Appendix E
ECCS Strainer Performance Testing for the U.S. EPR

E.1 Introduction

Appendix E documents the process and results for the U.S. EPR ECCS strainer testing, which confirms the performance of the U.S EPR ECCS strainer following a postulated loss of coolant accident (LOCA). Strainer testing is based on guidance specified in NEI 04-07 Volumes 1 [1] and 2 [2] and the March 2008 testing guidance [3] and input from Appendix C Debris Generation Evaluation for the U.S. EPR and Appendix D Chemical Effects Evaluation for the U.S. EPR .

E.1.1 Background

During a postulated LOCA inside containment, pipe and equipment insulation and coatings can be fragmented by the jet forces emitted from the break location. Chemical precipitant debris may be created from coolant system fluid and the buffering agent solutions interacting with the generated debris. This mixed debris potentially transports from the area of the break to the IRWST. The generated debris consists of fibrous material (from latent fiber and destructed insulation such as NUKON insulation), particulates (from destructed paint coatings, latent dirt and dust, and microtherm), reflective metallic insulation (RMI), miscellaneous debris, and chemical precipitates. A strainer is installed upstream of the ECCS pumps to prevent debris from entering the pump suction. Debris that transports to the IRWST must not cause a strainer head loss that impacts net positive suction head (NPSH) and satisfactory operation of the ECCS pumps during a LOCA condition. The overall head loss attributable to the strainer is a combination of the debris deposited on the strainer and the head loss associated with the clean strainer.

Strainer performance testing was performed at the Alden Research Laboratory, Inc. (ALDEN). Initial U.S. EPR strainer testing was performed in December 2009. The

December testing demonstrated debris transport characteristics of RMI and other debris, such as coating chips. This testing also illustrated the need to re-model the retaining basket to the prototypical height to support other additional type tests. Following the December testing, the test apparatus was re-constructed with the retaining basket built to full scale height. In addition, selected debris generation amounts were adjusted.

Following re-construction of the test apparatus, subsequent U.S. EPR strainer testing was performed during the week of February 22, 2010 with one additional test performed on March 5, 2010. The testing was conducted with a modified test flume. The strainer performance test plans contain the debris requirements, flume description with detailed measurements, data recoding methods, test set-up, detailed testing steps, calibration records, and data collected while testing. All testing was performed in accordance with the AREVA quality assurance program.

E.2 Scope and Objective

The objective of the U.S. EPR ECCS strainer performance testing is to determine the head loss (differential pressure) across the U.S. EPR strainer based on prototypical water flow and debris mix conditions expected in the U.S. EPR containment following a postulated LOCA.

The ECCS strainer test program consists of two phases.

Phase 1:

- Debris Transport Test - Test No. 1

Phase 2:

- Clean Strainer Head Loss Test - Test No. 1
- Design Basis Debris Loaded Strainer Head Loss Test - Test No. 2
- Fibrous Debris Only Sample Bypass Test - Test No. 3
- Debris Loaded Strainer Head Loss Thin Bed Test - Test No. 4

Initial ECCS strainer performance testing was intended to include a total five (5) ECCS strainer performance type tests. However, testing was terminated prior to completion of all testing. To ensure the test facility design responded prototypically for all planned testing, the test facility configuration was subsequently modified and the debris generation amounts adjusted. Based on review of the Phase 1 test data, the results for the Debris Transport Test (Test No. 1) were acceptable. The remainder of the four (4) strainer performance type tests were completed in Phase 2 following modification of the test facility configuration. Table E.2-1 lists and describes Phase 1 Testing. Table E.2-2 lists and describes Phase 2 Testing:

Table E.2-1 U.S. EPR Strainer Performance Tests - Phase 1

Phase 1 Test			
Type Test	**Test No.**	**Title**	**Description**
1	1	Debris Transport Test	Test determines the transportability of reflective metallic insulation (RMI), coatings (in the form of paint chips), and miscellaneous debris including other miscellaneous debris (gloves, labels, etc). (performed December, 2009)

Table E.2-2 U.S. EPR Strainer Performance Tests - Phase 2

Phase 2 Tests			
Type Test	**Test No.**	**Title**	**Description**
1	1	Clean Strainer Head Loss Test	Test determines the head loss of the clean strainer for five (5) different flow rates. (performed February, 2010)
2	2	Design Basis Debris Loaded	Test determines the debris bed head loss for the design basis accident for the U.S.

Phase 2 Tests			
Type Test	**Test No.**	**Title**	**Description**
		Strainer Head Loss Test	EPR design. Debris bypass sampling was performed during this test which may be used to provide debris bypass results for downstream analysis. (performed February, 2010)
3	3	Fibrous Debris Only Sample Bypass Test	Test includes fiber only to establish the transport characteristics of fibers introduced incrementally up through the maximum design basis fiber load. This test also evaluates how a fibrous debris bed forms on the retaining basket and strainer. Debris bypass testing was performed during this test which may be used to provide debris bypass results for downstream analysis. (performed February, 2010)
3	3A	Fibrous Debris Only Sample Bypass Test	This test repeated the procedures for Test 3 after a small amount of fiber was discovered in the pump casing following the termination of Test 3. Debris bypass testing was performed during this test which may be used to provide debris bypass results for downstream analysis. (performed March, 2010)
4	4	Debris Loaded Strainer Head Loss Thin Bed Test	Test determines if a higher head loss is possible with a thin bed of fibers, particulate, and chemical debris present, rather than with the design basis quantity of debris. This test includes all particulates, chemical debris, and that fiber quantity determined to form a thin bed of fibers on the surface area of the strainer and retaining basket, and is expected to cause the highest head loss in a thin bed regime. (Performed February, 2010)

E.3 Test Apparatus

The test configuration is prototypical of the U.S. EPR design. The test loop includes a flume, strainer, retaining basket, instrumentation & controls, and associated piping and valves for a flow recirculation loop.

The test apparatus and configuration are based on the following conservative assumptions:

- 100% of all the debris passes through a single heavy floor opening
- 100% of the LOCA return flow passes through a single heavy floor opening.

The test apparatus is designed to simulate plant conditions and includes two simulated plant elevations; the containment level heavy floor and the lower IRWST level that contains the borated water supply used for ECCS operation. The test apparatus contains one retaining basket and one strainer which is representative of one of four ECCS trains in the U.S. EPR design. In the plant design, fluid from a postulated LOCA flows onto the heavy floor and then falls into the IRWST through one of four heavy floor openings. The test apparatus simulates the free-fall flow of water from the heavy floor by introducing the return flow at an elevation above the flume water surface. As the water enters the test flume, it flows through the retaining basket, towards the strainer and into the strainer sump. From the strainer sump, the water enters a recirculation loop and is pumped back to the top of the retaining basket to simulate the flow of water on the heavy floor through the floor opening.

