Experimental ECCS Sump Strainer Head Loss Testing and the Incorporation of CFD Computed Source Terms for Pressurized Water Reactors

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Abstract

High Energy Line Breaks (HELBs) inside nuclear reactor containment are recognized as challenges to Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) nuclear power plants arising from the collateral damage due to insulation, fireproofing, coatings, and other miscellaneous materials which are shredded and transported during the event. These materials, as well as latent debris (dirt and dust) will be transported towards the containment floor and the recirculation sump screens by flow from both the HELB and the containment spray headers. This debris, if washed towards the recirculation pumps, could potentially impede the performance of the Emergency Core Cooling System (ECCS).

To evaluate transport of material towards the sump and the potential for degradation in performance of the ECCS, Computational Fluid Dynamics (CFD) has been used to predict the volume of material transported to the sump screens [1]. This predicted volume is then used in full scale laboratory tests to determine head loss across the screen under design flow rates.

The laboratory sump strainer tests employed a flume facility measuring 14 m by 3 m by 1.5 m tall with a 2.5 m by 3 m by 2 m deep pit at one end, which can accommodate multiple full scale strainer modules. Head loss performance of the modules under different insulation debris loading conditions was evaluated. The internal walls of the flume were adjusted to reproduce prototypical average approach flow velocity and velocity gradients such that the transport of insulation debris to the strainer modules was accurately represented. A three-port isokinetic sampling system was integrated into the downstream piping for measuring debris bypass.

This paper will cover the sump screen head loss testing methodology, and the associated integration of the computational results for the source terms.

Introduction

High Energy Line Breaks (HELB's) inside reactor containment can be challenges to both Pressurized Water Reactors (PWR's) and Boiling Water Reactors (BWR's). The high pressure steam released during such a break can shred insulation, fireproofing material, and coatings as well as generating other debris from material near the break in the containment building.

During a HELB, water from the steam break and cooling spray are collected by the Emergency Core Cooling System (ECCS) to be reused as a coolant for the reactor core to remove the decay heat. The debris from the break may collect in the collection sumps and could potentially cause a high enough pressure head loss in the strainers filtering the debris to lower the ECCS flow rate below safe levels.

This has been an ongoing concern for the U.S. Nuclear Regulatory Commission (NRC), which performed basic research projects during the 1980's to evaluate the hazard and to develop regulations [2][3]. For PWR's, operating experience revealed new debris types, including degraded or failed containment paint coatings. The regulatory attention culminated in the identification of Generic Safety Issue 191 (GSI-191, "Assessment of Debris Accumulation on PWR Sump Performance"), identified in Footnotes 1691 (from 1995) and 1692 (from 1997) of NUREG-0933 [4].

In order to address the strainer head loss requirement in GSI-191, Performance Contracting, Inc. (PCI) , AREVA NP (originally Framatome NP), and Alden formed a team to manufacture, then test new strainers. This paper will describe the experimental procedure and methodology for testing strainers for use in specific power plants.

Nomenclature

BWR	Boiling Water Reactor
CFD	Computational Fluid Dynamics
ECCS	Emergency Core Cooling System
GSI-191	U.S. NRC Generic Safety Issue 191
HELB	High Energy Line Break
NRC	U.S. Nuclear Regulatory Commission
PWR	Pressurized Water Reactor

Strainer Evaluation Methodology

Figure 1 *Typical stack of strainer disks. The circular section in the top covers the core tube.*

As outlined in NEI 04-07[5], the approved methodology for evaluating strainer performance in any given plant entails the following steps: (1) debris inventory, (2) debris generation modeling, (3) debris transport modeling, and (4) strainer testing. Step (1) entailed a walkdown of each plant in question to evaluate what types of material were present in each zone of the containment building. In step (2), empirical debris generation models were used in order to determine the quantity, type, and size of debris that would be generated in a break of a certain size in a certain zone for each plant evaluated. In step (3), Alden employed Computational Fluid Dynamics (CFD) techniques [1] to determine how much of the generated debris would be transported to the sump region. After PCI designed a strainer appropriate to handle the worst case debris scenario computed in step (3), this strainer would be tested in a flume at Alden Research Laboratory.

