REASSESSMENT OF DEBRIS-INGESTION EFFECTS ON EMERGENCY CORE COOLING SYSTEM PUMP PERFORMANCE

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1. Introduction

A study sponsored by the United States (US) Nuclear Regulatory Commission (NRC) was performed to reassess the effects of ingesting loss of coolant accident (LOCA) generated materials into emergency core cooling system (ECCS) pumps and the subsequent impact of this debris on the pumps' ability to provide long-term cooling to the reactor core.[1] ECCS intake systems have been designed to screen out large post-LOCA debris materials. However, small-sized debris can penetrate these intake strainers or screens and reach critical pump components. Prior NRC-sponsored evaluations of possible debris and gas ingestion into ECCS pumps and attendant impacts on pump performance were performed in the early 1980s.[2] The earlier study focused primarily on pressurised water reactor (PWR) ECCS pumps. This issue was revisited both to factor in our improved knowledge of LOCA generated debris and to address specifically both boiling water reactor (BWR) and PWR ECCS pumps.

This study discusses the potential effects of ingested debris on pump seals, bearing assemblies, cyclone debris separators, and seal cooling water subsystems. This assessment included both near-term (less than one hour) and long-term (greater than one hour) effects introduced by the postulated LOCA.

The work reported herein was performed during 1996-1997.

1.1 Methodology and scope

The overall steps in the methodology used in this study are as follows:

1. The debris likely to be ingested by ECCS pumps was evaluated using all available information regarding the types and quantities of debris available for possible pump ingestion. Analyses were performed to develop time-dependent profiles of fluid-stream debris types and concentrations. Separate evaluations were performed for BWRs and PWRs.

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1. Sciacca, F., J. Brideau, D.V. Rao, and W. Thomas (Science and Engineering Associates, Inc.), and J. Simonis and A. Rogers (Southwest Research Institute), "Reassessment of Debris Ingestion Effects on Emergency Core Cooling System Pump Performance", SEA 97-3102-A:1, prepared for the USNRC, 31 July 1997.

2. Kamath, P.S, T.J. Tantillo, and W.L. Swift, "An Assessment of Residual Heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions", NUREG/CR-2792, CREARE TM-825, September 1982.

2. Important design features and characteristics of ECCS pumps currently installed in operating commercial nuclear power plants (NPPs) were reviewed to help identify susceptibility to debris-related damage. A failure modes effects analysis (FMEA) approach was used to systematically identify possible pump failures resulting from ingestion of small debris for a reference pump design. A generic pump design was used for the FMEA. Failure modes judged as "likely to occur" were evaluated further using analytical techniques.
3. A thorough review was made of NPP ECCS pump failures reported during the 20-year period prior to this study. Failure data for other NPP pumps were also evaluated for applicability to the ECCS pumps and for insights as to pump behaviour with debris-laden fluid streams.
4. Insights and conclusions of the likelihood of particular ECCS pump-failure modes then were developed. These insights were based on the qualitative FMEA, as supported by analytical calculations, pump-failure data, and engineering judgment.

This paper is organised according to the above steps. The projected ECCS pump-suction conditions following a LOCA are reviewed for both BWRs and PWRs; debris types, sizes, and concentrations are estimated. Pump features and characteristics that could be adversely impacted by the presence of debris in the fluid stream are reviewed. The results of the FMEA are discussed briefly. Pump-failure data is reviewed, including a comparison of failure data for pumps operating with debris-laden fluid streams vs. those operating with clean fluids. Finally, estimates are provided of the likelihood of ECCS pump failure during the post-LOCA period of required operation.

1.2 Assumptions and basis

The debris considered in this study included fibrous insulation debris, sludge (in BWRs), paint chips, concrete dust, rust particles, and reflective metallic insulation shards small enough to pass through the holes of a BWR pump-suction strainer (typically 1/8 inches diameter) or a PWR containment sump screen (typically ¼ inches × ¼ inches openings). The study focused on the effects of small fibrous and particulate debris on the pump system components downstream of the pump-suction strainer or screen. The effect of debris on ECCS system components downstream of the pumps was not included.

A time-varying strainer filtration model was developed to estimate the amount of debris passing through the strainers or screens over time. Separate models were prepared for BWRs and PWRs. These models include the filtering effects of fibrous debris-bed buildup on strainers and screens that serve to trap particulate materials. Also, the important differences in filtering characteristics between fibrous insulation debris materials and reflective mirror insulation (RMI) debris were factored into the models, as was the precipitation of hydroxides in PWR systems as an additional source of particulate debris.

The suppression pool strainers present in BWRs were assumed large enough that a thin (about 1/8 inches) debris bed would be formed on the surface of the strainer. For PWRs, typical sump screen sizes were assumed.

There is enough design variability among the installed pumps at nuclear power plants that a typical or generic pump could not be defined adequately. A reference pump design was used in the FMEA evaluation. However, alternative pump features were evaluated for potential debris-related degradation.

The focus of this effort was on low-pressure pumps because of their likelihood to be subjected to debris ingestion following a LOCA. However, under certain conditions, high-pressure safety injection pumps may be used in a recirculation mode, whereby they would draw from the suppression pool in BWRs or from the containment sump in PWRs [piggybacked onto the residual heat removal (RHR) pumps]. The high-pressure pumps are assumed more susceptible to debris-related degradation than are the low-pressure pumps.

1.3 Limitations

At the time of the study, there were no data regarding either short- or long-term ECCS pump performance or reliability under actual post-LOCA conditions. Therefore, this study was based on analysis and interpretation of available information; it did not have the benefit of a dedicated experimental program that might have resolved issues related to ECCS pump performance.

Relatively little NPP data were available for pumps operating with significant debris in the fluid streams.

Vendors that have supplied ECCS pumps to operating NPPs were contacted to determine if they had information on pump performance with debris-laden fluid streams; however, they were unwilling to share this type of information.

The pump-failure data reviewed for this study sometimes were limited in the description of the failure modes and root causes of the failure. Some failures appeared to be debris-related, even though debris was not mentioned specifically in the failure report. Thus, there was considerable uncertainty in interpreting much of the available data.

The work reported herein was performed during 1996-1997 and was based on the data, plant characteristics, and analytical methods available at that time. The study results have not been updated to reflect information that is more recent, ECCS improvements, or any improvements in our knowledge of debris-related impacts.

2. ECCS pump debris-ingestion conditions following a LOCA

2.1 LOCA-generated debris characteristics

Assessments were performed of the types, quantity, and characteristics of the post-LOCA debris likely to be ingested by ECCS pumps. The quantity of debris is characterised in terms of volume concentration, which is defined as “the ratio of the solid volume of the debris in the pumped fluid to the volume of the pumped fluid”. Debris conditions will be different between BWRs and PWRs because of factors such as the quantity of debris generated by LOCA forces, the size of the openings in containment sump screens or suppression pool strainers, and the volume of water that the debris mixes with and that acts as the ECCS-pump water source. Debris generation models developed as part of the USI A-43 study[3] and the BWR ECCS Strainer Blockage Study[4] were used to develop estimates of debris types and quantities.

3. Serkiz, A.W. “Containment Emergency Sump Performance”, NUREG-0897, Rev. 1, 1995.

2.2 Anticipated conditions for BWRs

The types of debris expected to reach the BWR suppression pool following a LOCA include insulation debris, paint chips, concrete dust, suppression pool sludge, and miscellaneous rust particles. The postulated LOCA was assumed to occur on a 24 inches diameter, high-energy line that suffered a double-ended guillotine break (DEGB) in the most congested part of a Mark I containment. The insulation on about 1 000 ft^2 of primary piping and other components was estimated as damaged or destroyed. For conservatism, a drywell transport factor of 1.0 was used, i.e. all debris generated was transported to the suppression pool.