The test apparatus contains two flow paths. The primary flow path circulates approximately 91% of the water from the strainer to above the retaining basket for re-introduction into the test flume. The secondary flow path simulates the ECCS miniflow lines that circulate approximately 9% of the water from the strainer suction to the IRWST pool. The secondary flow path bypasses the retaining basket. This flow split is based on plant design requirements and scaled for the test facility.

E.3.1 Test Configuration and Scaling

The test apparatus conservatively represents the U.S. EPR plant conditions for developing strainer head loss. Testing involved two different test configurations and scaling combinations for Phase 1 and Phase 2 testing. Sections 3.8 and 3.9 describe the scaling methodology used.

Phase 1 Test Configuration and Scaling

Figure E.3-1 and Figure E.3-2 illustrate the test configuration for Phase 1 testing. Table E.3-1 provides the test scaling summary for Phase 1 testing.

Figure E.3-1 Test Configuration for Phase 1 Testing (Side View, - inches)

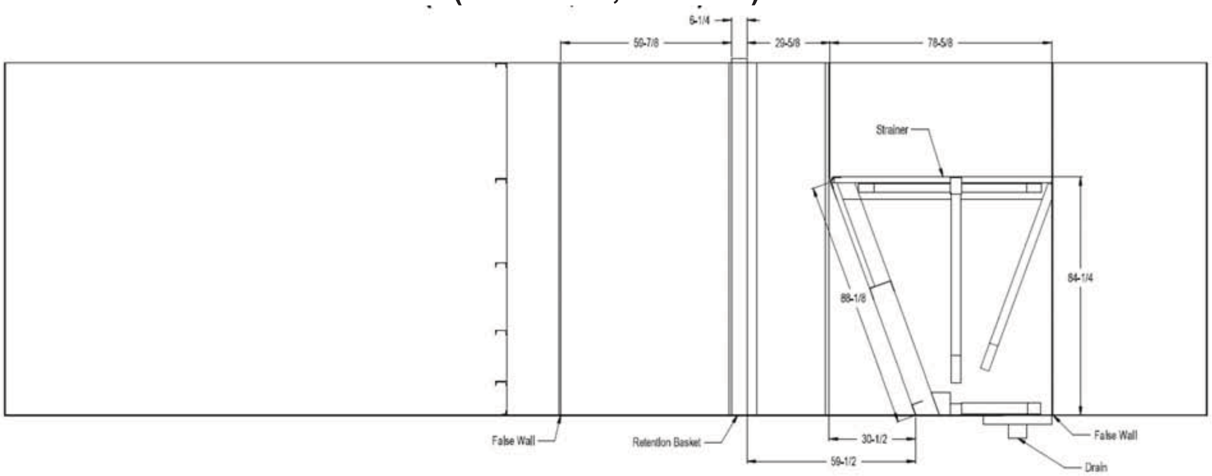


Figure E.3-2 Test Configuration for Phase 1 Testing (Top View, - inches)

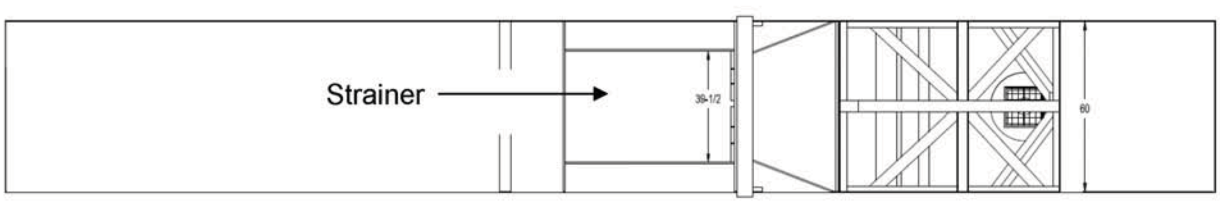


Table E.3-1 Scaling Summary for Phase 1 Testing

Description	Value	Unit
Flume / Strainer Width	5.0	ft
Water depth in flume	9.25	ft
Strainer length in flume	6.6	ft
Overhang length in flume	2.6	ft
Strainer height	7.1	ft
Strainer screened slant height	7.5	ft
Test strainer area	70.6	ft^2
Total active strainer area	753.5	ft^2
Scale factor[1]	9.37	%
Total active strainer flow rate	3,284.0	gpm
Heavy floor flow rate	2,997.0	gpm
Total test flume flow rate	307.8	gpm
Min wetted retaining basket surface area	306.4	ft^2
Flume screened retaining basket area	28.7	ft^2
Flume retaining basket width	3.1	ft
Retaining basket volume in plant	1,609.0	ft^3
Retaining basket volume in flume	150.8	ft^3
Basket depth	5.25	ft
Test flume volume	4,230	gal
Test flume piping	236.4	gal
Total flume volume	4,467	gal
Flume Turnover Time	15	min
Mini-flow	26.9	gpm

Note 1: A scaling factor is applied to total flow rate, heavy flow flow rate, mini-flow flow rate, strainer surface area, and retaining basket surface area/volume.

Phase 2 Test Configuration and Scaling

The Phase 2 test flume is different from the Phase 1 test flume. For Phase 2 testing the retaining basket scaling was modified to be more consistent with the plant design. The retaining basket height is increased. The bottom of the retaining basket is supported off the flume floor by foot pedestals and contains a perforated screen filtering area. In addition, the water management system is enhanced to prototypically control flume water levels consistent with design basis conditions.

Figure E.3-3 and Figure E.3-4 illustrate the test configuration for Phase 2 testing. Table E.3-2 provides the test scaling summary for Phase 2 testing. Figure E.3-5 and Figure E.3-6 depict the strainer, retaining basket, and components within the Phase 2 test flume.