Each unique SURE-FLOW^{TM} test module typically consisted of five three-dimensional rectangular disks constructed from stainless steel reinforced perforated plate, all connected by cylindrical core tube sections. An example of an assembled stack disk strainer is shown in Figure 1.

Test Facility

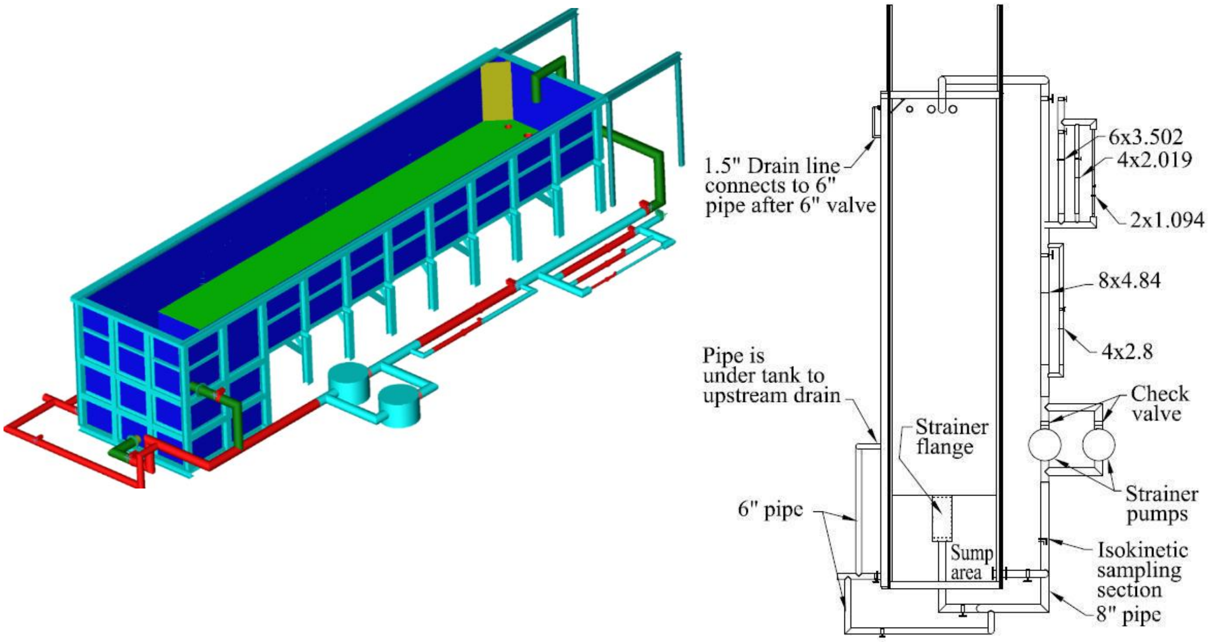


Figure 2 *3 m wide by 10.4 m long by 1.8 m high steel reinforced test flume and flow loop, with isometric and plan views.*

The main component of the new test facility is a steel flume measuring 3 m wide by 10.4 m long by 1.8 m high. The flume is re-enforced with tubular box steel to minimize both wall and floor deflection at full capacity (57.8 KL of water). At one end of the flume is a 1.8 m deep pit to accommodate various prototype sump arrangements. A three dimensional rendering of the flume geometry is shown in Figure 2.

The steel flume is used as a containment shell within which internal walls are constructed to reproduce the required average flow velocities and velocity gradients approaching the test module. These internal walls are removed and re-constructed for each individual plant test sequence, as the configuration of these walls depends upon the plant flow velocity field. Because clearances between the steel flume walls and the internal walls are small for some plant configurations, video cameras, connected to monitors, can be used to accommodate real-time observations.

