared to the thin bed to achieve close value of total head loss. The debris bed of $\eta = 1.15$ (~55 mm) was able to filter out 2.34 grams of aluminum precipitates to reach total head loss (conventional and chemical) of 42 H2O". The debris bed of $\eta = 2$ (~25 mm) filtered only 0.91 grams of aluminum precipitates to reach total head loss of 45 H_2O".

This work focused on the chemical head loss measured by introducing WCAP Aluminum precipitates prepared using bench scale experiment and added directly to the column. Chemical surrogates formed in situ could be more representative to those chemicals that could form in situ in the containment pool during LOCA. The chemical head loss corresponding to in situ chemical formation is the focus of the ongoing experiments at UNM.

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