Figure E.3-3 Test Configuration for Phase 2 Testing

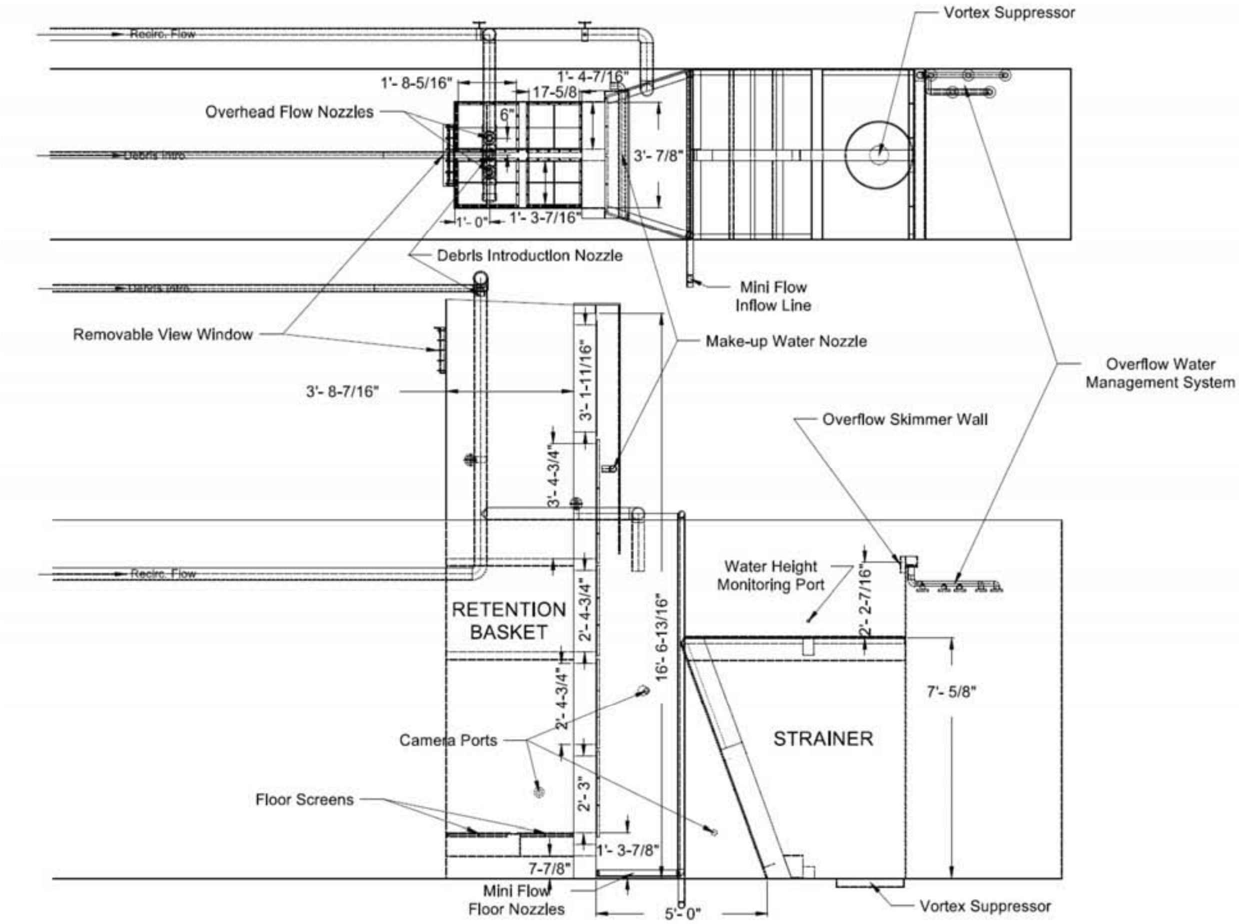


Figure E.3-4 Test Configuration for Phase 2 Testing (Recirculation Loop and Make-up Water Tank)