The flume is elevated approximately 1.2 m above the main laboratory floor with the pit resting on the floor of the building sump whose elevation is 0.6 m below the main floor level. A gantry hoist and rail system is used to install the strainer modules in the tank.

Figure 3 *Photo of test flume and flow loop. View angle is similar to Figure 1, but from a lower elevation.*

The basic flow loop is also shown schematically in Figure 2. Water is circulated through the test loop using two Aurora-class series 330 Centrifugal Pumps with flow capacities of up to 93.5 L/s at 9.1 m of water each. These pumps are also rated for water temperatures of up to 93 °C. The pump speed is computer controllable using Variable Frequency Motor Drives to maintain steady flow through the strainer and debris bed. Automated valve control may also be utilized to control flow rate. Flow through the return lines is measured using standard ASME orifice plate flow meters with pressure tap output fed through Rosemount DP cells/transmitters to data acquisition computers. Two data acquisition computers are used to read the DP cell output simultaneously to provide a single-failure redundancy to the data logging system. The output from two digital temperature probes is also monitored through the data acquisition system. Strainer head loss is measured using a four-point pressure tap array located just downstream of the strainer module discharge pipe with the output fed through a Rosemount DP cell to the data acquisition computer. The data acquisition computers are Dell Laptops configured for data acquisition (laptop data acquisition computers are used to take advantage of their uninterrupted power feed features). External USB data acquisition cards are used to process data signals and LabView data acquisition software is used to collect data and control instrumentation.

The main loop piping is 6 inch (15.24 cm) PVC with a maximum temperature rating of 60 °C. Transition pieces from plant-specific strainer core tube flanges were custom fabricated to join with the 6 inch PVC. Manual valves are used to isolate pipe runs depending on the configuration of the flume and the return pipe segments utilized.

To achieve elevated temperature testing in the flume, all tank and piping surfaces are wrapped with insulation and a boiler is placed in-line, upstream of the pump inlet suction.

Test Debris

Because the exact debris that would be generated in the plant would be difficult to generate for testing, appropriate debris surrogates are used. Latent debris are simulated using Nukon fines for fibrous debris and PCI PWR dirt mix for particulates, using NRC guidance [5] for size distribution. Zinc coatings are simulated using Tin in powder form. Epoxy coatings are simulated with pulverized epoxy powder or powdered walnut shells. Prepared epoxy chips are used in instances where paint is known to fail as chips. Miscellaneous debris (labels, etc) are site specific materials and information on the quantity for one module is provided by the plant in question.

The test debris (fibrous, particulate, etc.) appropriate for each plant are released into the water in a conservative order as the pumps are running so that the less transportable material does not impede the transport of the more transportable debris types.

In addition to fibrous, particulate, and latent debris, precipitates from chemical reactions are predicted to be present in the prototype containment. The amount and size is based upon the chemicals in solution during a HELB, the solid reactive materials present, the pH, and the temperature. Previous studies [6] have shown what environmentally benign surrogates are to be used for the precipitates (hereafter referred to as WCAP chemical debris).

The WCAP chemical debris is mixed in large vats using variable speed electromechanical mixers. The surrogate chemical flock is pumped to the flume from the mixing vats using one of two large paristaltic pumps (paristaltic pumps are used so as not to break up the chemical flock during delivery). The chemical is introduced into the flume below the water surface to distribute the chemical debris spatially and to minimize density currents in the flume.

Near-sump Velocity Reproduction

For typical strainer installations, it is believed that the opportunity exists in the regions surrounding the strainer sump for debris to settle to the floor prior to interacting with the strainer disk modules. Further, it is believed that approach velocities near the floor in the immediate region of the strainer modules and the vertical component of the velocity below the strainer modules are not sufficient to move all of the debris to the screen face.

