A short history of the sump clogging issue and analysis of the problem

BY GORDON H. HART

Although some unanswered technical questions remain concerning post-LOCA blockage of PWR emergency sumps, the problem should be solvable once the NRC defines all the regulatory requirements.

FOLLOWING ISSUANCE BY the U.S. Nuclear Regulatory Commission of Bulletin 96-03, all of the licensed U.S. boiling water reactors (BWRs) resolved the strainer blockage issue by replacing their original suction strainers with much larger surface area, high-capacity, passive strainers. The reason for this modification was to reduce high head losses that would otherwise result from the unlikely event of a pipe-break loss-of-coolant accident (LOCA) that could generate large quantities of particulate (i.e., iron oxide, paint chips, etc.) that could mix with small amounts of fibrous material and subsequently block the suction strainers.

In the BWRs, this particulate consisted mostly of iron oxide, referred to as "sludge," but also included dirt, paint chips, and some granular insulation debris. The source of the fibers can be thermal insulation, fireproofing material, and ancillary materials that are not necessarily part of a plant's inventory of controlled materials.

The NRC has reasoned, based on testing, analysis, and previous U.S. and foreign plant incidents, that in the event of a LOCA, the particulate and fiber mix would be suspended in the post-LOCA suppression pool water. This water would then flow to the emergency core cooling system (ECCS) suction strainers. There, the fibers would collect to form a thin layer and then filter the entrained particulate.

After extensive testing and analysis of hardware by both industry and the BWR utilities, it was concluded that the most cost-effective solution was to replace the existing passive suction strainers with new, larger surface area passive strainers at each U.S. BWR unit.

While a pipe-break LOCA is highly unlikely at both BWRs and pressurized water reactors (PWRs), the safety issue is essentially the same at both types of plants. The major difference is that the particulate debris at PWRs would not be dominated by the iron oxide found in the BWR suppression pools. Rather, it would likely consist of paint chips, concrete dust, and granular insulation particulate generated by LOCA forces, as well as latent dirt and dust. As in the BWRs, fibrous material can likewise be generated by LOCA forces impinging on thermal insulation and fireproofing materials, but can also consist of small quantities of "latent fiber," fiber not necessarily found in plant documentation. Given the small size of the existing PWR sump screens, post-LOCA sump screen blockage by a mixture of this debris would be highly likely, as it had been at the BWR plants prior to plant modifications.

With the release of NRC Bulletin 2003-01, "Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized-Water Reactors"[1] (June 2003), which addresses the safety issue of post-LOCA blockage of PWR emergency sumps, the NRC is following in the logical regulatory path that was applied to U.S. BWR plants to address the issue. While there are still some unanswered technical questions for the PWRs and probably always will be, it is clear that both the industry and several architectural/engineering (A/E) firms have already solved this problem at the BWR units. Furthermore, they should be prepared to do the same at the PWR units when the NRC defines all the regulatory requirements.

Definition of the problem

Bulletin 2003-01 identifies the issues of ECCS and containment spray system (CSS) loss of NPSH (net positive suction head) margin during recirculation as a result of sump blockage, sump screen structural integrity, upstream blockage of containment drainage, and subsequent downstream blockage of ECCS and CSS recirculation flowpaths. The NRC gave PWR licensees 60 days to respond to one of two options:

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Fig. 1: Photograph of a pair of "stacked disk"–type ECCS suction strainers in the torus of a U.S. BWR Mark I, installed in response to Bulletin 96-03. At Mark I and Mark II BWR units, replacement strainers were cylindrical so as to get them into the wet wells, which have small circular entrance hatches. At PWR units, with much larger equipment hatches, the strainers can be both larger and possibly box-shaped, as opposed to cylindrical. (Photo courtesy of Performance Contracting, Inc.)

1. The licensee has already analyzed the ECCS and CSS with respect to the debris blockage effects identified in the bulletin and is in compliance with existing regulatory requirements.
2. The licensee should describe any interim compensatory measure that will be implemented to reduce the risk that may be associated with potentially degraded ECCS or CSS until an evaluation to determine compliance is complete. The licensee is to provide justification if any of the example compensatory measures in the bulletin will not be implemented and for any extended implementation schedules.[1]

The bulletin also listed several example interim measures, such as operator training on sump blockage procedural modifications to delay recirculation, ensuring availability of alternative water sources, and more aggressive containment cleaning/foreign material controls, among other fixes." The NRC subsequently issued Temporary Instruction 2515/153[2] in October 2003 "to ensure that licensee actions are consistent with bulletin responses and the Bulletin's intent." The NRC plans to issue in February or March 2004—about the time that this article is first being read by subscribers to *Nuclear News*—a draft Generic Letter "to request information from [PWR] licensees concerning the adequacy of their recirculation sump performance."[3]

This safety issue is focused on the adequacy of ECCS and CSS sumps and their ability to recirculate the water flow following a pipe-break LOCA. It is hypothesized by the NRC that following a LOCA at a PWR, existing unidentified dirt and dust, along with insulation debris, paint chips, and concrete debris generated by LOCA forces, would be transported to the sump screens entrained in recirculation water (in a BWR, these materials would be blown into the suppression pool, where they would be transported to the ECCS suction strainers). This debris mixture would consist of particulate and fibers from various sources. This debris bed would provide sufficient resistance to the flow of recirculation water through it that the NPSH margin of the system could be exceeded, resulting in pump cavitation and subsequent loss of recirculation flow.