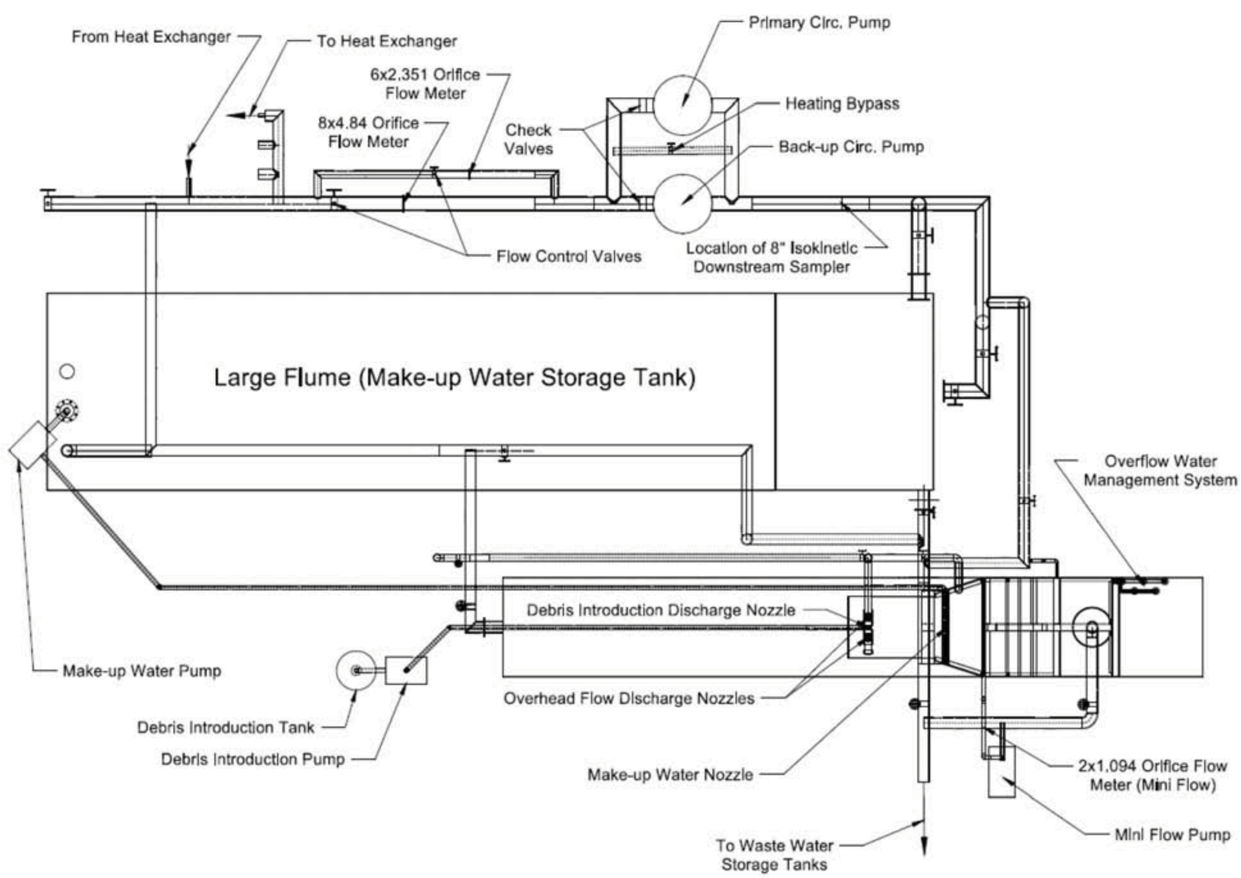


Table E.3-2 Scaling Summary for Phase 2 Testing

Description	Value	Unit
Flume / Strainer Width	5.0	ft
Water depth in flume	9.25	ft
Strainer length in flume	6.6	ft
Overhang length in flume	2.6	ft
Strainer height	7.1	ft
Strainer screened slant height	7.5	ft
Test strainer area	70.6	ft^2
Total active strainer area	753.5	ft^2
Scale factor[1]	9.37	%
Total active strainer flow rate	3,284.0	gpm
Heavy floor flow rate	2,997.0	gpm
Total test flume flow rate	307.8	gpm
Test flume heavy floor flow rate	280.9	gpm
Double retaining basket total surface area	642.0	ft^2
Test flume retaining basket area	60.17	ft^2
Test flume retaining basket width	3.1	ft
Double retaining basket volume in plant	2024.0	ft^3
Retaining basket volume in flume	189.7	ft^3
Basket length (depth)	3.7	ft
Test flume volume (without piping)	3,885	gal
Test flume piping	236.4	gal
Total flume volume	4,122	gal
Flume Turnover Time	14	min
Mini-flow	26.9	gpm

Note 1: A scaling factor is applied to total flow rate, heavy flow flow rate, mini-flow flow rate, strainer surface area, and retaining basket surface area/volume.

Figure E.3-5 Strainer, Retaining Basket, and Miniflow Lines Within the Phase 2 Test Flume

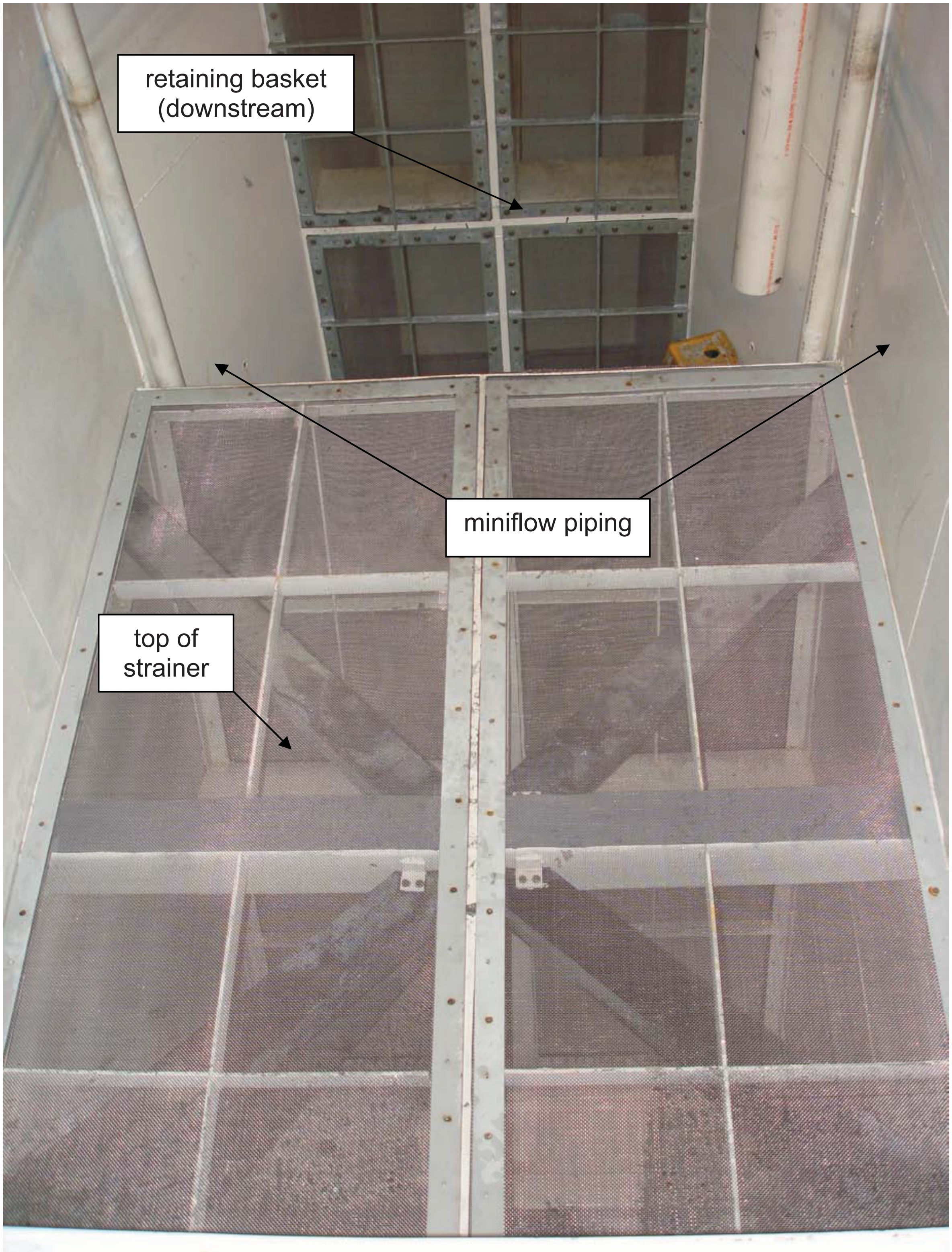
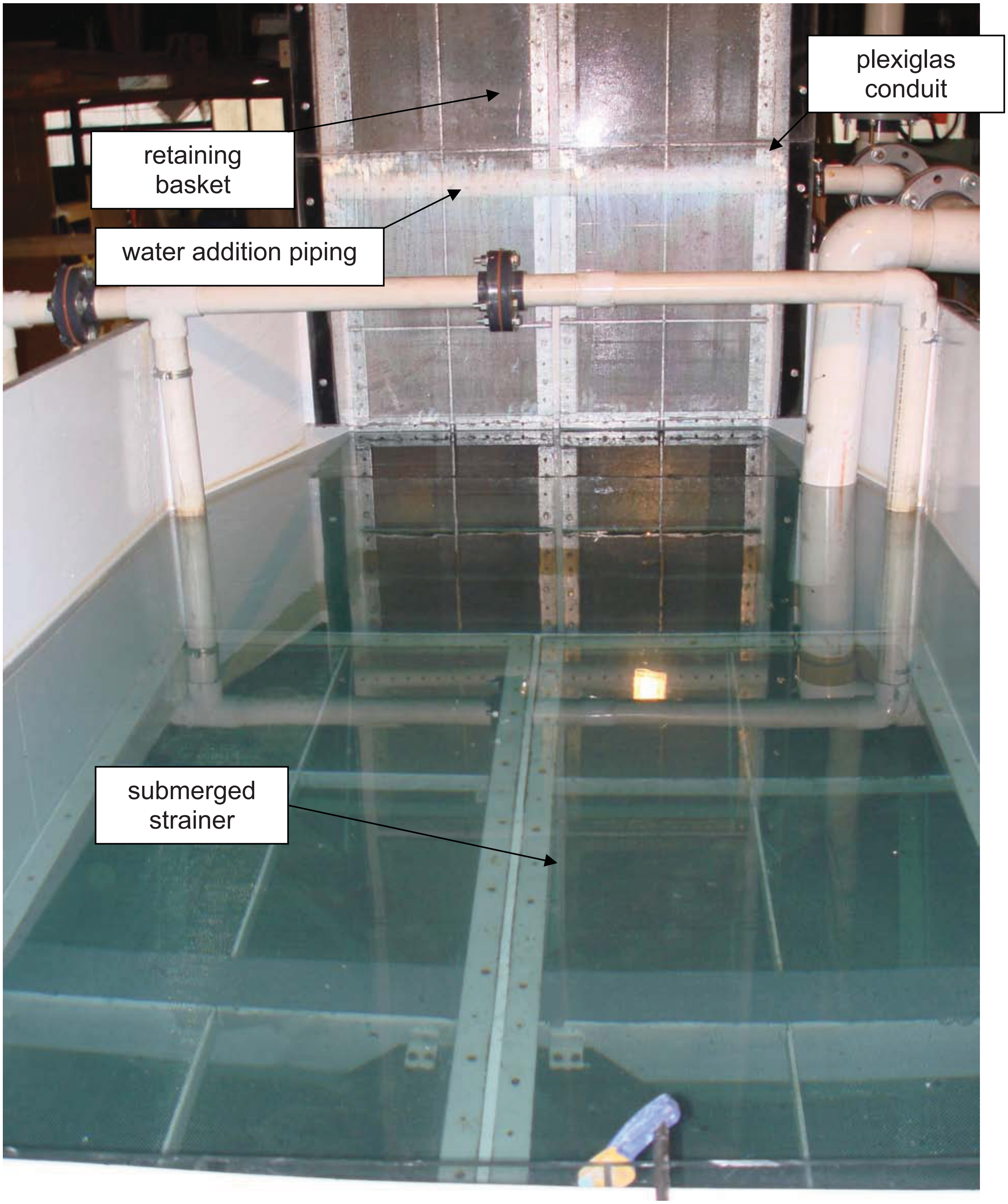