Surveys of operating BWR plants indicated that most of the primary insulation employed is either low-density fiberglass (NUKON™) or RMI.[5] Some plants employ both types; however, for the purposes of this study, individual plants were assumed to employ either 100% NUKON™ or 100% RMI. Table 1 lists the types and quantities of debris in the BWR suppression pool modelled for this analysis. The suppression-pool water volume was assumed to be 58 900 ft^3, the smallest suppression pool volume employed by any US BWR.

Table 1. Quantity and characteristics of debris reaching BWR suppression pools

Debris type	**Mass (lbm)**	**Mass conc. (lbm/ft^3)**	**Debris characteristics**			**Volume conc. (%)**
			Size range	**% by Mass**	**Density (lbm/ft^3)**	
NUKON™ fiberglass[a]	600	0.00640	100 to 1 800µm ≥ 0.5 in	5 95	180[b] 2.4[c]	0.000282 0.403200
RMI[a]	10 605	0.18000	0-1/8 in 1/8 to ¼ in ¼ to ½ in > ½ in	0.50 3.75 20.25 75.51	488	0.000183 0.001395 0.007460 0.027700
Paint chips	85	0.00090	0 to 800µm 800 to 3 000µm	50 50	131	0.001100
Dirt, dust, concrete	150	0.00160	0 to 50µm 50 to 150µm 150 to 2 000µm	25 50 25	156	0.001620
Sludge (iron oxide)	450	0.00480	0 to 5µm 5 to 10µm 10 to 75µm	81 14 5	324	0.002360
Rust particles (iron oxide)	50	0.00053	0 to 100µm 100 to 800µm 800 to 3 000µm	10 50 40	324	0.000260

a Either NUKON™ or RMI present, but not both.

b Density of individual glass fibers.

c Density of fiberglass blanket.

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4. Zigler, G., J. Brideau, D.V. Rao, C. Shaffer, F. Souto, and W. Thomas, “Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris”, NUREG/CR-6224, SEA No. 93-554-06-A:1, 15 September 1995.

5. Green, T., “BWR Owner’s Group Response to NRC Comments and Questions Regarding the Utility Resolution Guidance for ECCS Suction Strainer Blockage”, letter transmittal, OG97-044-161, January 1997.

The projected time-related variation in the debris concentration entrained in the flow to the example BWR ECCS pump is illustrated in Figure 1. Figures are shown based on plants with either 100% NUKON^{TM} or 100% RMI insulation types. The NUKON^{TM}-type insulation is expected to form a debris bed on the ECCS suction strainer surface, which will filter out substantial amounts of particulate and fibrous debris during the first hour of ECCS operation. RMI-type insulation does not serve as an effective filter medium. Particulate-debris concentrations in the ECCS flow to the pumps for RMI-insulated plants are expected to remain relatively unchanged throughout the period of ECCS operation.

Conservative assumptions were used in developing the trends shown in Figure 1. The suppression pool ECCS suction screens were assumed to be large enough that a thin bed ($\leq$ 1/8 inches) would form on the surface of the screen (NUKON^{TM}-type insulation).[6] Small-sized debris, unless filtered out by the debris bed on the surface of the ECCS screen, was assumed to remain in suspension. The ECCS suction screen openings were assumed to be 1/8 inches in diameter.

2.3 Anticipated conditions for PWRs

The debris types and concentrations in PWR ECCS fluid streams will be different than those expected for BWRs because of differences in the quantities of materials impacted by high-energy line breaks and differences in plant design features. Table 2 presents the debris types and quantities assumed for the PWR ECCS pump evaluations.[7,8] The quantities involved are considerably larger than those for the BWR, shown in Table 1.

The sump water volume used to derive the concentrations shown in Table 2 was 56 000 ft^3, which occurs after the refuelling water storage tank (RWST) water volume has been pumped into the reactor coolant system and has drained through the break into the sump. This RWST volume is reasonably typical of that of many PWRs.

When this study was performed, containment sump screens in PWRs typically were characterised by openings on the order of ¼ inches × ¼ inches. The analysis assumed that all debris smaller than ¼ inches would remain in suspension. Some filtration of particulate and fibrous material would occur on the surface of the sump screen for the case with fibrous insulation.

Figure 2 shows the estimated debris concentration approaching the low-pressure safety injection (LPSI) and containment spray pumps as a function of time. PWR ECCSs initially take suction from the RWST, which provides clean water to the ECCS pumps until switchover to suction from the containment sump occurs. The rise in the debris volume concentration starting at about 10 h for the 100% NUKON^{TM} case is due to boron precipitation, which is assumed to occur during one 24-h period. The effect of boron precipitation is less obvious for the 100% RMI case because more of the other particulate debris also remains in suspension. Note also that the concentration scales on the NUKON^{TM} and RMI plots are different.

6. Zigler, G., J. Brideau, D.V. Rao, C. Shaffer, F. Souto, and W. Thomas, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris", NUREG/CR-6224, SEA No. 93-554-06-A:1, 15 September 1995.

7. Kamath, P.S, T.J. Tantillo, and W.L. Swift, "An Assessment of Residual Heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions", NUREG/CR-2792, CREARE TM-825, September 1982.

8. Andreycheck, T.S., "Evaluating Effects of Debris Transport within a PWR Reactor Coolant System during Operation in the Recirculation Mode", Westinghouse Power Company, 1844.

Figure 1. Time-dependent volume concentration of debris in BWR ECCS flow to the pump

