February 11, 2004

MEMORANDUM TO: John A. Grobe, Chairman
Davis-Besse Oversight Panel
Region III

FROM: Eric J. Leeds, Deputy Director
Division of Licensing Project Management **/RA/**
Office of Nuclear Reactor Regulation

SUBJECT: EVALUATION OF DAVIS-BESSE MODIFICATIONS TO THE HIGH PRESSURE INJECTION PUMP AND ASSOCIATED MOCK-UP TESTING (TASK INTERFACE AGREEMENT (TIA) NO. 2003-04, TAC NO. MC0584)

By memorandum dated August 12, 2003, you requested technical assistance from the Office of Nuclear Reactor Regulation (NRR) to evaluate the Davis-Besse high-pressure injection (HPI) pump modification, the validity of the licensees mock-up test approach, and to determine whether the testing demonstrates acceptable pump performance under design-basis conditions.

The NRR staff has concluded from its evaluation that the licensee's overall approach to the modification of their HPI pumps and its testing, is acceptable and provides reasonable assurance that the HPI pumps will perform their required functions when called upon.

The detailed NRR staff determination is attached.

Docket No. 50-346

Attachment: As stated

cc w/att: W. Lanning, Region I
C. Casto, Region II
D. Chamberlain, Region IV
C. Thomas, SRI

Contact: Jon Hopkins, NRR/DLPM/PDIII-2
(301) 415-3027

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ADAMS ACCESSION NUMBER: ML040270181 *Previously concurred

OFFICE	PDIII-1/PM	PDIII-1/LA	PDIII-1/SC	PDIII-1/PD	EMEB/SC	DLPM/DD
NAME	JHopkins	THarris*	AMendiola	WRuland	DTerao	ELeeds
DATE	2/5/04	1/28/04	2/5/04	2/5/04	2/5/04	2/6/04

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EVALUATION OF DAVIS-BESSE MODIFICATIONS TO THE HIGH PRESSURE INJECTION PUMP AND ASSOCIATED MOCK-UP TESTING

DAVIS-BESSE NUCLEAR POWER STATION

DOCKET NO. 50-346

Executive Summary

In a memorandum dated August 12, 2003, Region III requested NRR's assistance in evaluating the validity of the overall mock-up test approach to simulate actual conditions under which the high pressure injection (HPI) pumps must perform their safety functions following a loss-of-coolant accident (LOCA). The evaluation was to include such considerations as the testing of individual pump components in lieu of testing a complete pump, effectiveness of the "engineered" slurry to simulate expected sump debris, success criteria, and associated calculations. Finally, Region III requested NRR's assistance in determining whether the testing supports the licensee's final pump modifications and demonstrates acceptable pump performance under design basis conditions.

The Davis-Besse HPI pump modifications are intended to address potential pump degradation during the recirculation mode caused by debris transported to the sump from LOCA blowdown and containment spray actuation.

The staff from the Division of Engineering, Mechanical and Civil Engineering Branch (EMEB) and the Division of Systems Safety and Analysis, Plant Systems Branch (SPLB) has completed its review of the HPI pump modifications and finds:

> The licensee has performed sufficient design, analysis and testing to demonstrate the ability of the strainers in their location on the fourth stage volute to perform the function of eliminating particles greater than 0.050 inches while continuing to provide flow to the hydrostatic bearing. The mock-up testing adequately demonstrated the self cleaning design of the strainer i.e., that it would not fully plug with debris thus limiting bearing supply flow. The strainer design was shown to be robust and will not fail due to flow induced erosion.
>
> The licensee has performed sufficient design, analysis and testing to demonstrate the ability of the as-designed bearing to operate with no plugging of the orifices or bearing pads with debris laden water.
>
> The licensee's design, analysis and testing demonstrate that fine clearance components such as wear ring and shaft sleeves may experience wear while operating with debris laden water during plant recirculation. However, the proposed hard facing of pump critical components reduces the predicted wear such that operations near pump critical speed is not adversely affected. The modifications to the fine clearance components provide reasonable assurance that these critical components will not fail due to excessive abrasive wear or flow induced erosion.

ATTACHMENT

> The licensee's design, analysis and testing provide reasonable assurance that the HPI pump will be able to perform its safety function under design basis conditions and that the hydraulic performance of the HPI pump will be maintained even with wear of the fine clearance components such as wear ring and shaft sleeves while operating with debris laden water during plant recirculation. The proposed hard facing of pump critical components reduces the predicted wear such that hydraulic capability is not adversely affected. The design modifications were found to meet design requirements and the testing provides reasonable assurance that critical components will not fail due to excessive abrasive wear or flow induced erosion.
>
> In-plant, post-modification, pre-service testing performed in accordance with the American Society for Mechanical Engineers (ASME) Code for Operation and Maintenance of Nuclear Power Plants (OM Code) provides assurance of the pumps operational readiness and that any hydraulic degradation will be identified and monitored.
>
> The approach taken by the licensee in its calculations for debris generation, transport, and characterization was a technically valid approach. The staff further concludes that reasonable assumptions based on engineering judgement and appropriate conservatism was utilized where necessary to account for inherent uncertainties in the prediction of debris generation or impracticalities associated with modeling actual containment debris. The staff therefore concurs in the use of the materials as practical substitutes for actual containment debris in the Davis Besse HPI pump mock-up tests.

1.01 Background

The licensee has implemented a building block approach for return to service that includes assuring the health of plant systems. As part of this approach, the licensee identified that the high pressure injection (HPI) pumps were susceptible to degradation from fine particles transported from the containment emergency sump during the recirculation mode. To resolve this issue, the licensee proposed to modify the HPI pumps such that the degradation is minimized and the pump is capable of performing its design and licensing basis functions.

This evaluation summarizes the staff's review and assessment of the required HPI pump functions, and the licensee's actions to ensure those functions are met. The proposed design change assumptions, mock-up tests, analyses, modifications, pre-service and post-modification tests were witnessed and reviewed for technical adequacy and for compliance with regulatory requirements and applicable guidelines.

2.0 HPI Pump Design and Functional Requirements

The Davis-Besse high pressure injection pumps, designated HP-P1A and HP-P1B, are horizontal, eleven-stage centrifugal pumps powered by 600 HP electric motors. The pumps were manufactured by Babcock and Wilcox, Canada in accordance with the requirements of the ASME Pump and Valve Code, Class II, November 1968. They were designed to a pressure of 2000 psig at 300°F and have a design operation point of 600 gpm at 3250 ft Total Developed Head (TDH).

Inservice testing is performed in accordance with the ASME OM Code, 1995 Edition with 1996 Addenda.

The HPI pumps are credited with the following safety functions:

> They operate in conjunction with the low pressure injection (LPI) system and the core flood tanks to provide emergency core cooling for small-break, loss-of-coolant accidents (SBLOCA)
>
> They deliver a source of borated water to decrease reactor coolant system (RCS) reactivity.
>
> They provide make-up for reactor coolant contraction due to excessive RCS cooling.
>
> The HPI pumps serve as an essential back-up to the make-up and purification system for support of a safe shutdown following an operational transient, fire or seismic event.
>
> They support feed and bleed operation in conjunction with the make-up and purification system during a total loss of feedwater event.
>
> The HPI pumps are the primary method for boron precipitation control during long term core cooling following a LOCA.
>
> While in ECCS recirculation mode following a large-break LOCA (LBLOCA), they perform their safety function only during the borated water storage tank (BWST) injection mode. The Davis-Besse LBLOCA safety analysis does not credit the HPI following the depletion of inventory from the BWST.
>
> While in ECCS recirculation mode following a SBLOCA , the HPI pumps must function in the BWST injection mode and in the long-term recirculation (LTR) mode. The primary function during LTR is control of boron precipitation. In the LTR mode, the HPI system is aligned in piggyback to the LPI System. The LPI System provides process fluid cooling and a source of net positive suction head (NPSH) to allow operation of the HPI pump.

3.0 HPI Pump Modifications, Testing and Analysis

As a result of a review of the HPI pumps, HPI system design and their functional requirements, the licensee identified three potential areas of concern. First, the hydrostatic bearing supply orifices and the hydrostatic bearing itself could plug with debris during LTR. Second, debris-laden fluid could cause the fine clearances in HPI internal pump components to wear to the point where operation of an HPI pump would be at or near critical speeds. Third, the increased wear in HPI pump internal components could affect the hydraulic performance of the HPI pump and reduce its ability to perform its required functions.

Using the results of its fluid analysis, the licensee hypothesized failure mechanisms and degradation rates and developed a plan to modify the HPI pumps with the objectives of:

1) Preventing debris from plugging the hydrostatic bearing orifices or clogging the hydrostatic bearing.