Through a series of parametric analyses conducted a couple of years ago by the NRC's engineering contractor, Los Alamos National Laboratory (LANL), it was concluded that following a large-break LOCA, at 60 of the 69 U.S. PWRs (referred to as "case studies" in NUREG/CR-6762, Vol. 1,[4] August 2002), sump screens are either "very likely" or "likely" to become blocked with the mixed debris, thereby leading to loss of recirculation water flow. Therefore, with the presumption of a large-break LOCA, post-LOCA sump screen blockage is a serious safety issue since the parametric analyses have predicted that the recirculation water flow could not be maintained in most U.S. PWR units.

In reviewing the NRC's numerous research reports and then performing head-loss calculations per the NRC's methodology outlined in NUREG/CR-6224,[5] there is a predictable and deterministic dependence of head loss on debris quantities and types. One aspect of this dependence is that head loss depends monotonically on the quantity of particulate. That is, the greater the particulate quantity collected, the greater the resulting head loss, and vice versa. In fact, for a given size distribution of particulate, this head loss is approximately linearly dependent on the volume of particulate that is transported to the sump screens.

A second aspect of this dependence, and one that surprises many people at first encounter, is that the head-loss dependence on the quantity of fibrous debris is highly nonlinear and not monotonic. In fact, over a wide range of fibrous debris quantities, the methodology predicts that the greater the fiber quantity, the lower the head loss, and the lower the fiber quantity, the greater the head loss, and it is only with very large quantities of fibrous debris (i.e., over several hundred cubic feet) that head loss finally increases with increasing quantities of fiber.

The research has further shown that for water flowing through a mixed (i.e., fibers plus particulate) debris bed, the head-loss dependence on the screen or strainer surface area is a power function where the exponent is approximately -2.5. What this means is that sump screen surface area is a powerful control variable in sump screen design, and that physically replacing existing screens with new ones, so as to increase the overall screen area, is an extremely effective means for reducing post-LOCA head loss.

Pre-Barsebäck: 1979–1992

Most nuclear units in the United States were originally licensed based on the 50 percent sump screen blockage criterion in Regulatory Guide 1.82, "Sumps for Emergency Core Cooling and Containment Spray Systems."[6] This criterion is based on the premise that with 50 percent of the surface area of the sump screens or suction strainers blocked, recirculation flow would be maintained following a LOCA, thus assuring core and containment cooling. As early as the late 1970s, however, the NRC started to question the basis of the 50 percent blockage criterion.

Accordingly, the NRC initiated Unresolved Safety Issue (USI) A-43: "Containment Emergency Sump Performance,"[7] which consisted of three concerns: (1) the effects of potential air ingestion on hydraulic performance under post-LOCA adverse conditions; (2) the effects of LOCA-generated insulation debris resulting from a pipe-break jet that is then transported to the sump debris screens and consequently blocks the screens, reducing NPSH margin below that required for recirculation pumps to maintain long-term cooling; and (3) the effects of air or debris ingestion on the capability of the residual heat removal (RHR) system and CSS pumps to continue to function.

Concern 2, regarding LOCA-generated insulation debris collecting on the screens or strainers, is particularly interesting since none of the recirculation systems' strainers or sump screens were designed with regard to differential pressure loss and consequential strainer/screen structural integrity. The collection of a porous, uniform debris bed over the screens/strainers, and their ability to withstand a differential pressure caused by water flowing through this debris bed, was not a previously considered design and operational issue. In USI A-43, the NRC concluded that each plant should be evaluated on a plant-specific basis for debris-blockage potential and that the original 50 percent blockage criterion may be nonconservative.

In late 1985, following several years of study and public comments, the NRC issued Generic Letter 85-22, "Potential for Loss of Post-LOCA Recirculation Capability Due to Insulation Debris Blockage."[8] It required that plants conduct a plant-specific analysis if and when they replace any of their existing thermal insulation with a new type of thermal insulation. Consequently, U.S. plants that made the insulation modifications after that time did so within the context of existing licensing design basis requirements previously reviewed and approved by the NRC. The modifications were performed under the 10CFR50.59 process and were not considered to be a backfit.

With the close of USI A-43 in 1985, post-LOCA sump screen and suction strainer blockage was believed by the NRC staff, by the industry, and by nuclear A/E firms to be solely a fibrous insulation problem. Accordingly, so the thinking went, the less fibrous material, the better, and the more fibrous material, the greater the possibility of a potential problem. No licensees seriously questioned the design adequacy of their sump screens (at PWRs) or suction strainers (at BWRs), and no U.S. plants modified and/or replaced them as a consequence of GL 85-22.