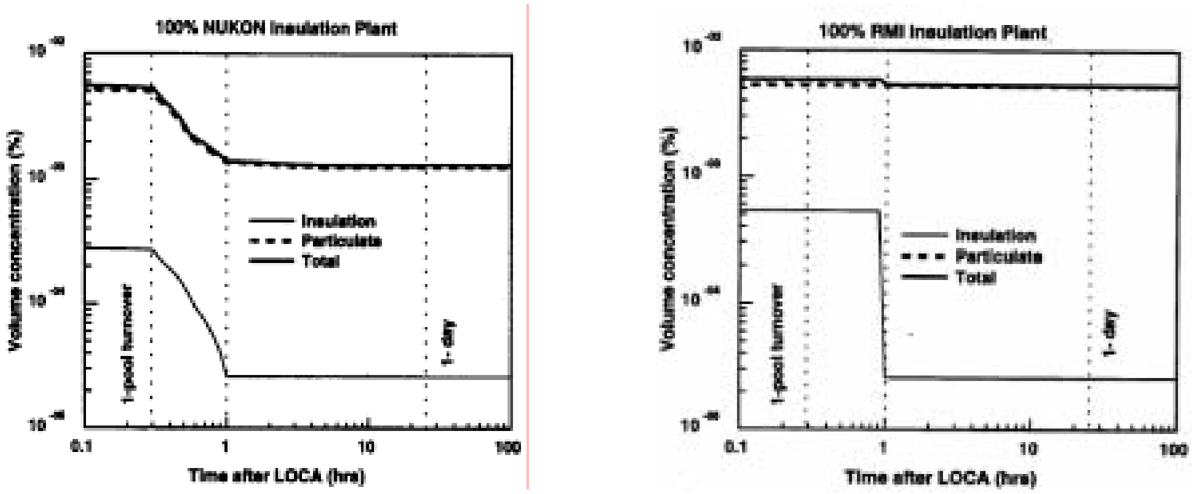


Table 2. Quantity and characteristics of debris reaching PWR ECCS sumps

Debris type	Mass (lbm)	Mass conc. (lbm/ft^3)	Debris characteristics			Volume conc. (%)
			Size range	% by Mass	Density (lbm/ft^3)	
NUKON™ fiberglass[a]	2 880	0.0179	100 to 1 800µm ≥ 0.5 in	5 95	180[b] 2.4[c]	0.000496 0.709300
RMI[a]	50 574	0.9000	0-1/8 in 1/8 to ¼ in ¼ to ½ in > ½ in	0.50 3.75 20.25 75.51	488	0.000323 0.002420 0.013070 0.048800
Paint chips	4 250	0.0759	0 to 800µm 800 to 3 000µm ≥ 3 000µm	2.9 3.1 94.0	131	0.057900
Dirt, dust, concrete	150	0.0016	0 to 50µm 50 to 150µm 150 to 2 000µm	25 50 25	156	0.017200
Hydroxide precipitates	5 000	0.0893	0 to 10µm	100	187	0.047800

a Either NUKON™ or RMI present, but not both.

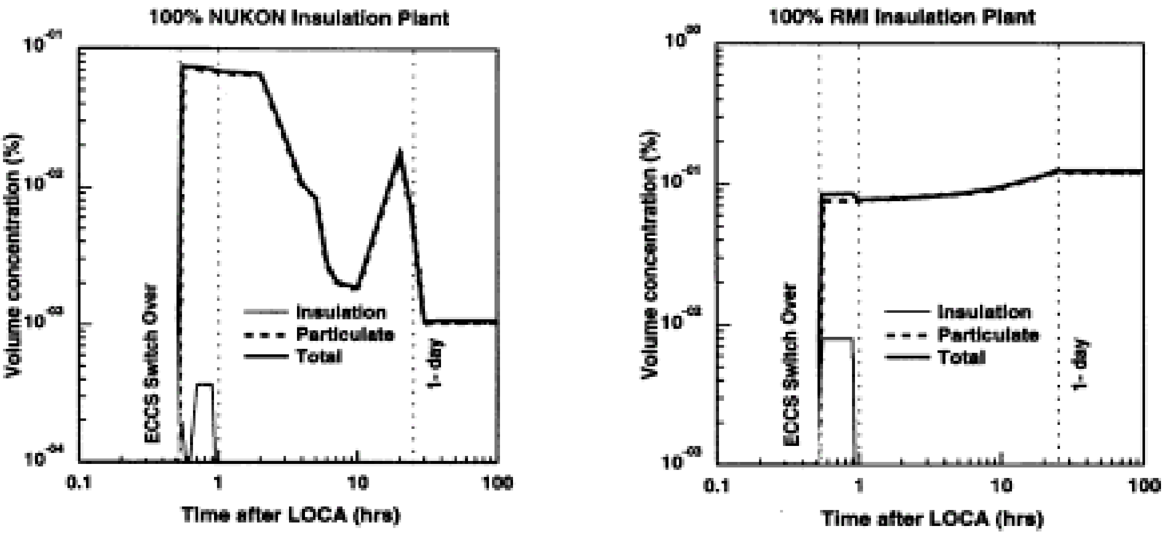
b Density of individual glass fibers.

c Density of fiberglass blanket.

A comparison of Figures 1 and 2 suggests the following:

- Volume concentrations of debris reaching ECCS pumps following a LOCA are potentially higher in PWRs compared with BWRs.
- In both PWRs and BWRs, the concentrations are higher for 100% RMI plants compared with 100% NUKON™ plants. Also, for fiberglass plants, debris concentration falls about an order of magnitude after about one day, whereas for the RMI plant, fairly uniform concentrations may be maintained for several days.

Figure 2. Time-dependent volume concentration of debris in PWR ECCS flow to the pump



- The volume concentration estimates were developed based on very conservative assumptions related to debris generation and transport. Despite the conservatisms, the estimated debris concentrations are well below 1%.

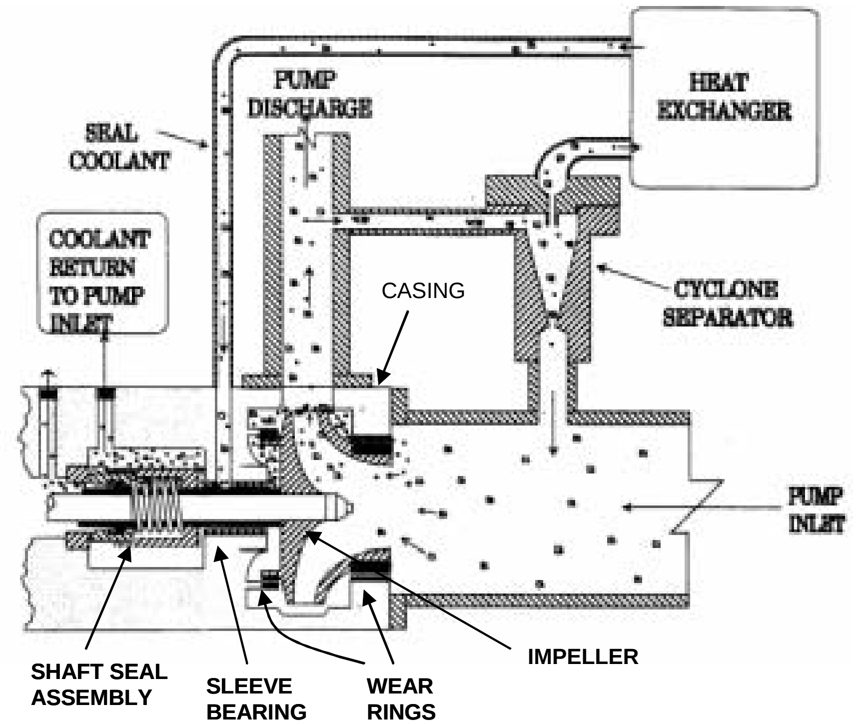
3. ECCS pump characteristics of concern

The ECCS pumps of primary interest to this study were the RHR and containment spray (CS) pumps. With few exceptions, practically all RHR and CS pumps installed in US NPPs are single- or multiple-stage centrifugal pumps. Multiple manufacturers have supplied these pumps, and there is considerable variation in particular design features from one pump to another. Nevertheless, essentially all of these pump designs have particular features that may be susceptible to debris-related degradation.

Figure 3 schematically illustrates key components typical of NPP ECCS RHR and CS pumps. A debris-laden fluid stream is depicted. Many ECCS pumps employ a cyclone separator and a heat exchanger to condition the water supplied to the shaft seals. The heat exchanger reduces the temperature of the filtered fluid and improves the fluid's effectiveness in cooling the seals and pump elements in the seal cavity. The heat removal decreases the operating temperatures of the seal cavity components.

The fluid that contains the debris flows from the pump inlet through the impeller and out of the pump discharge. Within each of the internal pump regions, the fluid and the debris may be circulated through small passages designed to provide water to pump components and other pump cavities, including the cavities formed between the impeller structure and the pump casing, the upper wear-ring support structure, and the lower wear-ring support structure. As illustrated in Figure 3, as the fluid and debris exit the pump, a small quantity of fluid and debris is drawn into the seal piping system. It then flows into the cyclone separator, where some of the debris is removed. The filtered fluid then passes through the heat exchanger, into the seal cavity, and then returns to the pump inlet.