(2) Modifying the bearing design such that debris reaching the hydrostatic bearing would exit the bearing pockets such that flow would be maintained through the bearing pocket.

(3) Minimizing close clearance wear while pumping debris-laden water.

These potential solutions and modifications were subjected to rigorous full- and part-scale, mock-up testing. The results of the testing were evaluated and incorporated into analyses in order to predict long-term effects and to confirm the adequacy of the proposed modifications. The HPI pumps were then physically modified and pre-service tested in accordance with the ASME OM Code under a range of flows to confirm operability of the HPI pumps. The process of hypothesis, testing and analysis was an iterative process. However, this report only addresses the final approved design. The staff's review and evaluation of the modifications that resolve the three concerns are contained in Sections 3.1, Potential Plugging of Hydrostatic Bearing and Orifices, 3.2, Operation of HPI Pump near Critical Speeds, and 3.3, Reduced Hydrostatic Performance. The staff's review and evaluation of the test approach is contained in Section 3.5, Mock-up Testing.

In addition, the licensee determined—through research and use of engineering judgement—the make-up of a post LOCA, containment sump fluid mixture. This mixture was then evaluated to determine its transport characteristics and the fluid properties that would be seen by the HPI system. The staff's review and evaluation of this issue is contained in Section 3.4, Debris and Debris Generation, of this report.

3.1 Concern 1 - Potential Plugging of Hydrostatic Bearing and Orifices

Hydrostatic bearing supply orifice and the bearing pad may fill with debris and plug when subjected to post LOCA containment long-term recirculation conditions.

During LTR, the LPI system takes suction directly from the containment sump. Fluid then passes through the LPI pumps and decay heat exchangers to the suction of the HPI pumps. Fluid then passes through the 11-stage pump prior to being re-injected into the RCS. The HPI pump had a hydrostatic bearing of a 'pocket' design that is lubricated by process flow supplied from the 4th stage pump volute. Flow to the bearing ranges from 11 to 20 gpm depending on operating conditions and is distributed circumferentially via five flow orifices with 0.109 inch diameter openings. Bearing/shaft sleeve clearances are a nominal 0.006 to 0.010 inch radially.

The containment emergency sump strainer has 0.188 inch openings. Since the bearing supply orifice openings are smaller than the sump screen opening, there is a potential to plug them with post-LOCA debris. Should debris pass through the orifices, there is also the possibility of plugging the bearing/shaft sleeve interface. The result of either condition would be to potentially degrade cooling supply to the bearing and, thereby, failing the bearing and the HPI pump.

3.1.1 Licensee Modifications to address Concern 1

To address issues identified in Concern 1, the licensee has implemented two modifications. The first was to install strainers on the suction supply to the hydrostatic bearing. The second was to re-design the hydrostatic bearing pocket in a configuration tolerant of debris accumulation.

3.1.1.1 Strainers in Bearing Suction Supply

The first modification was to install two strainers with 50-mil holes in the pump volute at the take-off for the hydrostatic bearing supply flow to preclude the introduction of debris larger than the orifice diameter. The two strainers are located 180 degrees apart on the volute. The 50-mil hole diameter was chosen to provide margin for the 109 mil bearing supply orifices. The strainers are made from nominally 1/8 inch thick, Haynes Alloy 25 (cobalt alloy) and welded in place.

The location of the take-offs for the hydrostatic bearing supply flow was relocated from the outer face of the volute to the inner radius on the pump volute discharge wear-ring side to reduce (concentration and size) the debris present at the supply line takeoffs. Volute takeoffs were moved from the pump's 4th stage to the 5th stage to maintain pressure drop and flow to the bearing. The takeoff location was chosen to account for additional volute-to-bearing pressure drop due to the addition of a screen, potential screen plugging with post-LOCA debris, and the need to lengthen the supply tubing from the takeoff to the bearing.

3.1.1.2 Re-design of Hydrostatic Bearing Pocket

The hydrostatic bearing pocket was re-designed from a rectangular arc pocket to a “Figure 8" pocket design. “Escape" grooves were added to the hydrostatic bearing pockets to allow debris larger than the bearing clearance to leave the pockets. This design was determined to be more tolerant of debris accumulation. The modified hydrostatic bearing was designed with a stiffness comparable to the existing bearing. Minimum required fluid flow rates to maintain bearing function were not changed, however normal operation bearing flow is approximately 13 % higher. This is insignificant with respect to overall pump flow.

3.1.2 Licensee Performed Testing to Confirm Design Adequacy

To confirm that the hydrostatic bearing supply orifice and the bearing pad would not fill with debris or plug when subjected to post-LOCA containment recirculation conditions, two tests were developed and performed. The first test (Test Loop 5), evaluated the as-designed strainer. The second test (Test Loop 3) evaluated the as-designed bearing. Test Loops 3 and 5 were operated in series with Loop 5 supplying the process fluid for Loop 3. The results, when considered together, confirmed the design adequacy of the strainer and bearing combination. The tests show that the hydrostatic bearing supply orifice and the bearing pad would not fill with debris or plug to the point where the bearing would no longer function during post LOCA containment recirculation conditions.

3.1.2.1 Strainer Testing, Test Loop 5

The intent of the mock-up testing of the strainer, Loop 5, in the new supply line take-off location was to confirm that the strainer would eliminate particles greater than 0.050 inches while continuing to provide flow to the hydrostatic bearing. The test also demonstrated the self cleaning design of the strainer i.e., that it would not fully plug with debris and restrict bearing supply flow.

Test Loop 5 set-up took suction from the tank containing the mock-up post-LOCA solution, Test Tank 1. The solution was supplied to a spare volute assembly at a constant flow of 250 gpm. The test monitored flow and pressure drop through the strainer. Discharge from the upper strainer was directed to Test Tank 2 to be used for the bearing test, Test Loop 3. Discharge from the lower strainer was routed back to Test Tank 1. The test was run for 21 continuous days, and the test equipment was disassembled and inspected for wear.

The test set-up used a spare pump impeller and volute and was, therefore, true to scale. The configuration acted as a single stage pump—modeling actual fifth stage pump conditions. The installed test strainer matched the as-designed strainer. The supply flow chosen was the assumed HPI pump design basis flow. In the test, flow though the strainer was initially set at 9.5 gpm nominal design flow through the two bearing supply lines (total flow to the bearing was 19 gpm) by varying the length of the discharge line. The minimum-required flow to a bearing is 3 gpm per line (or 6 gpm total). Flow and pressure drop were then monitored for the duration of the test period. The strainer would normally sees a 385 psi pressure differential (psid) rather than the as-tested configuration using 59 psid. This higher driving force of in-service pump operation aids in providing additional flow and would force through debris that could, in theory, accumulate on and plug the strainer. The mock-up test set-up was, therefore, conservative with respect to the potential for strainer plugging.

The results of the continuous 21-day run showed some wear on the leading edges of the strainer and some upstream coating and blockage. As expected, the strainer was shown to be partially self-cleaning and self-flushing. A review of the flow and pressure drop test data showed no significant change over the course of the test. After the initial loading of the strainer, flow and pressure drop remained constant and well above the minimum design basis requirements.

Based on a review of the mock-up test results, the proposed strainer design demonstrated its ability to eliminate particles greater than 0.050 inches while continuing to provide adequate flow to the hydrostatic bearing. The test also demonstrated the partial self-cleaning design of the strainer (i.e., that it would not fully plug with debris and restrict bearing supply flow).

3.1.2.2 Hydrostatic Bearing Testing, Test Loop 3

The intent of the mock-up testing of the hydrostatic bearing assembly, Loop 3, was to confirm operation of the bearing (no plugging of the orifices or bearing pads) with debris-laden water. The acceptance criterion for this test was no significant wear or plugging of the bearing after 21 days of continuous operation.

The debris-laden water used for this test was the discharge from the strainer test, Loop 5. Discharge water from Loop 5 was routed to a separate tank, Tank 2. Test pumps took suction from Tank 2 and supplied the inlet orifices of a full-scale hydrostatic bearing. The bearing test fixture consisted of a shaft and bearing of the same nominal dimensions of an HPI pump. Discharge from the bearing was routed back to Tank 2.

The supply pressure of 392 ± 40 psig was chosen to match the expected 5th stage pressure of the HPI pump when operating at 250 gpm. Flow and pressure drop were monitored for the duration of the test period. The test set-up closely modeled the expected initial and continued operating conditions of an installed bearing.

The results of the continuous 21-day run showed debris on the raised bearing flats and in the bearing channels. There was wear on the bearing surfaces due to flow induced erosion and wear from the entrained debris. There was no wear noted on the flow orifices and a small amount of wear on the bearing itself. These results were expected. After the initial debris loading of the bearing, the flow and pressure drop remained constant and well within the test requirements. A review of the flow and pressure drop test data showed no significant change over the course of the 21-day test.