For the next half-dozen years, until mid-1992, the issue of containment emergency sump clogging continued to be understood solely in terms of fibrous insulation debris generated by LOCA-induced damage of containment thermal insulation on piping and equipment. In this scenario, the post-LOCA containment was assumed to be generally clean, the post-LOCA recirculation water was likewise assumed to be generally clean, and the LOCA-generated fibrous debris exhibiting filtering behavior was not considered. These assumptions, however, did not last forever due to several strainer blockage incidents at both domestic and foreign BWRs in the early 1990s.

Post-Barsebäck: 1992–present

In summer 1992, this potential safety issue emerged from dormancy following a highly publicized strainer blockage incident at Sydkraft AB's (now Barsebäck Kraft AB) Barsebäck-2, a Swedish BWR. Quoting the NRC's Information Notice (IN) 92-85 that was issued after the incident:

> While the reactor was at 1 or 2 percent power and at 435 psi, a leaking pilot valve caused a safety valve for the reactor vessel to open. This valve discharges directly to the drywell. Reactor scram, high pressure safety injection, core spray, and containment spray systems initiated automatically in response to the event. Steam from the open safety valve, impinging on thermally-insulated equipment, dislodged 440 pounds of metal-jacketed, mineral wool. An estimated 220 pounds of insulating material was washed into the suppression pool. Two of five strainers on the suction side of the ECCS pumps were in service and became partially plugged with mineral wool. Plugging caused pressure to decrease significantly across the strainers and caused indications of cavitation in one pump in about an hour after the event began. The operators successfully back flushed the strainers and shut down the reactor without additional problems.[9]

As a consequence of this incident, several Swedish plants were forced by their regulators to resolve the issue through plant modifications. They chose to replace their existing sump screens or suction strainers with new, much larger, passive strainers, combined at each unit with small, active strainers.[10]

In spring 1992, shortly before the strainer blockage incident at Barsebäck, there had been an unpublicized strainer blockage at Cleveland Electric Illuminating Co.'s (now FirstEnergy) Perry-1 plant, a BWR 6 with Mark III containment. This event was not immediately considered by the NRC to be significant. In fact, it was not until April 26, 1993, that it issued IN 93-34[11]. That, in turn, was due to a second event at Perry-1 that occurred in February 1993, and it was that second event that actually caused the issue to take center stage in the United States.

The 1992 incident (the first of the two incidents) occurred during a plant outage and followed the intentional release of steam from a safety relief valve (SRV) and subsequent operation of the RHR system. The RHR system pumps' NPSH margin dropped considerably, to 0 psig, and it was determined to have resulted from some miscellaneous fibers in the suppression pool having been drawn to an RHR suction strainer. There, these fibers apparently proceeded to filter iron oxide particulate that originated from the interior of main steam (MS) and feedwater (FW) carbon steel piping and equipment. The particulate had become stirred up during RHR operation and then became entrained in the suppression pool water. The filtration of this particulate by a very thin layer of fibrous material resulted in a very high head loss that deformed a couple of the suction strainers, requiring their replacement in that same year, 1992. This incident, while not immediately understood, eventually changed the NRC's and the nuclear industry's understanding of USI A-43.

The NRC's analysis of the second Perry-1 strainer blockage incident, which occurred in 1993, is best summarized in IN 93-34, Supplement 1[12]:

> IN 93-34 described clogging of emergency core cooling (ECC) pump suction strainers at the Perry Nuclear Plant, a BWR-6. The latest strainer clogging event occurred in March 1993, 2 months after the licensee had replaced the strainers and thoroughly cleaned the suppression pool. After the IN was issued, the licensee chemically analyzed the debris on the strainer. The debris consisted of fibers from air filter material that had been inadvertently introduced into the suppression pool and corrosion products that had been filtered from the pool by the fibers adhering to the surface of the strainer. A small amount of the fibrous filter material also was found in the suppression pool near the weir wall. . . . NUREG-0897, Rev. 1, "Containment Emergency Sump Performance," which was written in conjunction with resolution of Unresolved Safety Issue (USI) A-43, addresses transport of fibrous thermal insulation from the containment to the strainers during a loss-of-coolant accident (LOCA). Resolution of USI A-43, in part, was based on strainer head loss tests with fibrous thermal insulation obstructing flow. USI A-43 did not address the consequences on head loss of the filtering action of the fibrous material on the strainer. The Perry event showed that filtering corrosion products, dust, and other debris from the drywell during a LOCA may cause an unexpectedly rapid loss of net positive suction head for the ECC pumps when they are needed to perform their intended function.