To represent prototypical approach flow patterns and velocities correctly in the test protocol, a full size strainer module must be tested. Further, the geometry of the flume must be adjusted to reproduce the average approach flow velocities and spatial velocity gradients as they are predicted to exist in the actual containment floor during recirculation. This requires analysis of containment flow patterns approaching each module in each new strainer array installed in the containment. A defensible approach to obtain this information is to use CFD to model the containment flow patterns and turbulence intensities with the new strainer array installed.

Using the CFD predicted results[1], the flow stream to each module is identified by numerically seeding each module surface with mass-less tracer particles and back-calculating their trajectories through the computational domain. This analysis identifies the three dimensional volume within which all flow enters the module. Within each of the volumes identified for each module in the installed strainer array, cross sectional average floor-parallel velocities are computed at up to 30 locations upstream. The maximum interval between cross sections is limited to about 0.3 m, as measured along the centerline of the three dimensional volume). The average velocities at each cross section identified are subsequently averaged across all modules for each of the 30 upstream locations. Mathematically, the average one-dimensional velocity at each selected distance from the strainer module (V_j) can be expressed as

$$V_j = \frac{\sum_{i=A}^{N} V_{av_{ij}}}{N}$$

where Vav_{ij} is the average one-dimensional velocity for each strainer module at the selected distance and N is the number of strainer modules. This is depicted schematically in Figure 4.

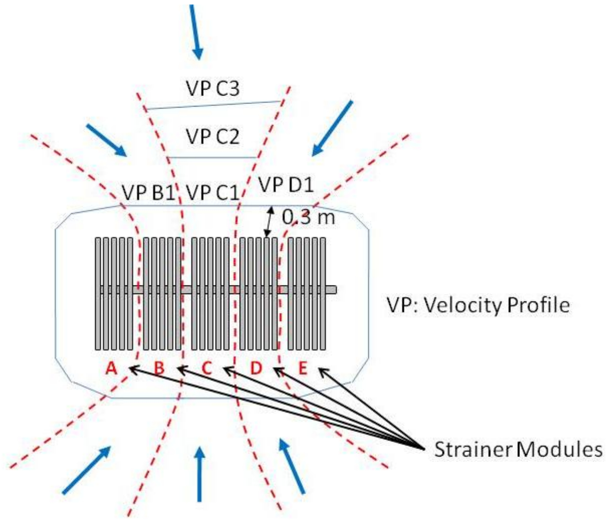


Figure 4 *Schematic depiction of velocity averaging technique using CFD results.*

The resulting averaged velocities are then used at as the basis to configure the test flume geometry to reproduce a "typical" approach velocity variation with distance for the installed strainer array. If multiple strainer arrays exist for a given installation, the array with the highest or bounding approach velocities may selected or averaging between the arrays may be employed.

The test flume velocities approaching the sump are controlled by modifying the flume side walls. Figure 5 shows a photo of the temporary side walls for a typical flume set-up. The shape of the converging side walls is dictated by the required average cross sectional velocities approaching a typical strainer module as described above.

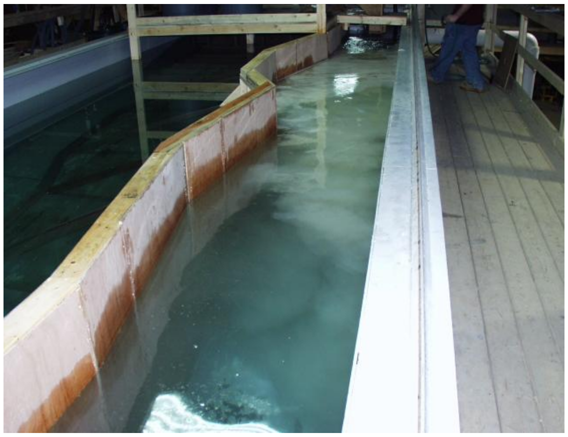


Figure 5 *Temporary flume side walls adjusted to reproduce averaged approach flow velocities and gradients.*