Based on a review of the mock-up test results, the staff found that Test Loop 3 confirmed the ability of the as-designed bearing to operate with no plugging of the orifices or bearing pads with debris-laden water that would preclude the bearing from performing its required functions. The staff further found that the testing verified that the strainer design was robust and will not fail due to flow-induced erosion.

3.1.3 Licensee Analysis

The licensee performed finite element analysis (FEA) on the proposed strainer design, the as-modified volute, the bearing-supply tubing, and the redesigned bearing to confirm their structural adequacy. The results of the analyses showed all components to be adequately designed and demonstrated that they will operate well within the stress allowables of Section III of the 1971 ASME Boiler and Pressure Vessel Code—the design Code of record for Davis-Besse.

The licensee also performed computational fluid dynamic analysis (CFD) on the proposed strainer design, the as-modified volute, and the re-designed bearing to evaluate the resulting flow fields. The results of the analyses demonstrate the adequacy of the strainer takeoff location. The strainer CFD predicted the backside debris accumulation that was confirmed by test. The analyses showed that the presence of eddies or other flow disturbance areas within the volute that would be detrimental to pump integrity or operation do not exist. CFD evaluations showed that the resulting flow patterns to be reasonable and confirmed the results of strainer testing.

The modified hydrostatic bearing hydraulics (new takeoff location and strainer) was evaluated for hydraulic performance. Analysis showed no appreciable increase in pressure drop across the strainer at up to 90% blockage. This was confirmed in Test Loop 5 where the strainer was visibly plugged and test data confirmed no significant decrease in pressure drop or fluid flow rate.

The licensee also performed an analysis to size the bearing supply tubing. This analysis formed the basis for changing the location of the takeoff from the pump fourth to the fifth stage.

The licensee performed rotor dynamics analyses to confirm the adequacy of bearing stiffness of the new hydrostatic bearing design. Analysis was performed considering 1X and 2X clearances. Wear rates were extrapolated assuming 40 days of wear and used as an input into the analyses. Analyses show that an HPI pump with the redesigned bearing is stiffer than the previous design. The 1st mode natural frequency is greater than 18,000 Hz which is much greater than the 300 Hz vane pass frequency. Evaluation of wear rates and rotor dynamics are discussed Section 3.2.4.

The licensee also performed a failure modes and effects analysis to assess the potential for, and implications of, postulated failure modes.

3.1.4 NRC Staff Evaluation

The licensee's solution to the issue of the potential of the hydrostatic bearing supply orifice and the bearing pad to fill with debris and plug when subjected to post LOCA containment long-term recirculation conditions consisted of modifying the supply to the bearing and of modifying the bearing itself in order to minimize debris intrusion into the bearing system. The modifications were analyzed for structural and fluid dynamic acceptability and then tested to confirm the design assumptions.

The results of Test Loops 3 and 5, when considered together, confirm the design adequacy of the strainer and bearing combination. The tests show that the hydrostatic bearing supply orifice and the bearing pad would not fill with debris or plug to the point where the bearing would no longer function during post-LOCA containment recirculation conditions.

The staff reviewed the stress analyses methodology, inputs, assumptions and results and found that the licensee met the stress limits of the 1971 ASME Boiler and Pressure Code, Section III using appropriate analysis techniques and analysis assumptions. The staff also reviewed the CFD and hydraulic performance analyses and found that the licensee used reasonable methods and conservative assumptions to validate the mock-up testing and to determine the adequacy of the proposed modifications.

The staff reviewed the wear rates, rotor dynamic models and analysis and finds that the assumptions, models and analysis are reasonable and conservative. These subjects are discussed in further detail later in this evaluation.

The modifications alone do not eliminate the intrusion of debris in the bearing. The mock-up testing and analysis confirmed this phenomena. The licensee performed additional evaluations to show that, while debris will pass through the 50 mil strainer, the re-designed bearing would accommodate the debris and function as intended. The staff has reviewed the licensee's design drawings, calculations, analysis and mock-up tests. The specified design parameters, assumptions and analytical methods were found to be reasonable, technically acceptable and complete.

3.1.5 Conclusion

The staff concludes that licensee has performed sufficient design, analysis and testing to demonstrate the ability of the strainers in their location on the fourth stage volute to perform the function of eliminating particles greater than 0.050 inches while continuing to provide flow to the hydrostatic bearing. The mock-up testing adequately demonstrated the self-cleaning design of the strainer (i.e., that it would not fully plug with debris and restrict bearing supply flow). The strainer design was shown to be robust and will not fail due to flow induced erosion.

The staff also concludes that licensee has performed sufficient design, analysis and testing to demonstrate the ability of the as-designed bearing to operate with no plugging of the orifices or bearing pads with debris-laden water.

3.2 Concern 2 - Operation of HPI Pump near Critical Speeds

Fine clearance components such as wear rings, shaft sleeves, bushings and bearing may experience wear while operating with debris-laden water during plant recirculation. Due to the increased clearances, HPI pump operations near pump critical speed may be adversely affected.

The pump's primary load bearing components are a roller thrust bearing located at the motor end of the pump, a hydrostatic bearing at the outboard end of the pump, suction and discharge wear rings located on each stage, and a central volute bushing located between the 2nd and 11th stages. The hydrostatic bearing clearances are nominal 6 to 10 mils radially. Wear ring clearances are nominally 9 to 10 mils and the central volute bushing clearance is nominally 6 to 7 mils. The listed components are either stainless steel or bronze and may be susceptible to hard particle erosion or abrasive wear when exposed to post-LOCA sump fluid. The existing impeller wear surfaces are stainless steel coated with LW-5 tungsten carbide and are, therefore, not as susceptible to hard particle wear.

3.2.1 Licensee Modifications to address Concern 2

The licensee modified the components that had 'soft' wear surfaces with hard face material to minimize wear during pump operation with debris-laden fluid. Hard facing is to be a minimum of 30 mils in depth. The suction wear rings, discharge wear rings, hydrostatic bearing and shaft sleeve, and central volute bushing and shaft sleeve were hard faced. The new components are of the same size, shape and manufactured to the same tolerances of the original manufactured parts. The following chart summarizes the material modifications.

Part	**Original Material**	**New Material**
Wear Rings	ASTM A461-630 Con H 1150 (stainless steel)	Inconel Alloy 600 (UNS N06600) with Stellite 6 on ID
Central Volute Bushing	ASTM A461-630 Con H 1150 (stainless steel)	Inconel Alloy 600 (UNS N06600) with Stellite 6 on ID
Central Volute Bushing Sleeve	ASTM B143 Alloy 903 (bronze)	Inconel Alloy 600 (UNS N06600) with Stellite 12 on OD
Hydrostatic Bearing	ASTM A314 Gr 341 (stainless steel)	Inconel Alloy 600 (UNS N06600) with Stellite 6 on ID

Hydrostatic Bearing Sleeve	ASTM B103 Gr D (bronze)	Inconel Alloy 600 (UNS N06600) with Stellite 12 on OD
Impeller	ASTM A351, CF8 (cast SS) coated with LW-5 Tungsten Carbide	no change

In order to compensate for expected wear and clearances in the hydrostatic bearing to sleeve, the hydrostatic bearing pocket design was modified to increase the bearing stiffness. The hydrostatic bearing pocket was re-designed from a rectangular arc pocket to a “Figure 8" pocket design. “Escape" grooves were added to the hydrostatic bearing pockets to allow debris larger than the bearing clearance to leave the pockets. This design was determined to be more tolerant of debris accumulation. The modified hydrostatic bearing was designed with a stiffness comparable to the existing bearing. The licensee did not alter the fluid flow rates required to maintain bearing function.

3.2.2 Licensee performed Testing to Confirm Design Adequacy

In-plant testing was performed in May and June 2003 with a new HPI pump and a spare HPI pump artificially worn to large clearances (twice the normal design, 2X). Pump hydraulic performance data was acquired for both tests. Both tests showed an slight increase in vibration level. Hydraulic data was consistent and within normal test variances for the 1X tests. Testing at 2X showed an approximate 8% decrease in TDH (total developed head). A decrease in TDH and pump hydraulic performance would be expected as internal clearances are increased. This information was input into the rotor dynamics model.

To determine reasonable and conservative wear rates of the pump fine clearances while pumping debris-laden water, four mock-up tests were developed and performed. Wear rates were determined for the suction wear ring, discharge wear ring, hydrostatic bearing, and central volute bushing, and their associated rotating parts. Mock-up testing was performed off-site at Wyle Laboratories in Huntsville, Alabama.