Figure E.3-6 Strainer, Retaining Basket, and Components Within the Phase 2 Test Flume



E.3.2 Flume Recirculation Loop

The flume recirculation loop is constructed mostly from four and six inch diameter pipe. Flow is provided by a centrifugal pump controlled by a variable frequency drive. The main flow from the strainer suction is routed above the retaining basket to simulate plant flow conditions from the heavy floor into the retaining basket. This flow is measured through a calibrated orifice meter and discharges through a common header. A secondary flow loop circulates a small portion of the total flow from the sump suction directly into the flume water pool between the retaining basket and strainer to simulate the ECCS miniflow. The miniflow is also measured by a calibrated orifice meter. The miniflow is split into two pipes (each 2 inches in diameter) that route water to the bottom of the flume's pool between the retaining basket and the strainer. At the bottom of the pool the miniflow is discharged via perforations in the piping along the flume floor. The perforations are oriented such that the discharge flow conservatively creates turbulence to prevent debris settling. The tests are conducted with city domestic water. For testing, the flume water is heated and maintained at approximately 120ºF via a heat exchanger connected to the recirculation loop.

E.3.3 Test Instrumentation

The flume test instrumentation consists of flow meters, level indication, differential pressure cells, and temperature instruments. A debris scale is used for weighing debris.

Flow instrumentation is provided for the flume recirculation loop. Differential pressure cells measure the flow differential pressure across the retaining basket and strainer. Level instrumentation is provided to monitor and control the flume water levels. Temperature instrumentation monitors the flume water temperature. A debris scale is used to weigh the debris in a dry state. The test instrumentation is calibrated using methods traceable to National Institute of Standards and Technology (NIST) or other reputable standards or procedures.

E.3.4 Debris Mixing

The test debris was thoroughly wetted with warm water and mixed with a power mixer prior to introduction into the test flume. To prevent fibrous debris agglomeration, the fiber was separated into batches of approximately ½ lb_m per 33 gallon drum prior to mixing. The fiber was allowed to soak in the warm water prior to flume introduction.

E.3.5 Debris Introduction

For the Phase 1 Debris Transport Test, debris was manually introduced into the flume above the retaining basket.

For Phase 2 testing, the debris was primarily introduced through a nozzle above the retaining basket using a pump and debris introduction tank. Figure E.3-7 depicts the debris introduction nozzle and Figure E.3-8 depicts the debris introduction tank and pump. After the particulate and fiber were added to the test flume, the debris introduction tank was flushed with clean water. Additionally, after the debris introduction tank and hose was flushed, the pump and feed hose was drained at the base of the pump. Except for Test 3 (Fibrous Debris Only Sample Bypass Test), the pump was dismantled following the introduction of all non-chemical debris to ensure debris was not trapped within the pump internals.