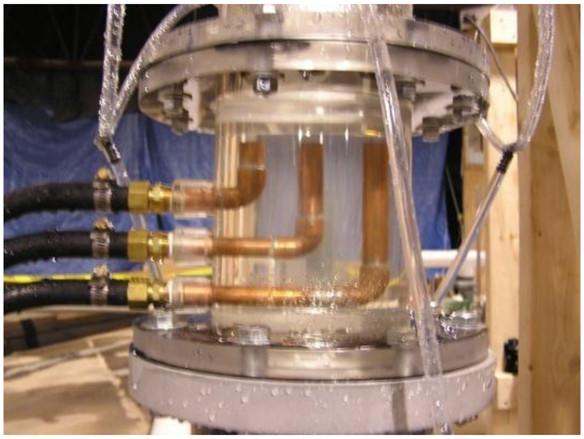
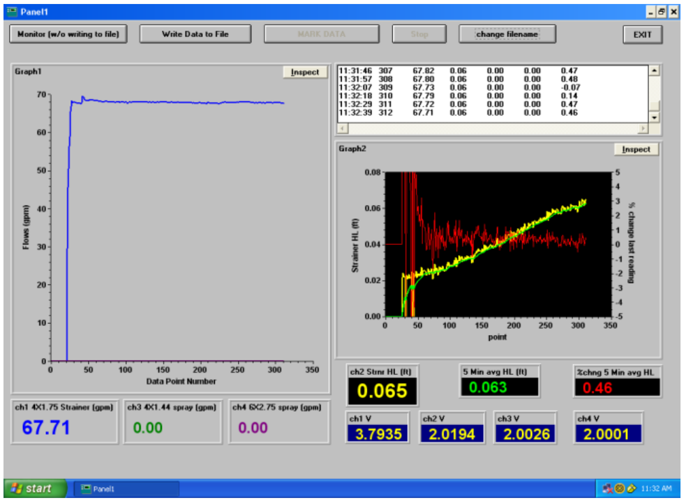


Figure 6 *Isokinetic sampling section downstream of strainer module.*

Downstream Sampling

Another piece of information that is desired in test results is the amount and type of material that bypasses the strainer modules. Therefore, in conjunction with the strainer head loss testing, isokinetic sampling was performed downstream of the modules. Three sampling points in a pipe cross-section are used, with water being withdrawn at the same velocity as the flow in the pipe, in order to avoid any biasing. Figure 6 shows a typical sampling section in the downstream piping.

Testing Results



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11:31:46  307     67.82   0.06    0.00    0.00    0.47
11:31:57  308     67.80   0.06    0.00    0.00    0.48
11:32:07  309     67.73   0.06    0.00    0.00    -0.07
11:32:18  310     67.79   0.06    0.00    0.00    0.14
11:32:29  311     67.72   0.06    0.00    0.00    0.47
11:32:39  312     67.71   0.06    0.00    0.00    0.46
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ch2 Stnr HL (ft) 0.065

5 Min avg HL (ft) 0.063

%chng 5 Min avg HL 0.46

ch1 4X1.75 Strainer (gpm) 67.71

ch3 4X1.44 spray (gpm) 0.00

ch4 6X2.75 spray (gpm) 0.00

ch1 V 3.7935

ch2 V 2.0194

ch3 V 2.0026

ch4 V 2.0001

Figure 7 *Data acquisition screen view of instantaneous test results, including flow rate (blue), instantaneous total pressure head loss (yellow), five minute averaged head loss (green), and percent change in head loss over a five minute period (red).*

Test termination is achieved when the head loss across the test module varies less than 1% in 30 minutes and after the pool volume is calculated to have recirculated at least 15 times from the start of the test. Test duration under this termination protocol has ranged between 6 and 24 hours.