The first test, Loop 1, evaluated the suction wear ring. The second test, Loop 2, evaluated the discharge wear ring. Test Loop 4 evaluated the central volute bushing. The tests were performed in parallel, all taking suction from Test Tank 1. Test Loop 3 evaluated the as-designed bearing and took suction from Test Tank 2. Test Tank 2 contained the discharge from the strainer tests. The test results were incorporated into the analytical wear models.

3.2.2.1 Suction Wear Ring Testing, Test Loop 1

Test Loop 1 was developed to test the suction wear ring. Loop 1 was a full scale test fixture designed to model a suction wear ring / shaft sleeve assembly. The major dimensions of the mating pieces were surfaced with a stellite overlay and tungsten carbide, respectively, and machined to nominal size according to the proposed design. Test flow across the wear ring assembly was set to 250 gpm with a differential pressure (DP) of 139 psid (150 ± 15 psig) as the controlling setpoint. Actual flow across a wear ring at the start of the test was approximately 95 gpm each. These parameters match the expected operating conditions between stages.

After 21 days of test, the stellited suction wear rings showed no signs of wear and the shaft sleeves showed minor wear. When extrapolated to 30 days post-LOCA operation, suction wear ring clearances would be expected to be approximately 1.2 times design. Test data showed no significant decrease in pressure drop across the test assembly for the duration of the test. The flow increased from 95 gpm to 110 gpm. The test rig drive power remained essentially unchanged for the duration of the test.

3.2.2.2 Discharge Wear Ring Testing, Test Loop 2

Test Loop 2 was developed to evaluate the discharge wear ring. Loop 2 was a full scale test fixture designed to model a discharge wear ring / shaft sleeve assembly. The major dimensions of the mating pieces were surfaced with a stellite overlay and tungsten carbide, respectively, and machined to nominal size according to the proposed design. Test flow across the wear ring assembly was set to 50 gpm with a DP of 50 psid as the controlling setpoint. Actual flow across a wear ring at the start of the test was approximately 27 gpm each. Normal expected DP is approximately 38 psid. These parameters are conservative with respect to the expected operating conditions between stages since the driving force may cause more wear on the rotating elements.

After 21 days of test, the stellited, discharge wear ring showed no signs of wear and the impeller hub showed general wear in the range of 10 to 15 mils. When extrapolated to 30 days post-LOCA operation, discharge wear ring clearances would be expected to be approximately 2.8 times design. A groove that extended through the hard facing to the base metal did form on the hub downstream section. This groove was postulated to form due to an accumulation, of debris. This mat of debris formed a continuous abrasive surface that wore through the hard facing. If the groove penetrated to the shaft, the disengaged ‘ring’ of wear ring would provide a larger flow bypass path but would not become a loose part or an internal missile causing the pump to become inoperable. Test data showed no significant decrease in pressure drop across the test assembly for the duration of the test. The flow increased from 27 gpm to 41 gpm. Test rig drive power was essentially unchanged for the duration of the test.

3.2.2.3 Central Volute Bushing Wear Rate Testing, Test Loop 4

Test Loop 4 evaluated the central volute bushing. The quarter scale test fixture was designed to model the discharge central volute bushing/shaft sleeve assembly. The major dimensions of the mating pieces were surfaced with a stellite overlay and tungsten carbide, respectively, and machined to nominal size according to the proposed design. Test flow across the assembly was set with a differential pressure of 410 psid. The combined clearance flow rate was 64 gpm implying a flow rate of 32 gpm to each side. The test pressure was scaled back from 1450 psid to match the expected pressure differential across the length of the test piece. These parameters match the expected operating conditions across the bushing assembly.

After 23.5 days of test, the central volute bushing with stellite hardfacing showed no signs of wear. The shaft sleeve inboard section showed significant wear with some debris adhering to the shaft assembly. The matted debris was located in the vicinity of the deeper shaft grooves. The inboard sleeve assembly configuration is not representative of the actual pump configuration. As such, wear rates on the inboard side were not considered in the overall wear rate analysis. The shaft sleeve outboard assembly wear was uniform and in the range of 100 mils. The outboard wear data was used for analysis of volute bushing wear rate. When extrapolated to 30 days post-LOCA operation, central volute bushing clearances would be expected to be approximately 3.2 times design. Leakage flow depends on plugging and the axial extent of abrasive wear. Total leakage flow increased from 64 gpm to 290 gpm. Flow across each side was conservatively assumed to be equal. In this case high flow would increase wear rates and decrease pump performance. Test data showed no significant decrease in pressure drop across the test assembly for the duration of the test.

The results confirmed the design adequacy of the hard-faced, fine-clearance components and their respective rotating assemblies. Test data showed that, while some wearing of the shaft sleeves did occur, the wear did not significantly alter the operating characteristics of the central volute bushing after 23.5 days of test. The data obtained is suitable to be used in extrapolating further wear predictions and for use in overall evaluation of pump operation. The test rig drive power was essentially unchanged for the duration of the test.

3.2.2.4 Hydrostatic Bearing Wear Rate Testing, Test Loop 3

The primary intent of the mock-up testing of the hydrostatic bearing assembly, Loop 3, was to confirm operation of the bearing (no plugging of the orifices or bearing pads) with debris-laden water. Acceptance for this test was no significant wear or plugging of the bearing after 21 days of continuous operation. The results of this portion of the test are discussed in report section 3.1.2.2. A secondary purpose of the Loop 3 test was to determine the wear rates of the bearing and shaft sleeve due to operation with debris-laden water.

The debris-laden water used for this test was the discharge from the strainer test, Loop 5. Discharge water from Loop 5 was routed to a separate tank, Tank 2. Test pumps took suction from Tank 2 and supplied the inlet orifices of a full scale hydrostatic bearing. The bearing fixture was a shaft and bearing of the same nominal dimensions of an HPI pump. Discharge from the bearing was routed back to Tank 2.

The supply pressure of 392 ± 40 psig was chosen to match the expected fifth stage pressure of the HPI pump when operating at 250 gpm. Measured test flow at the start of the test was 18.5 to 19 gpm at 400 psig. Flow and pressure drop were monitored for the duration of the test period. The test set-up closely modeled the expected initial and continuing operating conditions of an installed bearing.

The results of the continuous 21 day run showed debris on the raised bearing flats and in the bearing channels. There was also wear on the bearing surfaces due to flow induced erosion and wear from the entrained debris. When extrapolated to 30 days of post-LOCA operation, hydrostatic shaft sleeve clearances would be expected to be approximately 3 to 4.5 times design. There was no wear noted on the flow orifices and a small amount of wear on the bearing itself. After the initial debris loading of the bearing, flow and pressure drop remained constant, 15 to 16 gpm at 400 psig. A clean water test was performed at the end of 21 days. The clean water test flows were 19 to 19.5 gpm. The reduction in flow from dirty to clean test is the result of the debris found in the flow channels

Tests showed no wear or plugging of flow orifices.

Based on a review of the mock-up test results, Test Loop 3 confirmed the ability of the as-designed bearing to operate with no plugging of the orifices or bearing pads with debris-laden water that would preclude the bearing from performing its required functions. Test rig drive power was essentially unchanged for the duration of the test.

3.2.3 Licensee Analysis

The licensee developed a rotor dynamics model based on in-plant testing and measurements performed in May and June 2003. In-plant testing was performed for a new HPI pump and a spare HPI pump artificially worn to large clearances (twice the normal design, 2X). Detailed vibration data were acquired for both tests (in addition to demonstrating that the pumps operated satisfactorily).

The results of mock-up wear testing were used to predict the increases in the fine clearances during pump operation with debris-laden water. Wear rates at 0, 10, 20, 30 , and 40 days were determined. The resulting clearances of the wear rings, bushings and bearing ranged from 1.2 to 4.5 times design after 40 days of operation.

A pump bearing stiffness analyses was performed to demonstrate that the HPI pump would operate satisfactorily, without excessive vibration, over the full range of pump flows considering the new bearing design and the predicted increase in fine clearances. No credit for suction wear ring support or stiffness was assumed. Maximum bending was assumed at the pump hydrostatic bearing end. Evaluation of operation at intermediate and maximum clearances showed no evidence of operation near critical speeds. Analysis show that even with maximum wear assumed, the pump operation would remain stable. Licensee analysis shows that pump operation with the fine clearances opened to as much as four and a half times the normal design clearances will not detrimentally affect pump operation, hydrostatic bearing load carrying capability. Pump stiffness does not change appreciably and vibration levels would be acceptably low.

The licensee performed a Failure Modes and Effects Analysis (FMEA) to assess the potential and effects of failure or mis-application of hard facing material. The FMEA identifies the design controls to preclude such failures.