Figure 3. Typical RHR and CS pump arrangement



The key pump components that could be adversely affected by debris during post-LOCA operation include the pump shaft seals, bearings exposed to the fluid stream, hydrostatic and hydrodynamic bearings, wear rings, cyclone separators, and heat exchangers. These components typically are designed with small passages or small clearances that could be blocked by debris. In addition, the components' critical clearances could be impacted adversely by debris in the fluid stream.

3.1 Concerns for individual pump components

Wear rings. Wear rings, or clearance rings, are incorporated into pumps to reduce the leakage of the pumped fluid from the discharge to the suction sides of the impeller. They provide tight clearances between the stationary pump housing and the rotating impeller. The gap between the stationary and rotating wear rings typically varies with ring diameter. Wear-ring diametral clearances for ECCS pumps likely are to be about 0.01 to 0.02 inches. Entrained debris with the appropriate geometric form will find its way into the gap between the stationary wear ring and the impeller. As the particles pass through this gap, they are expected to cause surface damage and wear. The wear and other attributes of the surface damage caused by the debris will enlarge the gap and reduce the effectiveness of the hydrodynamic film that serves to minimise the metal-to-metal contact between the rotating and stationary wear-ring surfaces. In addition, as this gap increases, the impeller will become more susceptible to wobble, which is manifested as increased vibration of the pump and increased loads on the bearings.

Some wear-ring designs employ weep holes, which help to control: (1) the flow of fluid between the rotating and stationary rings; and (2) the hydraulic forces acting on these components. Fluid and debris may be draw into the cavity in the wear-ring support structure and then will exit through the weep holes in the wear ring.

If the debris alters the flow of water through the weep holes, the hydrodynamic support provided by the water between the wear ring and the impeller is reduced. Vibration and wobble of the rotating components can result, and metal-to-metal contact between the rotating and stationary components may occur. Any such imbalance increases the forces and stresses on bearings and support structures. Further, frictional heating caused by the rubbing of the impeller and wear ring may increase if the water flow is degraded. This reduced water flow may cause excessive thermal expansion of the wear ring and impeller structure, thus leading to actual seizure of the wear ring and impeller. Failures of this type have been observed for centrifugal pumps used in commercial applications. For some similar failures, the wear-ring retaining pins were sheared and the wear ring rotated in its support housing. Loose retaining pins also can pose direct hazards to continued pump operation because they can become wedged between the rotating and stationary pump components. Pump failures due to ingestion of objects such as retaining pins have been noted for ECCS pumps.

The wear-ring failure modes induced by excessive wear and abrasion would degrade the pump performance over the long term and could result in complete pump failure. Failures resulting from weep-hole blockage, which then induces imbalance, wobble, and/or vibrations, could occur any time debris is present. Such failures could occur early or late, depending on when a blockage might occur and the significance of any associated hydraulic imbalance effects.

Bearing assemblies. The pump shaft and attached impeller are supported on bearings that are either within the pump housing or external to the housing. Bearings located within the pump housing are typically sleeve or journal bearings. Bearings external to the housing are typically ball or roller bearings lubricated by an oil bath. These external bearings normally are not exposed to debris-laden pumped fluid. Some pump designs also employ hydrostatic bearings internal to the pump casing to stabilise the rotating components and to provide a low-friction arrangement. Metal-to-metal contact between the rotating and stationary components is minimised in such designs by the hydrostatic pressure of the pumped fluid. Thus, journal and hydrostatic bearings are of primary concern when considering the deleterious effects of debris ingestion in ECCS pumps.

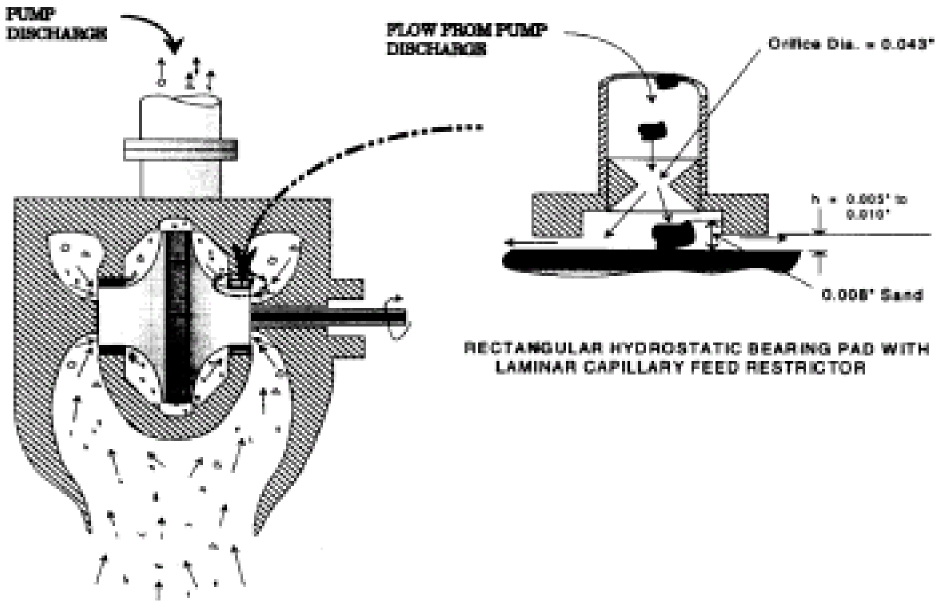
In some designs, journal bearings are cooled and lubricated by the pumped fluid. Wear is expected on these components, and they are designed to be replaceable. RHR and CS pumps employing journal bearings of this type may be designed with internal passages that provide pumped fluid to the bearings.

Some journal bearing designs are self-lubricating and do not rely on the pumped fluid for lubrication. Self-lubricating bearings for water-pump applications are carbon or graphite based and may contain metals or resins to achieve the desired structural and low-friction characteristics. These types of bearings do not require external sources of lubrication, but their performance is enhanced significantly by the presence of a liquid film between the sliding surfaces (the coefficient of friction is reduced about an order of magnitude compared with "dry" conditions). These self-lubricated bearings do not require internal coolant passages that direct coolant to the bearings. The pumped fluid acts to remove the frictional heat generated in the bearings. Also, these types of bearings are not subject to galling or seizure.

An illustration of a hydrostatic bearing of the type used in some RHR pumps is provided in Figure 4. This type of bearing is used to keep the impeller centred and rotationally stabilised within the pump housing by way of hydraulic-pressure control between the bearing pad and the rotating impeller. As indicated, hydraulic pressure is provided by diverting a small portion of the pump discharge flow to the bearing pad. Flow control is provided by orifices located at each bearing pad (the orifices are referred to as the "laminar capillary feed restrictors"). Several bearing pads are located around the circumference of the hydrostatic bearing. The dimensions of the orifice and the clearance between the bearing pad and the impeller shown in Figure 4 typify those that exist in CS and RHR pump designs. For comparison purposes, the size of a grain of sand also is illustrated.