Figure E.3-7 Debris Introduction Nozzle

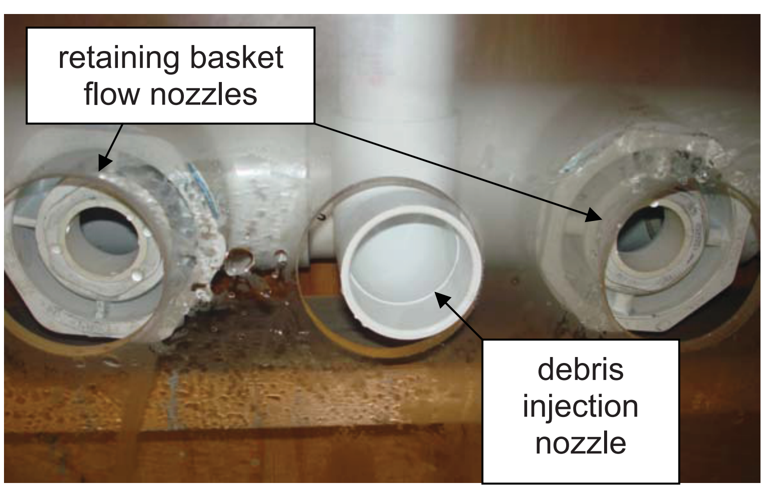


Figure E.3-8 Debris Introduction Tank and Pump

During Test 2 (Design Basis Debris Loaded Strainer Head Loss Test), the pump seal failed during the addition of the ‘dirt and dust’ debris source. Debris introduction was temporarily halted and the debris introduction tank was drained via the pump drain into a container to be added to the flume. The pump was dismantled and the debris within the pump casing was collected and added to the container holding the drained debris. Some debris laden water that leaked from the pump was recovered and also added to the storage container. The failed pump was replaced. It was determined that the debris pumps were unable to pump the ‘dirt and dust’ debris. Therefore, the ‘dirt and dust’ and tin powder were added through the observation window (via the debris introduction chute) above the retaining basket for Test 2 and Test 4 (Debris Loaded Strainer Head Loss Thin Bed Test). The contents recovered during the pump malfunction were also added to the test flume through the observation window. The plexiglas window was replaced after the debris constituents were added to the flume. Figure E.3-9 depicts the flume observation window and Figure E.3-10 depicts the debris introduction chute.

Figure E.3-9 Flume Observation Window

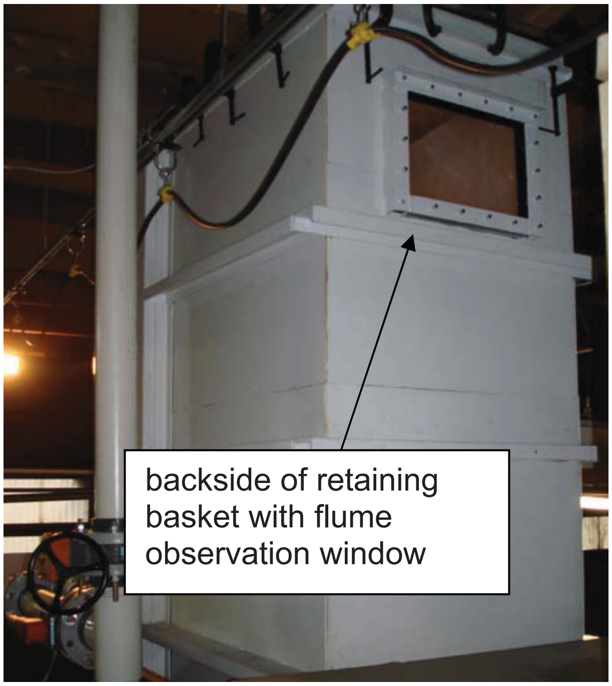
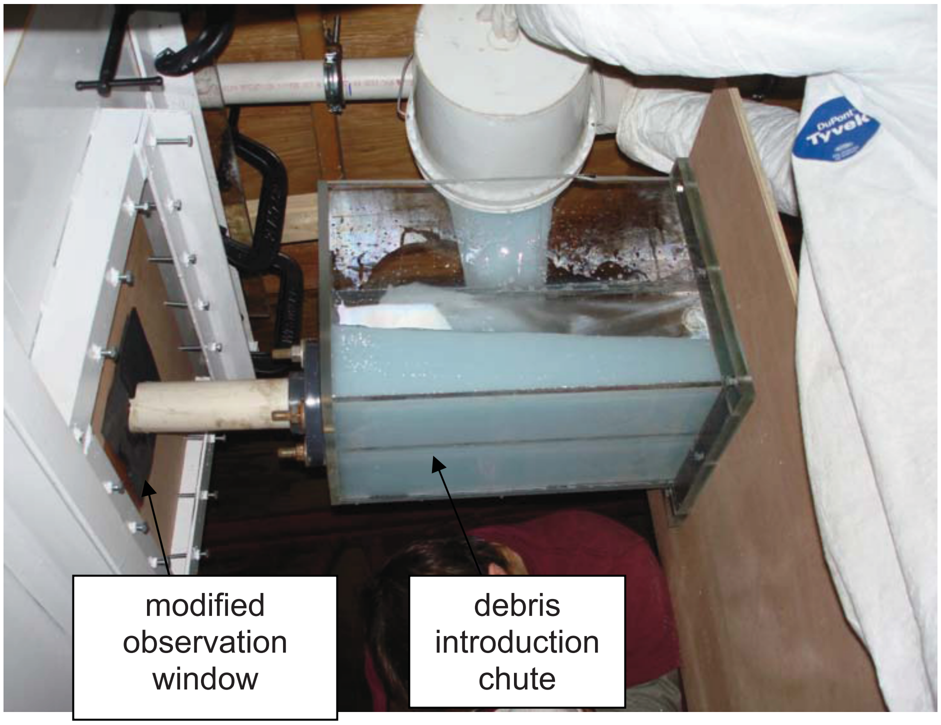


Figure E.3-10 Debris Introduction Chute



E.3.6 Downstream Debris Sampling

Three sampling ports are installed in the flume recirculation flow loop downstream of the pressure taps used to measure strainer head loss. Each port is connected to a valve in a three-valve array. Two pumps (main sampling pump and a back-up pump) are calibrated to a desired flow such that the flow velocity in the three ports is representative of the velocity in the recirculation flow loop. Samples are drawn during debris testing as required by procedure. Samples are collected at a location downstream of the test strainer and miniflow line tap and upstream of the main recirculation pump. Therefore, the debris load collected in the bypass samples is representative of the test fluid that would bypass the strainer and enter the ECCS. Prior to drawing a sample, the sampling lines are flushed to remove any residual debris from the previous sample.

E.3.7 Water Management

The water management system functions to control and maintain a prototypical test water level by adding and removing water from the test flume. The flume water volume increases as the wetted debris is added to the flume. To maintain the prototypical strainer submergence, an overflow weir is built into the rear wall of the test flume. The overflow weir captures the debris laden water mix and filters out the debris with 10 micron bag filters located behind the rear wall of the flume. The debris captured by the bag filters is periodically flushed and the captured debris is added back into the test flume. Figure E.3-11 depicts the overflow weir and Figure E.3-12 depicts the micron bag filters.