Hard faced parts equivalency evaluations were performed by the licensee. Form, fit and function were addressed. Hard facing contains a small amount of cobalt which may be added to the system as a result of hard face wear. However, at the point in time during a postulated accident when the cobalt is introduced, the amount of cobalt released and its potential for activization as it passes through the reactor coolant system was determined to be minimal. The selected hard face materials are industry proven wear couples and have performed satisfactorily in similar fluid environments.

3.2.4 Evaluation

The staff reviewed the licensee's analyses and finds it to be reasonable and technically complete. The analyses adequately modeled the test results, assessed component condition, and confirmed the acceptability of the design changes to the HPI pumps.

The Davis Besse HPI pump shaft is a flexible shaft. Pumps with rigid shafts typically operate below the pump 1st critical speed, while pumps with flexible shafts generally operate above the 1st critical speed. Pumps that operate at speeds greater than 3600 revolutions per minute (rpm) and multistage pumps are usually flexible. The Davis Besse pumps are 11-stage design and operate at 3550 rpm. There is the potential for the 1st critical and normal operating speed to converge as clearances increase. Should this occur, pump vibration and pump inter-stage leakage will increase. This would be a long-term effect. Pump in-plant testing and analysis confirm that at the point where the potential for convergence increases, the HPI pumps would be well beyond their stated mission time of 30 days.

The Stellite 6 to Stellite 12, Stellite 6 to LW5, and Stellite 6 to chrome wear couples have demonstrated reliable performance in safety-related equipment (i.e., pumps, valves, etc.) in similar environments. The materials have good corrosion resistance in borated water solutions and are appropriate materials for this application.

The Davis Besse HPI pumps operate in 2-9 configuration. The thrust bearing is on the motor end, opposite to the hydrostatic bearing. Axial thrust is balanced across the pump stages 1 and 2, the central volute bushing and pump stages 3 thru 11 and the hydrostatic bearing. In-plant testing and analysis assume uniform wear along a pump shaft thus producing no significant change to axial thrust. The staff finds this assumption and conclusion to be reasonable.

Fluid bearings such as the Davis Besse hydrostatic bearing are a primary source of damping and can inhibit excessive vibration. In-plant testing confirmed this assumption. The licensee conservatively did not credit the vibration dampening and load carrying capacity of the wear rings. The wear rings would also provide additional margin against increased vibrations as a pump becomes less stable due to close clearance wear. The staff finds the licensee's approach used in its vibration analysis and evaluation to be reasonable and conservative.

The licensee tested and recorded wear data for a minimum of 20 days for each critical component. Data were then evaluated, and wear rates were extrapolated to 40 days. In general, stationary components exhibited little to no wear. The rotating parts experienced the bulk of the wear. Licensee specifications require a minimum of 30 mils hardface on all rotating wear surfaces. Field testing and analysis confirm that this minimum thickness is adequate for a pump mission time of greater than 30 days.

The licensee's Failure Modes and Effects Analysis (FMEA) was reviewed. The FMEA did not discuss discharge wear ring failure mechanisms or the implication of a postulated failure of the discharge wear ring. After 21 days of test, the stellited, discharge wear ring showed no signs of wear and the impeller hub showed general wear in the range of 10 to 15 mils. A groove extending through the hard facing to the base metal did form on the hub downstream section. This groove was postulated to form due to an accumulation of debris. This mat of debris formed a continuous abrasive surface that wore through the hard facing. If the groove had penetrated to the shaft, the disengaged 'ring' of wear ring would provide a larger flow bypass path but would not become a loose part or an internal missile causing the pump to become inoperable. The disengaged ring would merely spin in place. The licensee's analysis did take credit for any support or dampening function of the ring. The staff concurs that the FMEA does address all other internal failure modes.

Post modification, pre-service testing in accordance with the ASME OM Code showed the as-modified pumps to be operating within established industry guidelines. Baseline testing showed the as-modified pumps to be operating smoothly over the entire range of pressure and flow. The results compare favorably with results predicted from the rotor dynamic analysis.

3.2.5 Conclusion

The staff concludes that licensee's design, analysis and testing demonstrate that fine clearance components in the HPI pump, such as wear ring and shaft sleeves, may experience wear while operating with debris-laden water during plant recirculation. To minimize this effect, the proposed hard facing of pump critical components reduces the predicted wear such that operations near pump critical speed is not adversely affected. The modifications to the fine clearance components provide reasonable assurance that these critical components will not fail due to excessive abrasive wear or flow-induced erosion. The testing of the as-modified pumps in accordance with the ASME OM Code provides baseline data and a reasonable basis for analysis assumptions. Future monitoring and testing in accordance with the ASME OM Code will provide assurance that the HPI can operate as required when called upon under design basis conditions.

3.3 Concern 3 - Reduced Hydraulic Performance

Fine clearance components such as wear ring and shaft sleeves can experience accelerated wear while operating with debris-laden water during plant recirculation and may adversely affect HPI pump hydraulic performance.

With the new bearing system strainer design, there is the potential for the strainer 50 mil openings to elongate during debris operation. The wider opening of the strainer holes could allow larger debris than assumed to enter the bearing system.

During LTR the LPI system takes suction directly from the containment sump. Fluid then passes through the LPI pumps and decay heat exchangers to the suction of the HPI pumps. Fluid then passes through the 11-stage pump prior to being re-injected into the RCS. The HPI pump has a hydrostatic bearing of a 'pocket' design and operates on process flow supplied from the 4th stage pump volute. Flow to the bearing ranges from 11 to 20 gpm depending on operating conditions and is distributed circumferentially via five flow orifices with 0.109 inch diameter openings. Bearing/shaft sleeve clearances are a nominal 0.006 to 0.010 inch radially. Bypass flow also occurs between stage via leakage past the wear rings. Interstage wear ring flows may range from 25 to 50 gpm depending on suction or discharge side and on actual clearances. Wear ring clearances are nominally 0.009 to 0.010 inches and the central volute bushing clearance is nominally 0.006 to 0.007 inches. The listed components are either stainless steel or bronze and susceptible to hard particle erosion and abrasive wear as may be contained in post-LOCA sump fluid.

3.3.1 Licensee Modifications to address Concern 3

The components with wear surfaces were replaced with new components with hardfaced surfaces to minimize wear during debris operation. Specifically, the suction wear rings, discharge wear rings, hydrostatic bearing and shaft sleeve, and central volute bushing and shaft sleeve were hardfaced and reinstalled. The new components are of the same size, shape and tolerances of the original manufactured parts. The volute strainer, designed to reduce debris intrusion into the hydrostatic bearing is Haynes Alloy 25 (cobalt alloy). The following chart summarizes the material modifications.

Part	Original Material	New Material
Wear Rings	ASTM A461-630 Con H 1150 (stainless steel)	Inconel Alloy 600 (UNS N06600) with Stellite 6 on ID
Central Volute Bushing	ASTM A461-630 Con H 1150 (stainless steel)	Inconel Alloy 600 (UNS N06600) with Stellite 6 on ID
Central Volute Bushing Sleeve	ASTM B143 Alloy 903 (bronze)	Inconel Alloy 600 (UNS N06600) with Stellite 12 on OD
Hydrostatic Bearing	ASTM A314 Gr 341 (stainless steel)	Inconel Alloy 600 (UNS N06600) with Stellite 6 on ID
Hydrostatic Bearing Sleeve	ASTM B103 Gr D (bronze)	Inconel Alloy 600 (UNS N06600) with Stellite 12 on OD
Volute Strainer	na	Haynes Alloy 25 (cobalt alloy)

In order to compensate for expected wear and clearances in the hydrostatic bearing to sleeve, the hydrostatic bearing pocket design was modified to increase the bearing stiffness. The hydrostatic bearing pocket was re-designed from a rectangular arc pocket to a “Figure 8" pocket design. “Escape" grooves were added to the hydrostatic bearing pockets to allow debris larger than the bearing clearance to leave the pockets. The modified hydrostatic bearing was designed with a stiffness comparable to the existing bearing. Required fluid flow rates to maintain bearing function were not changed.

3.3.2 Licensee’s Testing to Confirm Design Adequacy

In-plant testing was performed in May and June 2003 on a new HPI pump and a spare HPI pump artificially worn to large clearances (twice the normal design). Pump hydraulic performance data was acquired for both tests. Results of the tests showed that vibration levels remained fairly constant with some imbalance at upper end operation near design operating point and run out conditions (high flow, low head). Hydraulic performance did decrease by about 8% when close clearances were worn to the 2X level.

Mock-up testing at Wyle Laboratories monitored flow and DP and analyzed performance as a function of wear rate. The Test Loops 1, 2, 4, and 5 were performed in parallel, all taking suction from a common test tank, Test Tank 1.

Test Loop 1, evaluated the suction wear ring. Test results showed a small nominal increase in suction wear ring bypass flow, approximately 95 to 110 gpm. Since clearance wear at 40 days is only expected to be 1.2X, this small increase was expected.