Hydrostatic bearings may also be susceptible to debris-induced problems. Because the fluid for hydraulic control of the hydrostatic bearing is obtained from the pump discharge media containing debris, the debris will pass through the bearing flow-control orifice to the bearing pad. To illustrate the potential for debris to become trapped within the bearing pad, note in Figure 4 the size of a typical grain of sand (0.008 inches) in comparison to that of the bearing pad clearance (0.005 to 0.010 inches). This illustration demonstrates the potential for hydrostatic bearing failure because of: (1) debris accumulating within the bearing pad, resulting in friction that can cause the impeller to overheat and possibly seize; and (2) debris restricting flow through the bearing flow-control orifices, causing loss of hydraulic-pressure control. Loss of hydraulic-pressure control will cause the impeller to become vibrationally unstable. Thus, this is one mode of debris-induced pump degradation that could cause early, significant, and possibly total failure of the affected ECCS pump.

Figure 4. Hydrostatic bearing configuration

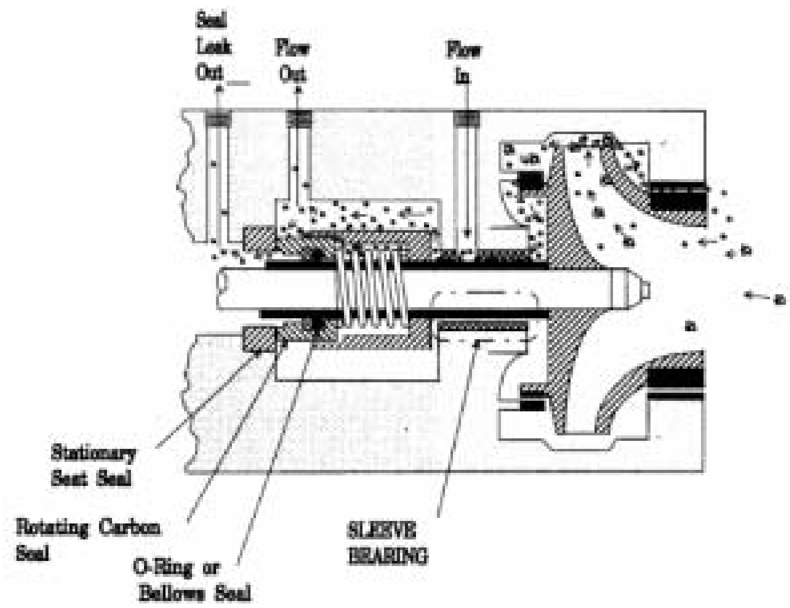


Sleeve bearings may be susceptible to debris-induced failures, depending on the bearing design and the materials used. As illustrated in Figure 5, debris will migrate from the high-pressure region of the impeller to the low-pressure region of the sleeve bearing and on to even a lower fluid pressure of the bearing seal cavity. The sleeve bearings may or may not be fed by internal passages that direct coolant to the bearing. Clearances between the bearing and the rotating pump shaft are typically about 0.005 to 0.020 inches. These clearances are such that paint chips, dirt, dust, concrete particles, sludge, and rust particles could enter the bearing. As the debris traverses the close-tolerance clearance between the pump shaft and the sleeve bearing, the debris is likely to be caught by the reduced clearances because of any nonconcentric operation of the pump shaft. Abrasion, galling, and frictional heating of the shaft and bearing surfaces can occur because of the presence of the debris. In the extreme case, the interactions with the debris can cause high-temperature effects and shaft bowing or seizure due to binding between the rotating and stationary members.

Graphite-based sleeve bearings may be less susceptible to debris-related damage in that these bearings are reportedly highly resistant to galling and seizure. The presence of debris undoubtedly would result in accelerated wear and erosion of the bearings. This degradation mode would serve to increase clearances between the pump shaft and the bearing surfaces, which in turn would allow more vibration and wobble of the rotating components. Some loss of pump performance would be expected. Loss of pump function due to graphite-based bearing wear is not deemed very likely, at least not during the early period of RHR pump operation following a LOCA.

Note that sleeve bearings made of materials such as babbitt metal or bronze are typically dependent on the presence of a liquid film for lubrication and cooling. These materials are more susceptible to galling and seizure if the liquid film is lost or degraded than are the graphite-based bearings.

Figure 5. Typical pump shaft seal and sleeve bearing designs



Seal coolant piping, heat exchangers, and cyclone separators. These components typically have orifices or flow restrictors on the order of 0.12 to 0.20 inches in diameter. These restrictors could become blocked by large pieces of debris or by the buildup of small pieces of debris. Cyclone separators are relatively effective for removing debris larger than about 0.008 inches in size but are less effective with smaller debris. Thus, small-sized debris will be sent on to the shaft seal even if the separator is functioning properly.

Partial or complete blockage of the orifices and flow restrictors in these components will reduce the coolant flow to the shaft seals.

Pump seals. Many types of devices are used to prevent the egress of fluid around a rotating pump shaft. Labyrinth seals, stuffing boxes, lip seals, spiral groove seals, and mechanical seals are used for sealing rotating shafts. From the available data and the review of pump designs, the escape of fluid from the RHR and CS pumps in both BWR and PWR NPPs usually is prevented by mechanical face seals. Face-seal designs used in ECCS pumps normally are configured so that the leakage is radial between plane surfaces (face seal) rather than axial between cylindrical surfaces (bushing seal). One seal member is attached to the pump housing and remains stationary. Other seal members are attached to the pump shaft and rotate with the shaft. Most designs employ a spring with the floating member to maintain a reasonably constant force between the seal faces. Several of these face seal features are illustrated in Figure 5.

A key failure mode for ECCS pump shaft seals is overheating of the seal faces due to loss of cooling flow to the seals. Flow obstructions at several points in the upstream flow path may be caused by debris accumulations or by single large pieces of debris. When coolant flow to the seals is reduced significantly or stopped, the frictional heating between the rotating and stationary seal face members will be sufficient to cause the liquid film to boil and vaporise. With the liquid film gone, the lubrication between the faces will be degraded considerably. The seal faces can be worn down rapidly, overheated, warped, or otherwise damaged.

Once the fluid and debris enter the seal cavity, the debris will be distributed throughout by the action of the pressure gradients present and by the rotating parts of the seal. Debris will impact the edges of the primary and secondary seals, will be drawn into the gap between the seal faces, and may accumulate in regions of low fluid flow. The fluid flowing into the seal cavity also will enter the cavity between the seal compression spring and the spring collar shown in Figure 5. Eventually, the accumulated debris can affect the functionality of the spring and other moveable parts. Operating plants have experienced the failure of ECCS pump seal springs to function properly because of debris accumulation, resulting in seal leakage.[9,10]

Debris that enters the area between the seal faces will scar and abrade the seal surfaces. Extensive wear can result in complete failure of the seal. Moderate to extensive leakage from the pump will result. Many pumps are believed to be equipped with backup or disaster bushings that limit the extent of leakage from a damaged or destroyed seal. The leakage beyond the disaster bushings is reported to be limited to about 80 gal./h. Without these bushings, the leakage from a damaged or destroyed seal could be considerably greater than 80 gal./h. Reported ECCS pump seal failure incidents indicate seal leak rates of about 300 gal./h. with the pump stopped (low-pressure differential across the seal), further suggesting that not all ECCS pumps have disaster bushings.

3.2 Typical internal clearances in ECCS pumps

Table 3 presents a compilation of internal clearances and gaps characteristic of some ECCS pump designs. The values shown are judged to be reasonably representative of a range of ECCS pumps. The clearances noted in Table 3 are derived from multi-stage designs with internal journal or sleeve bearings. The values shown were obtained from pump maintenance manuals for operating NPPs, as this type of information was not forthcoming from ECCS pump manufacturers.