Both the miscellaneous fiber from the 1992 incident and these HVAC filter media from the 1993 incident became what both the NRC and the industry today refer to as "latent fiber." Unlike documented fibrous thermal insulation or fireproofing material, "latent fiber" was not supposed to get into the suppression pool, nor was it documented from a possible debris source perspective.

Continued

Later in 1993, the NRC hired an independent consulting firm, Science and Engineering Associates (SEA), as its contractor to initiate a new research program. In this effort, which focused only on BWR units, SEA conducted numerous debris transport and debris head-loss tests at Alden Research Laboratory. Unlike USI A-43, however, debris was now considered in all cases to be some combination of fibers and particulate, with the fibers filtering the particulate. SEA developed a new head-loss correlation, still considered valid today, that predicted head loss as a function of water velocity, water viscosity, particulate type and quantity, and fiber type and quantity.[5] Furthermore, this correlation showed that head loss is roughly a linear function of particulate quantity, but a highly nonlinear, nonmonotonic function of fiber quantity.

Most surprising in this nonlinearity was that the developed head-loss correlation now gave a clear explanation of how the Perry-1 strainer blockage incident had occurred: With only a very thin layer of fiber and a large quantity of particulate, an extremely high head loss can result with water flow through a fiber-particulate bed.

Further, with the same flow conditions and particulate quantity, a thicker layer of fibers will result in a lower head loss. This head-loss equation (given as Equation B-21 in Ref. 5 on page B-44) and the NRC's parametric analyses conducted using this equation on the BWR units demonstrated convincingly that strainer surface area was the most sensitive design variable with regards to strainer head loss. Further, the head loss can be shown to have a power function dependence on strainer surface area with the exponent being between 2 and 3, or close to a power of 2.5. Therefore, if the surface area is doubled, head-loss reduction would be at least 80 percent. If the surface area is increased by 10 times, then the head-loss reduction would be over 99.5 percent.

In the middle of the NRC's investigation, in September 1995, there was another strainer blockage incident at a U.S. BWR, this time at PECO Energy Co.'s (now Exelon) Limerick-1. In this incident, as at Perry, RHR pumps came on in response to a steam release from an SRV. Subsequently, suppression pool sludge (i.e., primarily iron oxide particulate) was stirred up, resulting in its suspension in the suppression pool water. Further, there was some "latent fiber" in the suppression pool, prior to the SRV discharge, that also became suspended and was drawn, along with the iron oxide particulate, to the two RHR suction strainers. The result was cavitation of one RHR pump and a major loss of NPSH margin at the other. The NRC's explanation is given in IN 95-47,[13] issued after the incident:

> It is believed that, during operation of the suppression pool cooling system, the strainer filtered out fibers that were in the pool water. The resulting "mat" of fibers improved the filtering action of the strainers thereby collecting sludge and other material on the surface of the strainer. Whether the blowdown caused by the SRV opening increased the rate of accumulation on the strainer is not known. The licensee removed about 635 kg [1400 lb] of debris from the pool of Unit 1. A similar amount of material had previously been removed from the Unit 2 pool. Analysis showed that the sludge was primarily iron oxides and the fibers were of a polymeric nature. The source of the fibers has not been positively identified, but the licensee has determined that the fibers were not inherent with the suppression pool. There was no trace of either fiberglass or asbestos fibers.

The Limerick incident was still another U.S. BWR strainer blockage incident involving a very small quantity of fibrous material collecting on suction strainers and then filtering suspended particulate. It clearly demonstrated the need for BWR licensees to periodically clean their suppression pools to minimize the quantity of "sludge," or iron oxide particulate.

Furthermore, it clearly demonstrated that a high head loss, resulting from a thin layer of "latent fibers" and a large quantity of filtered particulate, was predictable using the NRC's new head-loss equation for combined debris as related to BWRs. It is significant to point out that even today (to the best of this author's knowledge), the source of this "latent fiber" in the Limerick incident has not yet been positively identified. Sources of "latent fiber" probably do not show up on engineering drawings or in other forms of plant documentation, but the material still probably exists inside all nuclear containments.

In May 1996, after several years of study, testing, and analysis, the NRC issued Bulletin 96-03, "Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling-Water Reactors."[14] This bulletin essentially required all BWR licensees to reanalyze their RHR and CS systems, with regard to new information available from recent testing, and make necessary modifications to their suction strainers to assure operable recirculation cooling systems following a LOCA.

In response, every U.S. BWR unit was eventually backfitted with new, large-surface-area suction strainers. Indeed, there was a large variety of designs incorporated among the 33 (at that time) licensed U.S. BWR units. This variety of designs resulted from there being four domestic strainer vendors, numerous different ECCS designs, numerous types and mixes of insulation, and three different BWR containment configurations.

The reasons for using large-surface-area, passive suction strainers are simple. First, strainer surface area was the most sensitive design variable with regard to post-LOCA strainer head loss. Second, installing these strainers provided the simplest, least-risk solution to resolve this safety issue.