The second test, Loop 2, evaluated the discharge wear ring. Test results showed a bypass flow increase from approximately 27 to 41 gpm. The nominal clearance increase for a discharge wear ring is 2.8X after 40 days, therefore this flow is reasonable as compared to the inlet wear ring.

Test Loop 4 evaluated the central volute bushing. Test results showed a dramatic increase in bypass flow from approximately 64 gpm to 290 gpm as clearances opened up. The central volute bushing has the highest differential pressure with a resulting 3.2X final nominal clearance.

Test Loop 5 tested the volute strainer. Flow and differential pressure through the strainer did not vary appreciable during the course of the testing.

Test Loop 3 evaluated as designed bearing and took suction from Test Tank 2. Test Tank 2 contained the discharge from the strainer tests, Test Loop 3. Bearing flow over the course of the testing dropped from a nominal 19 gpm to 15 gpm, primarily due to accumulation of debris in bearing flow passages. Debris accumulation is addressed elsewhere in this report.

Test results over the span of 21 days, confirmed that bypass flow will increase as close clearance wear increases. The test results were incorporated into the analytical flow and wear models.

Testing was also performed post-modification in accordance with the ASME OM Code to confirm as-modified performance and to provide a basis for future evaluation.

3.3.3 Licensee Analysis

The licensee performed a series of analyses to determine required HPI system performance at different stages following a postulated LOCA and subsequent long-term cooling. A required performance curve was then generated and used to evaluate HPI pump and system performance.

Licensee analysis shows that an HPI pump must initially be capable of delivering 263 gpm at 2413 feet TDH to prevent boron precipitation following a postulated LOCA at the cold leg pump discharge. The flow requirement drops to 172 gpm at 1167 feet TDH after 1 day, 95 gpm at 520 feet TDH after 10 days and 74 gpm at 410 feet TDH after 30 days. These conditions constitute the limiting basis for acceptable performance of an HPI pump under post-LOCA, long-term recirculation operation with debris-laden water.

To determine if HPI pump hydraulic performance could meet the required conditions, the mock-up test results were tabulated and analyzed to predict hydraulic performance. Wear rates were calculated, evaluated and extrapolated to predict wear at 10, 20, 30 and 40 days. Bypass flow and overall pump hydraulic performance was evaluated based upon the predicted wear. Finally predicted pump performance was compared to the HPI system hydraulic requirements.

Hydraulic analyses demonstrated that considerable hydraulic margin exists for the modified pumps throughout the range and duration of required operation.

3.3.4 Evaluation

The staff reviewed licensee hydraulic assumptions, analysis and testing. Overall, the staff finds the methods and approach used by the licensee in evaluating pump performance and operation are reasonable and conservative.

Pre-modification, in-plant testing showed an 8% decrease in hydraulic performance when fine clearances were at 2X standard tolerance. Results of the tests showed that vibration levels remained fairly constant with some imbalance at upper end operation. Based on mock-up testing, predicted wear will be approximately 3.2X after 30 days. Hydraulic performance would also be expected to decrease past 8% as wear increases. The Davis-Besse pumps have been demonstrated to operate well in excess of 900 gpm. The required flow at the start of long-term recirculation is 263 gpm. At the start of LTR, no hydraulic degradation due to wear is assumed as operation up to this point would have been with ‘clean’ water supplied from the BWST. The 900 gpm available versus the 263 gpm required at the start of LTR and the 74 gpm required after 30 days operation provides ample margin even considering worst case pump degradation.

Flow through the HPI system is set and monitored by plant equipment operators utilizing Emergency Operating procedures. As the debris-laden water wears internal components, increasing fine clearances, bypass flow will increase reducing pump performance. If operator needs to maintain system pressure or flow, discharge valves may be throttled in accordance with plant operating procedure. As designed, the HPI system will ride the system resistance curve (with no system adjustment, flow and pressure will drop) and maintain system flow and temperature without a considerable amount of operator action. As the event progresses, less HPI flow is needed and pump operating margin will increase even with increased bypass flow. Based upon a review of system requirements and pump performance, there is ample margin assuming worst-case degraded pump performance.

Testing was also performed post-modification in accordance with the ASME OM Code to confirm as-modified performance and to provide a basis for future evaluation. This testing did show the pumps to be operating less efficiently than pre-modification. The licensee identified that these differences affected maximum peak clad temperature in other LOCA scenarios, however the difference did not effect the assumptions in the analysis supporting operation with debris-laden fluid. The licensee had adequately incorporated these changes into plant calculations, specifications and other controlled documents.

3.3.5 Conclusion

The staff concludes that licensee’s design, analysis and testing provide reasonable assurance that the HPI pump will be able to perform its safety function under design basis conditions and that the hydraulic performance of the HPI pump will be maintained even with wear of the fine clearance components such as wear ring and shaft sleeves while operating with debris-laden water during plant recirculation. The proposed hard facing of pump critical components reduces the predicted wear such that hydraulic capability is not adversely affected. The design modifications were found to meet design requirements and the testing provides reasonable assurance that critical components will not fail due to excessive abrasive wear or flow induced erosion.

In-plant, post-modification, pre-service testing performed in accordance with the ASME OM Code provides assurance of the pumps operational readiness and that any hydraulic degradation will be identified and monitored.

3.4 Debris and Debris Generation following a LOCA

During sump recirculation operation, post LOCA, the HPI system is operated in a piggy-back mode with HPI pump suction through discharge of the LPI pumps. Sump water may contain debris from LOCA Blowdown and Containment Spray actuation. With regard to debris generation and HPI pump operation, SBLOCA operating conditions are the most challenging, but result in minimal debris in the process fluid. A LBLOCA is the most challenging debris generation scenario. However, following a LBLOCA, HPI is only used in BWST operation and is not credited for long-term cooling. Therefore, the HPI pump is not subjected to debris-laden sump water.

LBLOCA debris generation along with long-term cooling (boron precipitation control) combines worst case debris generation with long-term low flow, high head HPI pump operation.

This review evaluates the effectiveness of the “engineered debris” used to simulate expected sump debris in the HPI pump mock-up testing. It was determined by the licensee that the utilization of actual containment debris would be impractical. The licensee therefore performed a study which determined the characteristics of containment debris that would be expected to be generated by a LOCA and be available for transport to the HPI pump. This debris would necessarily bypass the containment sump screen in order to enter the HPI pump.
The licensee’s debris characterization for HPI modification testing is based on a postulated large break LOCA which generates the largest quantity of debris. The HPI pumps’ primary ECCS function is to provide core cooling for small break LOCAs. However, HPI pump #2 is required to provide long-term cooling flow to support boron precipitation control. This long-term cooling function is required following large break LOCAs as well as small break LOCAs.

3.4.1 Technical Evaluation

The licensee utilized a multi-step process to determine the appropriate debris to use for the mock-up testing. The licensee’s approach involved the following steps: The first step involved “debris generation.” This entailed determining the various types and bulk quantities of debris that would exist in a post-LOCA containment environment and have the potential to be transported to the containment sump. The second step involved “debris transport.” In this step the licensee determined the fraction of available debris, determined in the first step, that would be transported to the containment emergency sump during recirculation operation. The third step evaluated the “debris critical characteristics.” In this step the critical characteristics of each LOCA-generated debris type were established, e.g., particle sizes, quantities, types of material, material properties, etc., to define the selected characteristics to be simulated by the engineered debris. The fourth step involved selecting the representative debris for testing from commercially available materials.

The licensee performed the above four steps within three calculations prepared specifically for this analysis. Previous debris generation and transport analyses were done to support the new sump strainer design. Some aspects of this previous analysis were used as input to this analysis as well as results from NRC sponsored research and additional calculations. This review evaluates each of the four steps described above as well as the suitability of the previous analyses as input to this analysis.

3.4.1.1 Debris Generation

The licensee considered four sources of debris, they are: LOCA-generated or short term debris, LOCA exposure-generated or long-term debris, operational debris, and miscellaneous debris. Short term debris is generated in the vicinity of or “zone of influence” (ZOI) of a high energy pipe break due to jet impingement forces. This debris typically consists of insulating materials from piping, qualified or unqualified coatings, and eroded concrete. Long-term debris is generated hours to days after the initial pipe break due to the harsh environment within containment. In addition to jet impingement from the pipe break acting to dislodge material in the ZOI, it is postulated that containment spray water would impinge on a significant fraction of the surfaces within containment. Any latent debris on these surfaces could be transported to the floor. The licensee included in this debris source dirt, dust, corrosion products, and unqualified coatings. Also, the licensee considered the potential for the acidity in the borated water to create additional debris in the form of corrosion products from contact with uncoated metallic surfaces. Operational debris such as dirt, dust, and other known potential sources of debris were considered to be a form of long-term debris and treated as such. Miscellaneous debris was included by the licensee to account for materials that could be left in containment after an outage. The licensee assumed all miscellaneous debris to be in the form of small transportable fibers because preliminary pump testing indicated that the HPI pumps are most sensitive to this type of debris.