The pump-shaft-to-bearing clearances appear to be in the range of 0.005 to 0.023 inches. Essentially all of the debris types have characteristic dimensions small enough that the debris could enter into these shaft-to-bearing clearances. Materials such as paint chips and pieces of RMI foils are sufficiently thin that they also could enter these clearance spaces even though other dimensions of the debris pieces may be considerably larger than 0.02 inches.

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9. NPRD Report, “Nuclear Plant Reliability Data System-Failure Master Report”, NPRGO6AA, Job No. 3170.

10. Stanton, R.H., “A Characterization Update of Pump and Pump Motor Degradation and Failure Experience in the Nuclear Power Industry (1994-1995)”, ORNL/NRC/LTR/96-32, draft letter report, October 1996.

The clearances between the pump impellers and the wear rings are somewhat larger than those between the internal bearings. Here again, most of the debris that would be ingested by the pumps is sufficiently small that the debris pieces could enter the impeller-to-wear-ring gap.

Coolant flow passages feeding the pump shaft seals are estimated to be in the range of 0.1 to 0.2 inches in diameter. Most debris would pass through these passages; however, larger debris such as paint chips, clumps of fibrous debris, RMI pieces, and rust chips are large enough to obstruct or block the flow in these passages.

The shaft-face seals have clearances between the faces that are characterised by the face roughness. This roughness is very small, about a few micro-inches. Small dirt, dust, and concrete particles, as well as some of the smaller sludge particles, may be small enough to enter the spaces between the seal faces. Larger debris particles can enter the space between the seal faces if the faces are not held tightly together by the seal springs and the pressure in the seal cavity or if the seal faces are not parallel.

Table 3. Typical pump internal clearances

Characteristic pump clearances		
Components	**Minimum (inches)**	**Maximum (inches)**
Pump-shaft-to-bearing assembly, suction bell	0.005	0.02
Pump-shaft-to-bearing assembly, first stage	0.005	0.023
First-stage impeller to wear ring	0.02	0.039
Second-stage impeller to wear-ring eye	0.02	0.039
Third-stage impeller to wear-ring back	0.02	0.039
Pump shaft to bearing	0.01	0.023
Pump shaft to bushing	0.02	0.033
Shaft-seal coolant passages*	0.1	0.2
Shaft-seal face roughness	0.000005	0.00001
Cyclone separator orifices	0.125*	0.2

* Estimated values.

The clearances between the pump impellers and the wear rings are somewhat larger than those for the internal bearings. Again, most of the debris that would be ingested by the pumps is sufficiently small that the debris pieces could enter the impeller-to-wear-ring gap.

The cyclone separator passages appear to be reasonably large in comparison with the pump clearances. Most of the debris types could pass readily through the separator. The exceptions are long pieces of fibrous insulation (or clumps of fibers), large paint chips, large rust particles, and large pieces of RMI foil. Some plants have orifices located in the piping upstream of the cyclone separator. These orifices are used to control the flow rate. The examples found employed orifice diameters of 0.13 inches, just marginally larger than the 1/8 inches hole sizes found in most BWR suction strainers, but smaller than the ¼ inches openings in PWR sump screens. These orifices would be susceptible to blockage by the larger pieces of debris ingested by the ECCS pumps or by blockage from accumulations of smaller pieces of debris.

3.3 Note on slurry pumps

Centrifugal pumps designed for pumping water can be used for pumping slurries and sludge, but experience has shown that pump reliability, in general, is poor and that the pumps experience excessive wear.[11] The slurry and sludge cause seal leakage and degradation of pump internal components.

Commercial pumps available for handling slurries and sludge are specially designed to accommodate the abrasive and corrosive nature of the pumped materials. Slurry pumps generally have larger internal clearances, specialised seal designs, and components built of durable materials. For example, shaft seals designed for abrasive environments employ sealing elements with two hard surfaces, whereas general centrifugal pump applications usually employ one hard surface and one relatively soft surface. In addition, seal cavities for slurry pumps generally are supplied with clean coolant, while normal pumps may or may not filter the coolant supplied to the seal cavity. Other special features may include the use of special wear- and corrosion-resistant materials and replaceable wear liners that extend the life of the pump by decreasing the need to completely replace hardened parts within the pump. Slurry pump designs often include features that enhance servicing and component replacement. To our knowledge, ECCS pumps do not include these special design features.

4. Failure modes and effects analysis

4.1 Failure modes effects analysis basis

Failure modes and effects analyses were performed on a generic pump design. The assumed design features tend to make the overall analysis somewhat conservative. As such, the individual failure modes covered in the FMEAs may not be applicable to ECCS pump designs that do not employ a feature susceptible to particular failure modes. The key alternative design features are as follows (the underlined features indicate those considered in the FMEAs):

- Bearings – *internal sleeve or journal bearings* (with and without internal passages or grooves to promote coolant flow to the bearings), *internal hydrostatic or hydrodynamic bearings, external ball or roller bearings*;
- Wear rings – *wear rings with and without weep holes*;
- Cyclone separators – shaft-seal coolant supply systems *with* and *without cyclone separators*;
- Disaster bushings – pump *with* and *without bushings used to limit the amount of leakage flow from a failed shaft seal*.

The analysis assumed that the largest debris ingested by ECCS pumps in PWRs could have characteristic dimensions up to ¼ inches, whereas the corresponding debris for BWR ECCS pumps could have dimensions up to 1/8 inches. These dimensions are based on the ECCS suction screen or strainer opening sizes prevalent in the NPP population at the time of the study.

11. Lebeck, A.O., “Principles and Design of Mechanical Face Seals”, Wiley, 1991.

Differences between BWRs and PWRs also were addressed in the FMEA. The key differences that could impact ECCS pump debris ingestion and the deleterious effects on the pumps are as follows:

- PWR ECCS pumps initially supply coolant to the reactor system by taking suction from the RWST; only after depletion of the RWST would the pumps be put in a recirculation mode where they draw from the containment sump. Because the water in the RWST is essentially clean, pump degradation from ingested debris normally cannot occur early (about the first 30 min following a LOCA) for PWRs, whereas early degradation of BWR ECCS pumps is possible from debris-ingestion effects.
- PWR sump screens have larger holes than BWR suppression pool strainers. Therefore, larger debris sizes can be ingested by the ECCS pumps in a PWR compared with a BWR.
- The most limiting breaks for a PWR will produce more insulation debris, paint chips, concrete dust, etc. than is expected for the most limiting breaks in a BWR. Therefore, the debris concentrations reaching the PWR ECCS pumps are higher than those expected in BWRs. For materials such as dirt, dust, and concrete, the PWR concentrations are an order of magnitude higher than for a BWR.
- BWR debris available for possible ingestion by the ECCS pumps includes sludge and rust particles, whereas little of these materials are expected to be present for PWRs. However, the PWRs have hydroxide precipitates in relatively high concentrations, which is not the case for BWRs.

The analysis also was based on the assumption that features of ECCS pumps that are susceptible to debris-related damage are the same in pumps employed in PWRs and BWRs; i.e. the assumed pump designs are identical for the two reactor types.

The mission time for ECCS pumps following a large LOCA is assumed to be 100 days. The further assumption was made that all ECCS pumps would be in continuous operation for this period of time; options such as alternating pump operation or pump throttling after a few days or weeks were not factored into the FMEAs.