Figure E.3-11 Overflow Weir

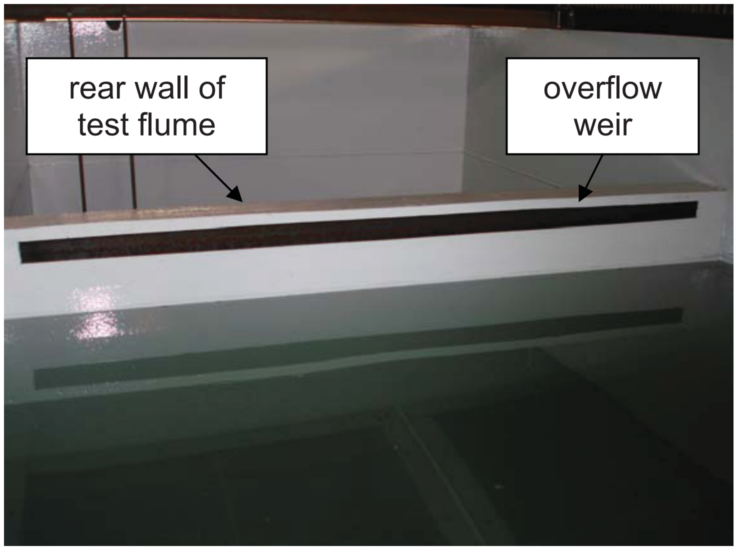
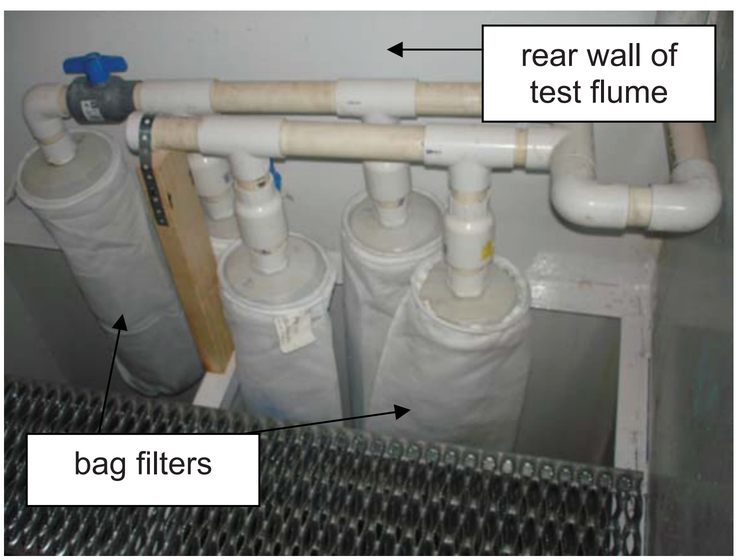


Figure E.3-12 10 Micron Bag Filters



The water addition system utilizes a make-up water tank to add water to the test flume as necessary. As the debris bed forms and clogs the retaining basket, the water level in the basket area increases above the water level surrounding the strainer. The water volume increase in the retaining basket area decreases the available volume of water around the strainer. As the water volume in the strainer area begins to decrease below the prototypical level, a make-up water pump adds water in front of the retaining basket to restore the normal prototypical water level surrounding the strainer. The make-up pump is controlled by float switches that monitor changes in the flume water level.

E.3.8 Strainer Scaling Methodology

The test strainer is prototypical of the U.S. EPR design. The strainer configuration used for Phase 1 and Phase 2 testing is the same. Table E.3-1 and Table E.3-2 provide the strainer scaling summary for Phase 1 and Phase 2 testing, respectively.

The basic geometry of the ECCS strainer is preserved for testing. Figure E.3-13 shows the strainer drawing with the outline of the modeled portion. Dimensions B and C are unchanged from the plant configuration. A small 0.75 ft portion on the bottom of the strainer is comprised of skirt and support feet. This portion is not considered an active screen area and is not included in the test strainer design. To maintain proper water submergence above the strainer, the modeled IRWST water level in the test flume is reduced from 10 ft to 9.25 ft. Dimension A is based on conservatively modeling the sump exit location with respect to the strainer faces.

Figure E.3-13 Modeled Portion of Strainer

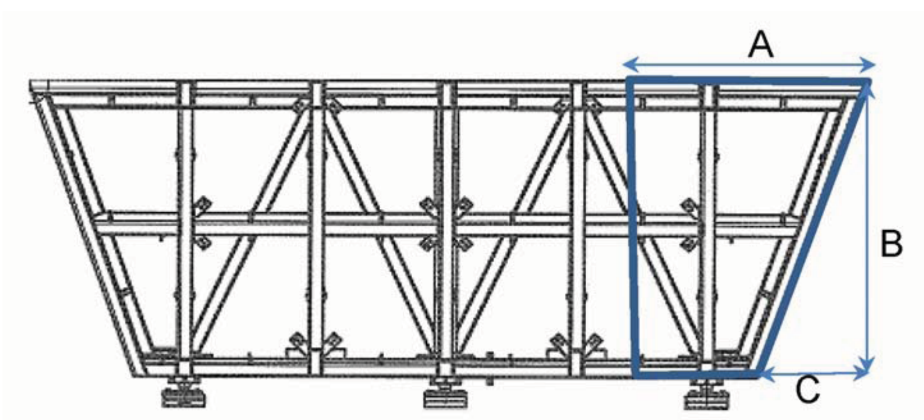
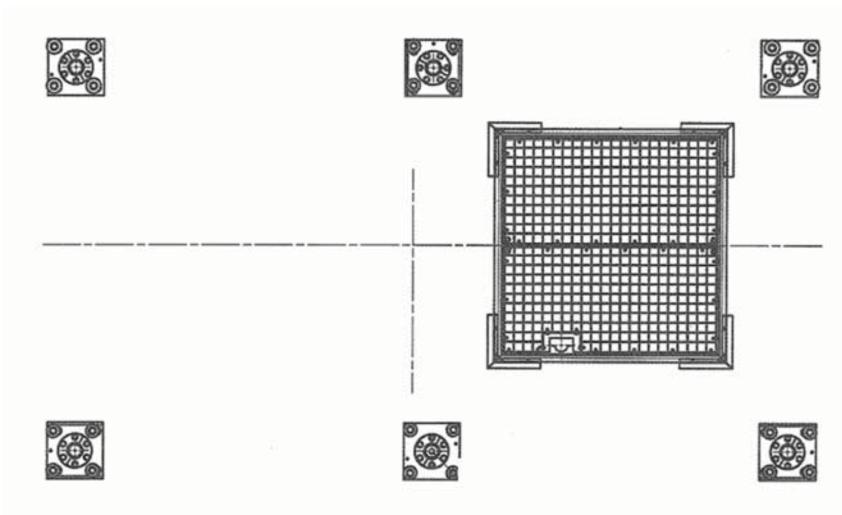


Figure E.3-14 shows the layout of the strainer supports with respect to the strainer sump cover. To conservatively represent the flow within the strainer, the test facility represents the strainer face with the minimum clearance from the sump to the face of the strainer. Dimension A is therefore determined by matching the distance from the strainer face directly to the leading edge of the sump cover. The sump cover size is scaled by flow area to the flow rate of the test flume.