Causes of post-LOCA clogging

Since the time that this issue was addressed by U.S. BWRs in the late 1990s, the NRC issued several reports on the related issue of containment paint integrity and the propensity for LOCA-generated paint debris to be generated. Relegated to a distant second place, behind iron oxide particulate in the suppression pools of BWRs, paint chips and concrete dust now became considered as primary sources of post-LOCA particulate debris in PWRs. Furthermore, the issue of fibrous mat filtering particulate and its relevance to PWRs was unknown due to (1) the significant difference in containment configuration (i.e., no suppression pool), (2) significantly less carbon steel piping to generate iron oxide particulate, and (3) significant differences in post-LOCA water chemistry between BWRs (i.e., neutral pH) and PWRs (i.e., acidic pH).

Therefore, a few years ago, the NRC identified a new Generic Safety Issue, GSI-191: "Thermal-Hydraulic Response of PWR Reactor Coolant System and Containments to Selected Accident Sequences."[15] As in 1993 with the BWR issue, the NRC contracted a research institution, Los Alamos National Laboratory (LANL), and directed it to conduct testing and analyses on insulation debris generation, transport, and, where necessary, head loss. In the process, LANL conducted a parametric analysis of all 69 U.S. PWR units (referred to in the report as "case studies"), concluding that there is a high risk of sump blockage, following a large-break LOCA, at 87 percent of the "case studies" (i.e., PWR units).[4] (Since then, one plant, Davis-Besse, replaced its existing 50-ft^2 sump screens with a new 1200-ft^2 screen. This article's following discussion of the PWR parametric "case studies," however, will include that plant's original 50-ft^2 sump screens, since that is what LANL used in developing these "case studies").

Independent analyses, conducted by this author using the same head-loss equation from NUREG/CR-6224 with an assumed design input of 300 lb of mixed particulate and a thin layer of "latent fiber" material on existing surface area sump screens, confirmed the NRC's findings. In fact, even though LANL predicted that 87 percent of the U.S. PWRs were either "likely" or "very likely" to experience "sump failure" following a large-break LOCA, these parametric analyses appear to actually be somewhat nonconservative. This author's analyses demonstrated that a very small quantity of fibrous material (as little as 0.5 ft^3) combined with 300 lb of mixed particulate could lead to pump cavitation at all but several of the PWR units. Furthermore, at most of the units, several hundred cubic feet of fibrous debris would result in a lower head loss under the same conditions.

Table 1 shows these predicted results, calculated by this author using the NRC's NUREG/CR-6224 head-loss methodology, more clearly for average values of 13 591 gpm of recirculation water and 157.5 ft^2 of sump screen area (this head-loss methodology is available on the Web through Alion Science and Technology, Innovative Technology Solutions Division, at <calcs.itsc.com/hloss/hloss.cgi>).[16, 17]

A cursory review of these head-loss values in Table I reveals the surprising results that 1 ft^3 of fibrous debris would lead to a higher head loss than 100 ft^3 of fibrous debris and about the same head loss as 300 ft^3 of fibrous debris. To put those values in perspective, a large pipe-break LOCA at a four-loop Westinghouse unit, completely insulated with 3-in.-thick low-density fiberglass blanket insulation, which initially shows destruction at 6 psi,[15] would probably end up with only between 100 and 300 ft^3 of finely shredded fibrous debris both generated and transported to the sump screens.

Hence, the worst-case scenario is probably not with a thick layer of fibrous debris. Rather, the worst-case scenario would be a thin layer resulting from only about 1 ft^3 of fibrous debris. And, this small quantity of fiber does not have to originate from thermal insulation or some other identifiable source. Rather, the fibrous material could simply be "latent fiber," such as was involved in the strainer blockage incidents at Perry and Limerick.

Table I. Results for Post-LOCA Head-Loss Across a 157.5-ft^2 (Average Size) Sump Screen and 13 591-gpm (Average Flow Rate) of 200 °F Water with 300 lb of Suspended Particulate Debris*

Volume of fibers, cu ft	Head Loss, ft of water
1	16.6
30	20.2
100	12.3
300	16.6

*Calculations performed using the NUREG/CR-6224 head-loss methodology and Alion's head-loss calculator

The graph in Fig. 2, again generated using the Alion Web-based head-loss calculator, illustrates more clearly this dependence of calculated head loss on the quantity of fibrous debris. The two curves together also show head-loss dependence on particulate quantity (150 lb compared to 300 lb). Finally, the graph shows that with the average PWR NPSH margin of about 4 ft of water, a PWR with the average flow rate and sump screen area would experience a head loss greater than the NPSH margin. Hence, this "average PWR plant" would definitely have problems with regard to this safety issue.