To then “characterize” the types and quantities of debris discussed above, the licensee prepared calculation no. 200-0060-00-01 titled “Post-LOCA Containment Debris Characterization for HPI Pump Test.” The calculation focuses on identifying the characteristics of debris that is generated by a LOCA and deposited in the pool on the containment floor. The licensee incorporated substantial conservatism in the calculation in order to account for inherent uncertainties. For example, where there was uncertainty as to debris sizes, the size distribution was biased toward sizes that can penetrate the sump strainers to maximize the impact on the HPI pumps. The following types of debris, established by field walk-down, were considered: fiber, qualified and unqualified coatings, concrete particles, rust, dirt and dust. The staff reviewed calculation no. 200-0060-00-01 to determine that the characteristics of the various debris types were adequately represented and that appropriate conservatism was introduced to account for uncertainties or impracticalities inherent in modeling actual containment debris with engineered debris. The calculation showed that the maximum quantity of debris is generated during a large break loss of coolant accident (LBLOCA).

The characteristics of containment debris which are being modeled by the engineered debris present two degradation modes for the HPI pumps. They are wear of critical pump surfaces by erosion or abrasion and plugging of pump internal strainers and hydrostatic bearing orifices and pockets. An excerpt from MPR-2578, “Davis-Besse HPI Pump Post-LOCA Debris Operation Issue Resolution Mock-Up Testing Debris Summary” which summarizes the approach taken and results of the analysis describes the degradation mechanisms involved as follows: “Hard particles that are ingested into the pump have the potential to wear the close clearances in the pump (hydrostatic bearing, central volute bushing, and wear rings). These clearances typically range from approximately 6 mils up to 10 mils radially. Hard particles with sizes similar to the clearances are most detrimental to pump performance from a wear perspective. These particles can become lodged in close clearances and abrade the surfaces of pump components. Size distributions for soft debris, such as insulation fibers and coatings were developed to increase their potential to block internal pump strainer openings.” The licensee developed the conservatism in calculation no. 200-0060-00-01 based on these wear considerations.

The staff reviewed the approach taken in calculation no. 200-0060-00-01, as well as the assumptions and conservatism that were applied and found them to be appropriate. The calculation was based in part on previously completed analyses of boiling water reactor (BWR) and pressurized water reactor (PWR) emergency core cooling system (ECCS) and containment sump strainer issues, and plant-specific calculations for Davis-Besse. The licensee reviewed the available literature for data on particle sizes from LOCA blowdown testing that generated debris. Based on this review, conservative particle size distributions were established. The staff reviewed the size distribution and found it to be conservative because it biased the number of smaller particles much higher relative to larger debris. This is conservative because particles similar in size to the hydrostatic bearing and wear ring clearances in the pumps will tend to cause the most wear because they are just able to “fit” into these clearances. Conservative assumptions incorporated into the calculation include:

1. No credit was taken for “thin bed effect.” That is, although fibrous debris has the potential to foul the containment sump strainers and filter out particles much smaller than the strainer openings, no credit was taken for this phenomenon. All debris smaller than the strainer openings is assumed to pass through the strainer.

2. Shorter fibers are expected to have a greater potential for damaging the HPI pump. Therefore, longer fibrous debris is assumed to become trapped at the strainer. The calculation biased the fiber size distribution toward shorter fibers that would fit through the sump screen openings (0.188 in.). All fiber material was included by mass.

3. The size ranges of other debris such as rust particles, coating particles, and chips were also biased toward those sizes that are most challenging to the HPI pumps.

4. Concrete, dirt, and dust particles were assumed to combine. The percentage by weight of concrete particles was biased high to present more of a challenge to the pump (concrete particles are harder than dirt and dust particles).

5. Fifty percent of the fibrous insulation damaged in the ZOI is transportable. This is conservative compared to 40% cited in NUREG/CR-6762, Vol 4, “GSI-191 Technical Assessment: Development of Debris Transport Fractions in Support of the Parametric Evaluation,” August 2002. This, combined with assumption no. 1 presents substantial conservatism with regard to fiber quantity.

6. All miscellaneous fibers assumed to exist within containment are assumed to be transported to and through the containment sump strainers.

The staff found that the data from the cited references was appropriate as utilized and that the assumptions made were reasonably based on engineering judgement and increased the overall conservatism of the calculation.

3.4.1.2 Debris Transport

As a sequential step in the process of defining the debris to be used for the HPI pump tests the licensee prepared calculation no. 0200-0060-00-03, “Evaluation of Debris Transport to Containment Sump for Refinement of Debris Source for HPI Pump Testing.” This calculation utilized results from calculation 200-0060-00-01, “Post-LOCA Containment Debris Characterization for HPI Pump Test,” discussed above to determine the “transport fraction” of debris from the water pool on the containment floor to the containment sump for small and large break LOCAs. That is, it predicts the portion of available debris that would be transported to the sump, bypass the sump screen, and be introduced into the HPI pump process fluid. The staff reviewed calculation no. 0200-0060-00-03 to verify methodology and that appropriate conservatism was utilized.

For the transport of coating flakes the licensee referenced a calculation done previously to support the new sump strainer design. This is Davis-Besse Calculation No. C-NSA-049.02-028, “Davis-Besse Debris Transport Logic Trees for Emergency Sump Strainer Loadings.” This calculation utilized a computerized fluid dynamics model to predict transport fractions of coating flakes. The staff reviewed this calculation and determined that the approach taken was valid and that the assumptions made therein were appropriately utilized such that the fraction of coating flakes predicted to be transported to the sump was conservative.

For coating particles, dirt and dust, fiber, and rust, the licensee made the conservative assumption that all of this material that enters the pool at the bottom of the containment is transported to the containment sump. This assumption was made for both small and large break LOCA. This assumption is conservative because some of this debris would likely remain in inactive regions of the containment pool.

The staff reviewed the licensee’s method and assumptions used to predict the transport fraction of concrete particles to the containment sump. A description of the method used is as follows: After a LOCA, the debris from the concrete wall adjacent to the postulated break is transported throughout the lower part of containment by the water that collects in the lower containment. The calculation assumes this debris to be in the form of sand particles and that all of the sand is deposited on the concrete floor at the 565 foot elevation. This is the floor just above the elevation of the upper strainer for the containment sump. The calculation then made the conservative assumption that all of the water drawn by the sump is drawn from the 565 foot elevation, i.e., where all of the sand is assumed to be deposited. The calculation determines the critical velocity at which sand on the containment floor is entrained or transported. An idealized mathematical model was used to represent the containment as a function of the radial distance from the sump. The staff determined that assumptions used in the calculation conservatively accounted for the idealized nature of the method used. For example, the idealized flow field does not explicitly account for walls and equipment bays that redirect and channel flow on its way to the sump. However, the magnitude of the fluid velocity toward the sump, calculated with the idealized approach, was multiplied by a factor of 2 to account for the local velocity increases that result from flow obstructions. The factor is based on engineering judgement. The staff agrees that it is valid and conservative because it is applied to the flow of water across the entire containment floor.

The idealized flow field and the critical velocity are then used to determine the radial distance from the sump at which the transport of sand begins. It is then assumed that all sand inside of the “critical radius” is transported to the sump. This method is applied to particles of different sizes by calculating a specific critical radius for each particle size considered. All particles of that size inside that radius are assumed to be swept into the sump. The range of particle size, determined in calculation 200-0060-00-01 above is from 1 to 31 mils (thousandths of an inch). The licensee determined that small break LOCA transport values are bounded by large break transport values. Another conservative assumption applied in the calculation is the height of standing water in containment from the break. The height is a factor that is utilized to calculate flow velocity. It was conservatively assumed that a portion of reactor coolant does not spill onto the containment floor. This amount, if used, would effectively increase the water level by approximately 1 foot which would reduce the calculated water velocity by 35 percent. This in turn would reduce the amount of particles transported to the sump. The staff agrees that this is another assumption that contributes to the overall degree of conservatism and validity of the calculation. The staff reviewed other assumptions utilized in the calculation and found them also to contribute to the conservative nature of the calculation.

The staff concluded that calculation no. 0200-0060-00-03, for transport fraction of debris, is valid and conservative.