A typical real-time result as depicted on the data acquisition computer screen is shown in Figure 7. Flow rate as a function of time is shown in blue on the left hand plot, indicating the steady flow rate maintained after a short start-up transient. Overlaid in the right hand plot are instantaneous total pressure head loss (yellow), five minute averaged head loss (green) and percent change in head loss over five minutes (red), providing the operator with a convenient tool for determining test termination.

Typical results delivered to the plant at the end of a test are shown in Figure 8, including both raw data and an exponential fit. Some spikes can be observed in the raw data, and these generally correspond to introduction of subsequent batches of debris.

Figure 9 shows a strainer at the conclusion of the test, after drain-down. The rectangular disks of the strainer are evident through the shape of the debris bed, and there are a few isolated regions in which the perforated plate can be seen. This can be attributed to the debris having fallen off during the post-test water level draw-down. The fibrous and particulate debris has a tan or light brown color, whereas the WCAP chemical precipitate surrogate appears as a white film.

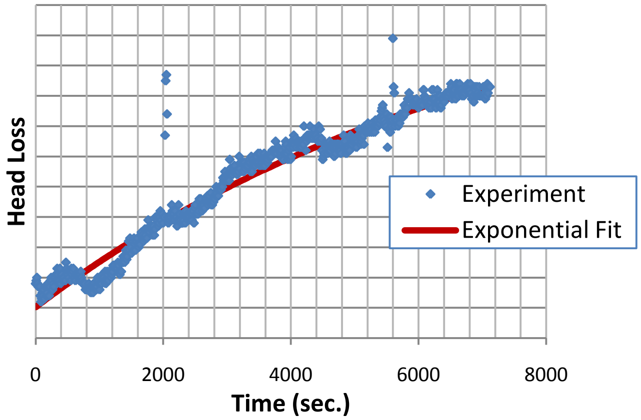

Figure 8 *Head loss curve delivered to plant. Ordinate non-dimensionalized for proprietary purposes.*

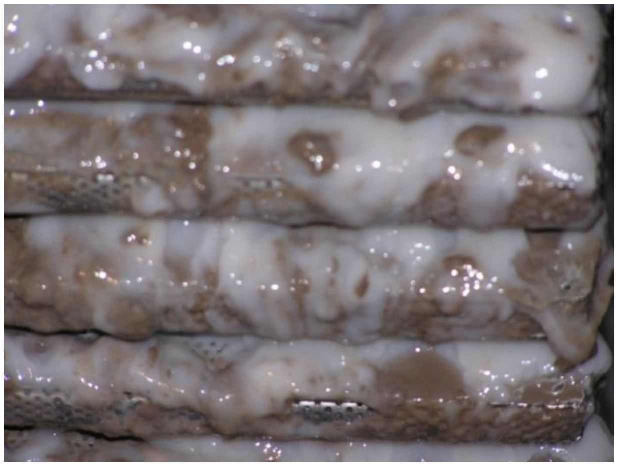

Figure 9 *Side view of a strainer after head loss testing.*

Summary

Concern over HELB related clogging of containment sump strainers led to the NRC's identification of Generic Safety Issue 191. This paper describes a strainer total pressure head loss testing methodology that has been employed by the AREVA, Alden, PCI team for those clients using the SURE-FLOW^{TM} Strainer technology as well as clients using other strainer vender screens. The protocol includes the use of CFD –predicted containment flow patterns to determine an average approach velocity to a typical strainer module as a function of radial distance, and subsequent representation of the calculated approach flow field in the test flume.

This testing procedure has proven valuable for eighteen of the PWR plant units in the United States who were required to retrofit strainer modules in conjunction with GSI-191.

References

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[5] NEI 04-07, "Pressurized Water Reactor Sump Performance Evaluation Methodology," Rev 0. Volumes 1(Methodology) & 2 (Safety Evaluation). December 2004.

[6] A. E. Lane, T. S. Andreychek, W. A. Byers, R. J. Jacko, Edward J. Lahoda, and R. D. Reid, "Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191," WCAP-16530-NP, Westinghouse Electric Company LLC, 2006.