The implications for PWRs

As can be clearly deduced from Table I and from Fig. 2, reducing quantities of fibrous material, such as thermal insulation, is usually ineffective in improving the post-LOCA performance of the ECCS. Unless the quantity of generated and transported LOCA-generated fibrous debris exceeds at least 300 ft^3 for the postulated "average PWR" case above, the worst-case volume of fibrous debris is about 30 ft^3 (the inflection point in the center of the above curves) and this is only a somewhat worse scenario than that with only 1 ft^3 of fibrous debris, a quantity that is sufficient to form a very thin layer of fibers on the sump screen.

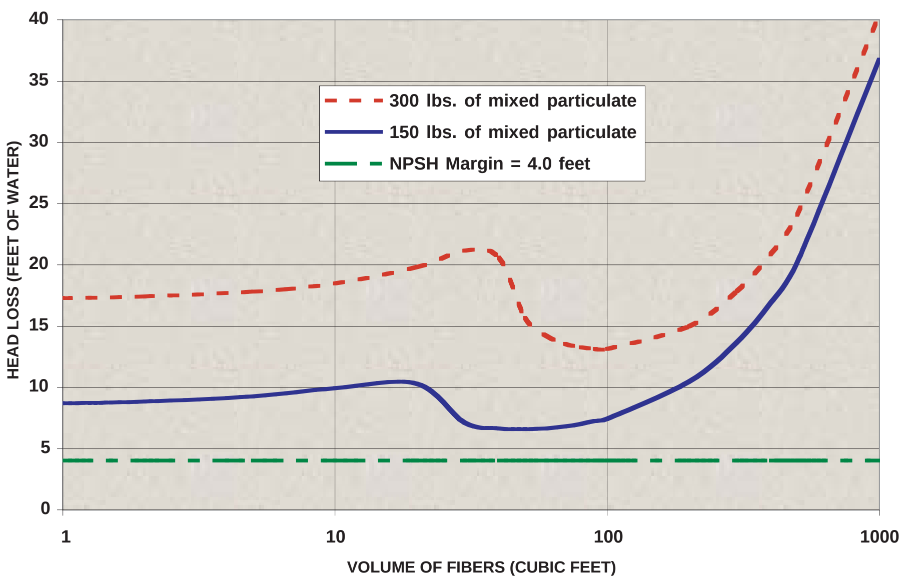

Fig. 2: Head-loss calculations for a PWR ECCS screen using Alion's head-loss calculator. 300 pounds of mixed particulate; flow rate at 13 591 gpm; water at 200 °F

There are some nuclear plants that are reported to have 100 percent reflective metallic insulation in containment. Some in the industry believe that such a PWR plant will not need to consider any fibrous material at all in a post-LOCA sump performance analysis. This author believes that the history and technical information on this issue show the fallacy of this assumption. It was clearly demonstrated by both the two Perry-1 incidents and the Limerick incidents that if only a cubic foot or so of "latent fiber," not necessarily identifiable in any plant documentation, is sufficient to filter particulate and lead to post-LOCA sump blockage, then the sump screens or suction strainers are simply undersized. Generally speaking, the problem for the PWRs is not with the fibrous insulation. The problem is with their undersized emergency sump screens.

Solution to the problem

To show the dependence of calculated values of head loss on existing screen areas, each of the 69 PWR "case studies"[16] was plotted in Fig. 3, in all cases using an assumed 300 lb of mixed particulate and a ⅛-in.-thin layer of fibers. This graph, also generated using the Alion head-loss calculator, demonstrates the strong dependence of head loss on sump screen area for the existing PWR sump screens. Note how strong this dependence is even though other variables, such as total sump flow rate, have not been considered in the plot. This author generated the curve fit using a head loss-screen area inverse power function with exponent of 2.5.

This author then used the same Alion head-loss methodology to evaluate the effect of replacing the existing small, passive sump screens with new, larger, passive sump screens or strainers. Figure 4 shows this dependence for the "average" PWR case, with five different screen or strainer sizes—100, 200, 300, 400, and 500 ft^2—on a plot of head loss vs. volume of fibers.

As can be seen in the curves for sump screen area on Figs. 3 and 4, increasing screen area results in a dramatic decrease in predicted head loss across the sump screen (note the logarithmic scales necessary for these graphs). For passive sump screens or strainers, increasing surface area simply gives the greatest reduction in head loss of any of the design variables.

The industry has performed its own cost studies for plant modifications to address this safety issue. The conclusion is that a screening review will cost \$75 000 to \$100 000 per design, a detailed engineering analysis will cost \$150 000 to \$300 000 per design, and the major modifications will cost \$3 million to \$5 million per unit.[19] While project costs always depend on the final specifications, as well as contract terms and conditions, this author believes that these numbers are credible.

Recent developments

During the summer of 2003, LANL personnel conducted testing to determine chemical effects on containment coatings. This has led to the finding that certain precipitates, resulting from chemical reactions of post-LOCA sprays with coatings and metals, could be present in recirculation cooling water. These precipitates, should they be formed, would also be filtered by a fiber mat on a sump screen. And, like other particulate, these precipitates would increase the head loss across a filtering fiber mat,[20] perhaps significantly.