Figure E.3-14 Strainer Support and Sump Cover (overhead view)



E.3.9 Retaining Basket Scaling Methodology

Two different retaining basket models were used for ECCS strainer performance testing. Phase 1 testing uses a retaining basket modeled in accordance with the scaling summary of Table E.3-1. Phase 2 testing uses a retaining basket modeled in accordance with the scaling summary of Table E.3-2.

Retaining Basket Scaling Methodology - Phase 1 Testing

The U.S. EPR design utilizes four retaining baskets consisting of two single compartment retaining baskets and two double compartment retaining baskets. A scaled single compartment basket was used for Phase 1 testing. For the retaining basket, a reference flow per unit area of wetted screen was determined. The flow per unit area of screen is determined using the minimum wetted surface area of the single compartment retention basket. The flow rate scale factor of approximately 9.37% was applied to the postulated conservative flow scenario of 100% of the break flow entering a single retaining basket. The flow rate together with the flow per unit wetted screen area determines the retaining basket modeled screen area. Conservatively, the retaining basket is modeled to only be open on the side of the facility that is facing the strainer. Arranging the test facility in this manner allows debris to travel freely from the retention basket to the strainer. The test basket frontal area mesh consists of 0.083" (2.1mm) openings, which is consistent with the U.S. EPR single and double compartment basket design. Both the retaining basket and the strainer are elevated in the plant. In the test flume these heights are not considered. This results in a conservative scenario of debris transport to the active strainer and retaining basket filtering surfaces. For the retaining basket, a low velocity area under the basket floor is not represented resulting in less debris settling. For the strainer, lowering the strainer face to the floor exposes the strainer to more floor transported tumbling debris.

The test facility retaining basket volume scaled by approximately 9.4%, matching the conservative plant flow per unit volume described above. Dividing the scaled retaining basket volume by the screened retaining basket area yields the test flume retaining basket depth.

Retaining Basket Scaling Methodology – Phase 2 Testing

The U.S. EPR utilizes two retaining basket designs in the IRWST. These designs consist of the single and double compartment retaining basket arrangements. The scaled large compartment of the double compartment retaining basket was used for Phase 2 testing. The double compartment retaining basket is separated into a large and small compartment. The small compartment basket is designed to capture any debris laden water that may enter the IRWST from the annular area of containment. The large compartment basket receives flow from the heavy floor opening. The screened area of the large compartment of the double compartment retaining basket contains less screened surface area than the single compartment retaining basket. Therefore, it is conservative to model the large compartment of the double compartment basket in the test apparatus. The portions of screened area that are scaled for the test apparatus include the large compartment's left, right, front, and bottom surfaces. For conservatism, the area between the large and small compartment of the double compartment basket is not modeled.

Table E.3-3, Retaining Basket (RB) Scaling Summary and Modeled Parameters provides the retaining basket scaling summary and modeled parameters for the large compartment of the double compartment retaining basket. The scaled volume ensures that the retaining basket receives a prototypical flow per unit volume. The double compartment retaining basket is positioned on pedestals 0.66 feet above the IRWST floor. The bottom surface area of the basket is covered with a meshed screen of the same perforation size as the remainder of the basket. Consistent with the retaining basket design, the test basket is raised above the test floor with the bottom area screened and scaled approximately 9.37%. Subtracting the scaled bottom portion of the retaining basket from the scaled total surface area of the retaining basket provides the scaled vertical portion of the test basket. Based on the test apparatus maintaining 1:1 vertical scale, the test basket is designed and constructed to reach 16.57 feet above the test apparatus floor which is consistent with the plant design. The test basket width is determined by dividing the 'scaled vertical surface area' by the 'RB screened vertical height' in the test apparatus (excluding the pedestal height). The test apparatus retaining basket length (screened basket front face to back wall) is determined by dividing the 'scaled RB volume' by the 'RB screened height' and the 'test apparatus RB width'.

Table E.3-3 Retaining Basket (RB) Scaling Summary and Modeled Parameters

Description	Value[2]	Unit
Scale	9.37	%
Total RB Surface Area	642.00	ft^2
Scaled Total RB Surface Area	60.17	ft^2
RB Floor Surface Area	120.38	ft^2
Scaled RB Floor Surface Area	11.28	ft^2
Plant Vertical RB Surface Area	521.62	ft^2
Test Apparatus Vertical Surface Area	48.89	ft^2
RB Vertical Height	16.57	ft
RB Pedestal Height	0.66	ft
RB Screened Vertical Height	15.91	ft
Test Apparatus RB Width	3.07	ft
Plant RB Volume	2024.00	ft^3
Scaled RB Volume	189.71	ft^3
Test Apparatus RB Length[1]	3.88	ft

Note[1]: A retaining basket length of 3.7 feet is used instead of 3.88 feet. This length creates the correct scaling for the surface area of the retaining basket bottom.

Note[2]: Only surface areas and volumes are scaled.

E.3.10 Flume Vertical Flow Water Management

The majority of the water flow downstream of the strainer was re-introduced to the test flume with a nozzle delivery system. This was accomplished to represent the LOCA return flow onto the heavy floor and into one of four retaining baskets through the heavy floor openings. The plant design provides approximately 15.3 feet of water free-fall before the water reaches the surface of the IRWST pool. The test flume represents an adjusted 1:1 vertical scale of the U.S. EPR IRWST design. To conserve the vertical scale in the test facility, the momentum produced by the water free-fall must be preserved. The test facility ceiling limits the free-fall of water to approximately 8 feet.

Therefore, the velocity of the water exiting the nozzles above the flume pool is increased to represent the plant's actual water free-fall conditions.

E.4 Debris Description

Debris types for strainer performance testing consist of non-chemical and chemical debris. The non-chemical debris types and amounts are based on the Debris Generation Evaluation for the U.S. EPR (Appendix C). The chemical debris types and amounts are based on the Chemical Effects Evaluation for the U.S EPR (Appendix D). The following sections discuss the debris types used for testing. Specific debris types, quantities, and surrogate materials used in testing are documented in the debris allocation tables in Section E.5.

E.4.1 Reflective Metallic Insulation (RMI)

During the Debris Transport Test conducted in December 2009, RMI debris pieces of 2 mil thickness and various sizes from 0.25 inch x 0.25 inch up to 4 inch x 4 inch were shown to sink and settle on the bottom of the retaining basket. Due to the non-transport characteristics of RMI under design flow conditions, RMI was not included in subsequent tests. Removing RMI from subsequent tests also prevents the possibility of RMI debris trapping fibrous debris in the retaining basket, thus resulting in less conservative test conditions. Figure E.4-1 depicts typical RMI test debris.