4.2 Failure modes effects analysis results

The FMEA results indicated that the pump components judged most susceptible to significant debris-related damage, such that total pump failure might occur during the 100-day period of required operation following a large LOCA, are wear rings (particularly with weep holes) and internal bearings. Only those bearings that have significant loads and that require a liquid film for adequate lubrication are of concern in this circumstance. Pumps that rely on small internal passages or grooves in the bearings to supply coolant to the bearings are especially susceptible to debris-induced failure modes. Pumps without these features are less likely to incur degradation or failure than those with these features. However, note that pumps with external bearings are susceptible to debris blockage of coolant flow to the bearing oil coolers if the cooling is provided by the pumped fluid.

Essentially all ECCS pumps supply cooling water flow to the shaft seal by drawing from the pump outlet. Cyclone separators and heat exchangers may or may not be used to remove debris and cool this supply to the seals. Therefore, the shaft-seal failure modes and rankings developed in the FMEA apply to essentially all ECCS pumps, whereas the wear-ring and bearing failures may apply only to a subset of the ECCS-pump population. The FMEA identified that debris has a significant potential to cause seal damage or failure. Note that seal failure would not necessarily disable the pump.

A greater number of "significant early" failures were assigned for cases with RMI insulation than with fibrous insulation. This outcome results from the judgments that: (1) RMI debris pieces can be relatively large and can block important passages readily; (2) the particles are hard and will induce more wear and abrasion; and (3) the minimal filtering qualities of RMI result in the circulation of more particulates through the ECCS pumps for a longer period of time than would be expected of fibrous debris.

5. Review of pump-failure data

An evaluation was performed to estimate the likelihood that RHR and other ECCS pumps would fail due to debris ingestion during their required period of operation following a LOCA. This evaluation combined a review and analysis of pump-failure data with engineering insights and knowledge gained from the pump-failure modes analysis. The review and analysis of pump-failure data were based on ECCS pump events contained in the INPO Nuclear Plant Reliability Data System (NPRDS).[12] Oak Ridge National Laboratory (ORNL) had analyzed the NPRDS information for all types of safety-related centrifugal pumps during 1990 through 1995, inclusive.[13] The ORNL findings were supplemented by a separate, independent review of two sets of NPRDS data containing pump-failure events from 1976 to 1994-1995. One of these NPRDS data sets contained failure events for BWR RHR/low-pressure coolant injection (LPCI) pumps, while the other data set contained failure events for PWR RHR/low-pressure safety injection (LPSI) pumps and PWR containment spray pumps.

The ORNL reports noted the type and severity of the failures in the database. "Significant" failures were those likely to result in degradation such that the pump no longer could perform its function.

No significant data is available on ECCS pump operation with debris-laden fluid such as is anticipated following a LOCA. Debris-related ECCS pump failures have occurred, but the debris source and type was often associated with debris left in the system or component following manufacturing or maintenance/repair activities. ECCS pumps are normally in standby mode. RHR pumps provide shutdown cooling for extended periods, but in mode, they are circulating clean reactor coolant. BWR ECCS pumps are tested periodically by drawing suction from the suppression pool, which contains sludge and rust particles. These particles are quite small and are likely to pass through the pump without clogging internal passageways.

To get improved insights into the effects of debris on pump performance and reliability, a comparison was made between pump-performance data for systems pumping clean water and pump-performance data for systems pumping potentially contaminated or dirty water. The systems compared were essential service water (ESW) and component cooling water (CCW). Both of these systems have accumulated many thousands of hours of operation because they are normally operating when the plants are operating. ESW handles raw water (sometimes debris-laden river water), whereas CCW

12. NPRD Report, "Nuclear Plant Reliability Data System-Failure Master Report", NPRGO6AA, Job No. 3170.

13. Stanton, R.H., "A Characterization Update of Pump and Pump Motor Degradation and Failure Experience in the Nuclear Power Industry (1994-1995)", ORNL/NRC/LTR/96-32, draft letter report, October 1996.

handles clean water. The data review indicated that relatively few plants (three of each type) were responsible for about 40% of all of the corresponding PWR and BWR significant pump failures.

Table 4 presents a summary of the data review results. Data for pump-failure rates are presented based on both the entire NPP population of each reactor type and for a few plants where the ESW pumps had relatively high failure rates and took suction from debris-laden sources. Failure rates are shown for all types of failures and for "significant" failures.

The data for all plants suggests that water quality plays a role in pump-failure rates. ESW pump "significant" failures were 3 to 5 times higher than those for CCW pumps. For the plants with high ESW failure rates and which included plants whose ESW systems took suction from silt-laden river water, the "significant" ESW pump-failure rates were about 25 times higher than typical CCW significant failure rates. Similarly, "all" failures for debris-ingesting ESW pumps were about 8 times higher than those for CCW pumps.

Table 4. Comparison of ESW and CCW pump-failure rates

	Data for all plants		Data for plants with highest ESW failure rates	
System	**"All" pump failures**	**"Significant" pump failures**	**"All" pump failures**	**"Significant" pump failures**
BWR pump-failure rates				
ESW	0.13	0.05	0.50	0.25
CCW	0.07	0.01	0.07	0.01
Ratio of ESW/CCW failure data	~2	~5	7	25
PWR pump-failure rates				
ESW	0.18	0.08	1.30	0.80
CCW	0.14	0.03	0.14	0.03
Ratio of ESW/CCW failure data	~1.3	~3	9	25

1. Failure data are expressed in failures/pump-yr.
2. CCW pump-failure rates for "all plants" are assumed representative of CCW pump-failure rates for plants with high ESW failure rates.

6. Likelihood of RHR/ECCS pump failure during the post-LOCA period of required operation

The data and insights discussed previously were used to support the derivation of estimates for RHR pump performance and reliability under post-LOCA conditions. In an attempt to bound these performance/reliability estimates, two scenarios were considered: (1) a baseline scenario in which RHR pump reliability essentially is unaffected by debris ingestion; and (2) a more pessimistic (and possibly worst case) scenario in which RHR pump reliability is degraded significantly by debris ingestion. Both scenarios are based on a post-LOCA operating interval of 100 days.

Baseline predictions of post-LOCA BWR-RHR/LPCI and PWR-RHR/LPSI pump performance were based on typical pump reliability data used in probabilistic risk assessments (PRAs) and Individual Plant Examination (IPE) studies. Pump reliability data contained in PRAs and IPEs are believed to represent baseline predictions of post-LOCA pump performance because: (1) failure data used in these analyses typically are based on actual plant experience; and (2) most of the plant experience related to RHR pumps involves relatively clean pump-suction water. The following data indicate typical RHR failure rates used in PRAs and IPEs:

- Failure to start: 3E-03/demand.
- Failure to run: 3E-05/h.

Assuming that a particular RHR pump is continuously operated during a 100-day period (2 400 hours), the pump's failure probability would be calculated by combining: (1) the pump "start" failure probability; and (2) the pump per-hour "run" failure rate multiplied by the exposure period of 2 400 hours. For both BWRs and PWRs, the baseline post-LOCA failure probability of an individual RHR pump would therefore be about 7E-02 (for significant failures).

A more pessimistic (and possibly worst case) prediction of RHR pump performance was generated by increasing the PRA/IPE "run" failure data above by a factor of 25 for "significant" failures. This factor is based on a comparison of ESW and CCW failures at the plants having the highest ESW failure rates. These higher failure rates were experienced by pumps operating with debris-laden water.

Table 5 summarises the probability of significant ECCS pump failure during the post-LOCA 100-day mission time.