As noted in the recent ACRS letter to the NRC,[2] to further study the effect of PWR post-LOCA water chemistry on both thermal insulation fibers and the subsequent breakdown of the same fibers, LANL has been studying corrosion of metals with precipitation of flocculent, in particular to identify the rate of corrosion for iron, zinc coatings, and aluminum and the head-loss effects of chemical precipitation. This came about as a result of a report from the 1979 Three Mile Island-2 accident that precipitated gelatinous debris had been formed.

Consequently, and more recently, the ACRS had expressed concern about this “gelatinous mass,” fearing it could collect on a sump screen or strainer and increase head loss. Indeed, LANL’s recent tests have shown that if chemical degradation of fibrous debris beds occurs, it can lead to slow compaction, increasing head loss and degradation of nonqualified coatings. At a public meeting in November 2003 on the chemical effects issue, however, the NRC reported: “Findings lend credibility to the concern raised by ACRS, but are not sufficient to provide a basis for plant-specific quantitative assessment of the issue.”[21]

While this does not necessarily end the issue for the PWR plants, it suggests that the NRC may not require that the plant staffs consider chemical effects when calculating long-term, post-LOCA head loss across a sump screen or strainer. Regardless, the industry is contemplating more tests in the next half year to help resolve this issue.

There is also some new information from LANL regarding calculated head losses resulting from a mix of fibers and calcium silicate insulation. Calcium silicate is a predominantly granular, as opposed to fibrous, insulation material that is very rigid and brittle. Hence, when destroyed by a pipe-break LOCA, calcium silicate insulation would generate particulate debris. Nevertheless, after testing, LANL reported in November that “It appears that the NUREG/CR-6224 correlation can predict calcium silicate head losses once appropriate input parameters are determined.”[22] Therefore, further testing is probably not necessary since the existing methodology can be used to predict head loss.

Had these issues of long-term chemical effects and head loss through calcium silicate insulation debris not been resolved, it could have been concluded that this safety issue does not have a deterministic solution. That is, if head loss always increases with time, or if the head loss is simply indeterminate, then the only acceptable solution would be an active device—i.e., one that somehow knocks debris off the screen or strainer. This would particularly be the case if LANL had not been able to develop equations with which to actually calculate head losses with known conditions of water chemistry, coating quantity types, insulation types, etc.

Fortunately for the industry, the solution to this safety issue of post-LOCA PWR sump system performance does appear to

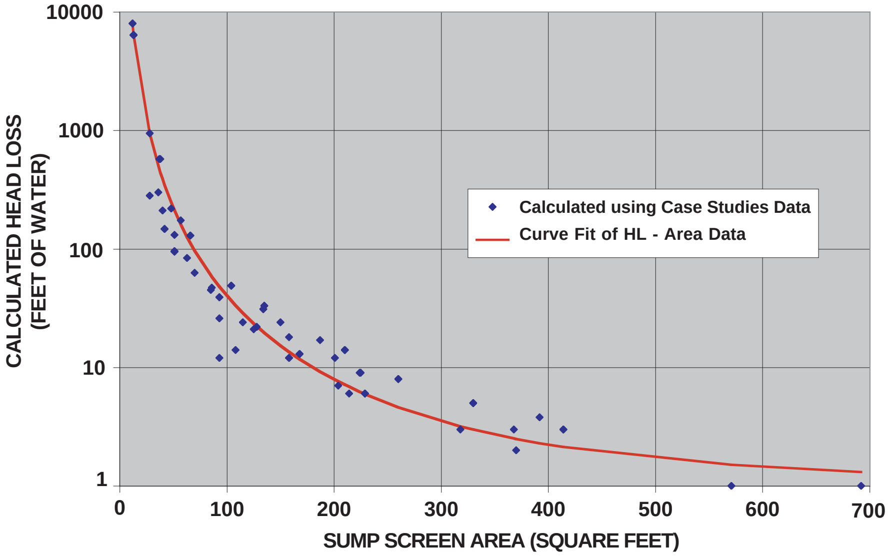

Fig. 3: Calculated head-loss as a function of sump screen area for the PWR "case studies" in NUREG/CR-6762, Vol. 1, Table 5.2 using Alion's head-loss calculator

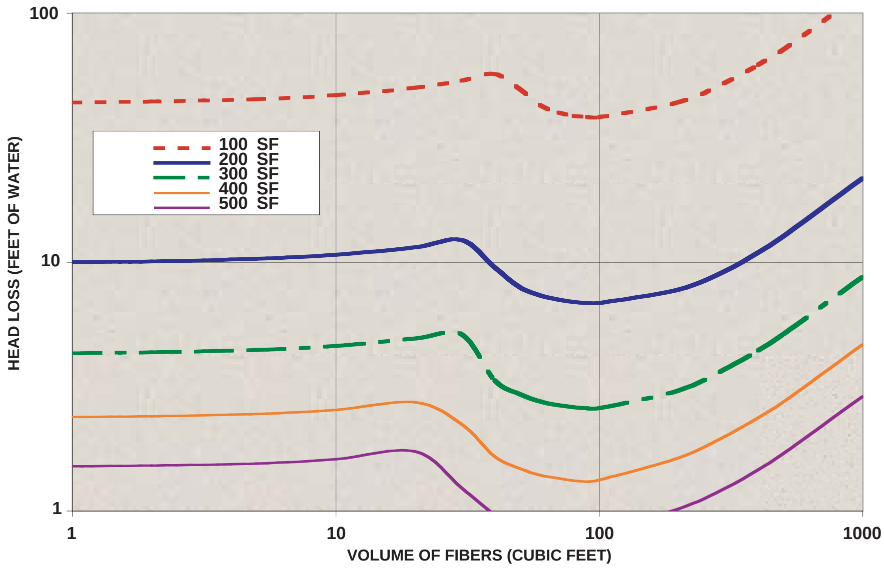

Fig. 4: Head-loss calculations for a PWR ECCS screen using Alion's head-loss calculator. 300 pounds of mixed particulate; flow rate at 13 591 gpm; water at 200 °F

be deterministic, as was the case with the BWRs. Hence, one can design passive, large-surface-area screens or strainers for the PWR units, given available head-loss equations from NUREG/CR-6224, and these can be shown to meet the sump requirements for long-term water flow.

In the event, however, that the chemical and other effects eventually show that a deterministic, passive solution is not defensible, there are still practical and defensible solutions to this safety issue for PWRs. In Sweden in 1992, at Ringhals-2, a Westinghouse PWR, the utility Statens Vattenfallsverk (now Vattenfall AB) installed a combination of large passive strainers and small active strainers.[10] The large passive strainers were designed to handle the predictable quantities of mixed debris, without considering long-term chemical effects, whereas the active, self-cleaning strainers were designed to handle the indeterminate, long-term effects on LOCA-generated debris. The utility staff installed this combination of strainers since, at the time, they were uncertain about the accuracy of their methodology, and so the active strainers gave them a back-up solution. In retrospect, this hybrid strainer system, installed almost a dozen years ago, seems simple and elegant and represents a solution that should stand the test of time.

One American vendor has proposed a self-cleaning strainer to resolve the issue. Such a strainer was included in the BWR Owners Group strainer-testing program at EPRI in 1995–96. In this author's opinion, this device is both inventive and clever, and merits consideration. It is worth noting, however, that none of the BWR utilities selected this option, possibly because of single-failure criteria and subsequent need for redundancy. Since this particular device depends on a continuously rotating blade to clean debris off the face of the strainer surface, it must be shown to be 100 percent dependable for a wide range of debris types, such as a thin piece of metal getting lodged in screen material and mechanically blocking the blade rotation. Nevertheless, active systems without passive screens may also have a place in the inventory of solutions, once qualification testing and design requirements are clearly defined and implemented.

On the same subject of recent developments, the huge French nuclear utility Electricité de France (EdF) recently told its regulators of plans to replace existing sump screens at all 58 of its PWR units with new ones. Georges Seviere, EdF's vice president of nuclear engineering, reportedly told the U.S. NRC that EdF hadn't yet finished all of its calculations, but added, "It's a complicated subject and we're not going to wait" until all the studies are complete before making the backfits to their plants.[23] EdF plans on starting the plant modifications next year and on making several plant changes, including enlargement of sump screen or strainer surface areas. It expects to spend €100 million, roughly $126 million (depending on the current exchange rate), equivalent to about $2.2 million per unit.

Finally, the international nuclear community was to have the opportunity to discuss developments concerning this safety issue February 25–27 at the 2004 International Workshop on Debris Impact on Emergency Coolant Recirculation, in Albuquerque, N.M. This meeting was organized by the U.S. NRC and the OECD/Nuclear Energy Agency, and the latter's Committee on the Safety of Nuclear Installations, Working Group on the Analysis and Management of Accidents, and Working Group on Operating Experience. This meeting was expected to provide a significant amount of new information since the last international meeting on this subject.

Overview

With the pending issuance by the NRC of a draft Generic Letter addressing PWR post-LOCA sump blockage, it is critical for PWR licensees to understand the cause of this potential safety issue: an undersized sump screen that would collect, in the unlikely event of a pipe-break LOCA, a mixed debris bed of thin fibers and particulates. This debris bed, on such an undersized screen, could lead to high head losses and failure of the recirculation system. NRC research has developed head-loss equations that can be used to design large passive sump screens or strainers that should be sufficient and adequate to resolve this issue. The reason for this is that head loss through debris beds on screens or strainers can be shown to be inversely proportional to screen or strainer surface area raised to a power of about 2.5. This passive solution approach resolved the safety issue at all the U.S. BWR units, and with proper engineering analysis and design, can likewise be implemented at the PWR units.

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