Table 5. Post-LOCA estimated ECCS pump-failure rates

Post-LOCA run period (days)	Pump-failure probability ("Significant" failures)	
	Baseline scenario[a]	Pessimistic scenario[b]
1	0.004	0.02
5	0.007	0.09
10	0.010	0.20
38	0.020	0.50
100	0.070	0.80

a Based on typical IPE failure-to-run rate of 3E-05/h.

b Based on typical IPE failure-to-run rate of 3E-05/h × factor of 25 for dirty vs. clean fluid.

The factor of 25, which is used to generate the pessimistic failure probabilities in Table 5, is the ratio of the significant failure rates for ESW pumps experiencing "dirty" operating conditions to the failure rates for pumps whose pumped fluid is clean. The high failure rate is based on the experience of a few pumps known to be operating with debris-laden suction conditions. The concentrations and types of debris present in the pumped fluid for these pumps were not characterised in the reports used to derive the failure estimates. The debris may or may not bear any resemblance to the debris ingested by ECCS pumps following a LOCA. The expectation is that a significant fraction of the debris was composed of silt and sand; these materials are hard and abrasive, as are the sludge materials found in BWR suppression pools and PWR containment sumps. In addition, the ESW pumps experiencing the high failure rates are not identical in design to ECCS pumps. ESW pumps are believed to be totally submerged designs where all of the pump components, including some shaft bearings, are submerged. The pumps are connected to the electric drive motors by long shafts. The pump seals and internal bearings may or may not have been fed by clean water sources rather than from the pumped fluid. However, it does appear that the debris ingested by the ESW pumps contributed significantly to their failure.

As noted above, the precise types and concentrations of debris ingested by the ESW pumps experiencing the high failure rates are not known. However, the overall concentrations in the river water sources can be estimated. One or more of the plants experiencing the high ESW pump-failure rates is located along a river with “average” soil/silt/sand concentrations of about 0.15% to 0.25% (volume concentrations). These river-water debris concentrations are higher than those estimated for ECCS pumps by at least an order of magnitude for most debris types for BWRs and are somewhat higher than the debris concentrations estimated for PWRs.

Note that the failure rates displayed in Table 5 apply to significant pump failures, i.e. those failures that could render a pump inoperable and unable to fulfil its function. Less severe failures, such as seal failure, are more likely to occur, but would not necessarily disable the pump.

7. Conclusions

The evaluations performed and the results developed indicated the existence of several key factors and considerations that are important in assessing the effects of debris ingestion on ECCS pumps, including the following:

- **Debris types, characteristics, and concentrations**. Debris likely to be generated and transported following a LOCA includes insulation debris, sludge in BWRs, paint chips from containment coatings, rust particles, and concrete dust. Fibrous insulation and paint chips are “soft” materials, while the remaining debris types are considered “hard”. Actual data regarding the behaviour of these combinations of materials as it may affect ECCS pump operation were not available at the time of the study, and thus, large uncertainties remained as to potential ECCS pump problems caused by these combinations of materials. Debris concentrations are estimated to be higher in PWRs than in BWRs, and the concentrations are expected to remain at relatively high levels for longer periods of time in plants insulated with RMI than in plants insulated with fibrous materials.
- **ECCS suction strainer or screen characteristics**. At the time the study was performed, the hole sizes for suction strainers in BWRs were as large as about 1/8 inches, while the sump screens in PWRs had holes as large as the equivalent of about ¼ inches in diameter. Thus, the debris sizes passing through the suction strainers in BWRs should not be larger than about 1/8 inches, and the debris ingested by PWR ECCS pumps should not be larger than ¼ inches. Either of these debris sizes is deemed large enough to potentially cause blockage of small passages within ECCS pumps.
- **Time dependency effects and the accident progression**. The accident progression following a large LOCA is different between BWRs and PWRs. In BWRs, the ECCS pumps take suction almost immediately from the suppression pool, whereas in PWRs, these pumps initially take suction from the RWST (a source of “clean” water) for the first 20 or more minutes following a large LOCA. Pump suction in PWRs then is switched to the containment sump as the RWST inventory is depleted. Thus, PWR ECCS pumps should not experience any debris-related degradation when they are drawing from the RWST; whereas in BWRs, the pumps may be subjected to debris-laden suction conditions as soon as they are placed into operation.
- **Pump experience for operation under post-LOCA conditions**. Essentially no experience exists of ECCS pump operation under conditions of debris ingestion similar to those expected following a LOCA. Therefore, pump behaviour under these conditions has a large degree of uncertainty.

- **Pump features**. Particular pump features play a key role in determining the susceptibility of a given pump design to debris-related damage, including:

    – shaft seal design (with or without cyclone separators);

    – presence or absence of internal bearings;

    – internal flow passages that supply coolant to journal/sleeve bearings; and

    – features relied on to provide hydrodynamic or hydrostatic balance to the pump impeller and other rotating components.

The results of the evaluations indicate the following:

- Pump shaft seals have a relatively high potential for failing during the 100-day post-LOCA mission time. Seal failure should not disable the pump or degrade its performance to the point where the pump is considered failed, unless the leakage is very high. For many ECCS pumps, the leakage flow is limited by disaster bushings. If such bushings are not present, the leakage rates can be significant. The resulting loss of coolant for recirculation to the reactor core could impact the long-term effectiveness of the ECCS.
- Pump bearing assemblies, particularly those designs that depend on coolant availability to provide hydrodynamic or hydrostatic balance to the pump impeller and other rotating components, are susceptible to coolant-passage blockage by debris. Blockage of critical internal flow passages that feed hydrodynamic or hydrostatic bearings could lead to imbalance of the rotating components. The attendant wobble and vibrations can result in possible contact between rotating and stationary components (e.g. wear rings and pump housing). Pumps that rely on hydrostatic and hydrodynamic bearings are judged to have a significant potential for failure due to debris-related effects. Extensive use of such designs in ECCSs is not supported by the surveys and inquiries performed for this study.
- Any imbalance of pump rotating components, such as those induced by loss of hydrodynamic balance, imposes loads on the shaft bearings. This loading, coupled with the lack of coolant for heat removal and lubrication, can result in overheating and possible seizure of the internal sleeve/journal bearings. This scenario is particularly true for metallic bearings of this type. Failure of the bearings could disable the pumps completely. This type of debris-related pump failure can occur essentially any time during the required period of ECCS pump operation following a large LOCA. Note that graphite-based bearings are self-lubricating and are less vulnerable to this type of failure.

Cycling of pumps on and off or alternating the operation of individual ECCS pumps during periods of low core decay heat may not be benign. Evidence indicates that debris will settle into the gaps, clearances, and internal passages when the pumps are idled. The accumulated debris may interfere with the restart of the pump. These types of occurrences have been observed in available ECCS pump-failure data.

High-pressure pumps, such as those used in the HPCI or high-pressure core spray systems in BWRs or HPSI pumps in PWRs, may be used in a recirculation mode for certain types of accidents. Because they are typically multistage units with tight clearances, these pumps may be more susceptible to debris-related damage than the low-pressure ECCS pumps.

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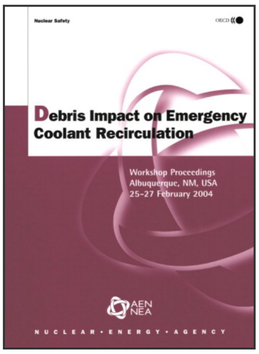

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