3.4.1.3 Debris Characteristics

A third step the licensee employed in the process of defining the debris to be utilized in the HPI pump testing was performed by calculation no. 0200-0060-00-06, “HPI Pump Test Characteristics.” This calculation utilizes the results of calculation nos. 200-0060-00-01 for debris generation and 0200-0060-00-03 for debris transport, discussed above, to “characterize” the debris by further defining debris size ranges, defining densities, thickness, hardness, etc. This calculation then identifies the “critical parameters” for each debris type among those mentioned above. Critical parameters are defined in the calculation as the characteristics of the debris particles that have the potential to affect operation of the HPI pumps. These parameters are identified so that commercial materials can be selected for use as engineered debris in the HPI pump mock-up tests that will closely simulate the wear characteristics of the actual (LOCA-generated) debris they represent. The debris size distributions for the HPI pump tests are established in this calculation by considering the transportable debris distributions (established in calculation no. 0200-0060-00-03) and the debris critical parameters.

The staff reviewed calculation no. 0200-0060-00-06, again, to determine that appropriate assumptions and conservatism were utilized. In defining debris characteristics, the calculation considers the damage modes of the pumps and matches the characteristics of actual containment debris with the engineered debris that is intended to simulate it in the HPI pump testing. A damage mode denotes what detrimental effect debris may have on the HPI pumps. The three damage modes considered in the calculation for LOCA-generated debris are: plugging or blockage, abrasive wear, and erosive wear. The HPI pump design utilizes strainers which would block flow if they became plugged with debris. Abrasive wear occurs when debris becomes compressed between two surfaces. Erosive wear occurs when debris particles impinge on the surfaces of the HPI pumps. Critical parameters were defined based on these wear characteristics.

The fourth step in the analysis, performed also in calculation no. 0200-0060-00-06, was to select commercially available materials that would simulate the critical parameters of the LOCA-generated debris in the mock-up tests. A tolerance for acceptance of commercially available materials was applied to the critical parameters established by the calculation to account for variations in material properties. The staff reviewed these tolerances and concluded that they are reasonable and acceptable for the applied purpose. The licensee established formal receipt inspection procedures to verify that the commercial materials received for use in the mock-up tests are within the established tolerances. The staff reviewed “Debris Receipt Inspection Procedure” no. 0200-0060-00-10, rev. 3 and found it to be comprehensive. Examples of receipt inspection procedures are as follows: Fiber size is verified by inspection under a laboratory optical microscope. Particle sizes are verified by sieving through sieves of known dimension. Densities are verified by calculation based on weight and volumetric displacement of water. Material hardness is verified by chemical analysis and comparison to known hardness properties. Debris samples have been archived by the licensee per the receipt inspection procedure if, for any reason, additional testing is warranted in the future.

The critical parameters arrived at in calculation no. 0200-0060-00-06 for each engineered debris type that are necessary to adequately model actual containment debris, by the potentially detrimental effect each type might have on the HPI pumps if ingested, are as follows: For fiber fragments, critical fiber length, diameter, and density were established. The critical parameters needed to model the abrasive behavior of concrete debris were determined to be hardness and density. Size ranges were also specified to simulate expected sizes of LOCA-generated concrete particles although this is not a “critical parameter” as defined for material selection. For rust particles the size and hardness were determined to be critical parameters. For conservatism the licensee increased the size of the simulated rust particles such that an increased amount of wear would be expected. Modeling accuracy was introduced by specifying that the simulated rust particles must have a hardness and density comparable to iron oxide. Dirt and dust particles were determined in calculation no. 200-0060-00-01 to be similar in size to rust particles as well as their damage mode (erosive wear). The licensee accounted for the influence of dirt and dust particles by increasing the quantity of simulated rust particles with critical parameters as discussed above. The staff concurs with this practical approach for simulating dirt and dust. The damage mode of coatings is the potential blockage of the pump strainer openings. The critical parameter for coatings is therefore size. Size ranges were determined for coating particles and coating flakes. Also, in order to accurately simulate actual coating particles and flakes, the licensee applied a requirement on the density of the polymeric material used to simulate actual coating material.

The materials arrived at by the licensee to utilize in the mock-up HPI pump testing intended to simulate the wear or plugging characteristics of actual containment debris are: for fiber fragments chopped glass strands are substituted in sizes with a tolerance that ensures that of the critical parameter size. Critical density is ensured by receipt inspection. For concrete, silica particles (sand) are used in the appropriate size range determined by the above calculations. Critical parameters are verified in a test laboratory upon receipt of the material. Magnetite is used to simulate rust, dirt, and dust. Again, the test lab is required to verify the critical parameters of chemical composition for hardness, density, and size. Small grains of plastic abrasive sized to the predetermined specifications will be used to simulate small coating particles. Thin plastic discs and chopped plastic coatings are used to simulate coating flakes with appropriate tolerances and lab testing to verify critical parameters upon receipt of the material. Calculation no. 0200-0060-00-06 also determined the LOCA-generated debris concentration in the containment pool in terms of pounds of debris per pound of water for use in the mock-up tests. The staff concluded that calculation no. 0200-0060-00-06, for debris characterization, utilized appropriate assumptions and conservatism.

Other considerations related to the use of engineered debris are borated water effects and temperature effects. Boric acid which would be present in the water pool on the containment floor was not modeled in the mock-up tests. The licensee stated that this was due to personnel safety concerns and corrosion of the test loop materials that would occur. The licensee presented reasoning which validates the use of neutral water in lieu of borated water, examples include: the effect on fibers immersed in borated water is similar to that of neutral water, that is, the coating applied to glass fibers during manufacture will dissolve at a similar rate in either acidic or neutral water leaving uncoated glass fibers, neutral water will have a minimal effect of leaching of inorganic elements from the glass fibers, decreasing the tensile strength of the fibers, but not significantly enough to effect the testing, borated water would act to degrade some of the coating debris in a post-LOCA environment therefore the use of neutral water in the mock-up tests is conservative in this respect, there would be no effect on of the use of neutral water on the simulated rust or concrete particles. For these reasons the staff concurs in the use of neutral water for the mock-up tests. Also, temperature and fiber aging effects were considered by the licensee. Fibers inside containment may be weakened due to years of exposure to high temperatures. The use of new materials is conservative in this respect because they would not have undergone the weakening caused by aging. The staff also concurs in this assessment.

3.4.2 Conclusion

The staff concludes that the approach taken by the licensee in the above calculations for debris generation, transport, and characterization was a valid approach. The staff further concludes that reasonable assumptions based on engineering judgement and appropriate conservatism was utilized where necessary to account for inherent uncertainties in the prediction of debris generation or impracticalities associated with modeling actual containment debris. The staff therefore concurs in the use of the materials discussed above as practical substitutes for actual containment debris in the Davis Besse HPI pump mock-up tests.

3.5 Mock-up Testing

The licensee performed mock-up testing of pump components, utilizing an “engineered” slurry of debris similar to that expected during a LOCA. The testing identified that fibrous debris can accumulate, forming a mat in critical areas within the pump such as within the hydrostatic bearing pads, serve to collect harder debris particles, potentially causing significant wear, loss of bearing cooling, or early pump failure. While the Davis Besse HPI pumps are unique to U.S. nuclear power plants, in that they utilize a hydrostatic bearing that receives lubrication from the pumped water via internal ports and tubing, the testing also identified that small, hard debris can result in significant damage to other pump components with critical clearances such as wear rings, shafts, and bushings.

The objectives of the mock-up testing were to:

(1) confirm that the proposed modifications to the HPI Pumps will accomplish the intended function of preventing potentially damaging debris from reaching the hydrostatic bearing, and

(2) determine the wear rates for the HPI pump fine clearances when pumping debris-laden water. This information was to be used in analysis and evaluations of pump operating characteristics and hydraulic performance.

In support of these objectives five separate test loops were assembled. The test loops modeled a specific critical pump component. This method enabled the licensee to vary component design to determine an optimal solution to the aforementioned concerns.

The five test loops are as follows:
Test Loop 1 - Suction Wear Ring Test
Test Loop 2 - Discharge Wear Ring Test
Test Loop 3 - Hydrostatic Bearing Test
Test Loop 4 - Central Volute Bushing Test
Test Loop 5 - Volute Strainer Test

The test loops were operated at approximately 130°F for 21 days minimum. Testing was stopped after 2 days, 6 days and 13 days respectively to take measurements of critical component parameters. The intent was to generate data such that component degradation could be extrapolated for longer terms of operation.

The length of test and operating time was reasonable to adequately extrapolate and predict future trends. The Davis-Besse UFSAR notes that during Long-term Recirculation (LTR), the recirculation fluid has an operating range of 120 °F to 240°F. The operating mission time of the HPI pumps are expected to be 30 days. The three data points and a 21 day test time provide reasonable data to extrapolate to 30 days. In the analysis, the licensee extrapolated to 40 days

Debris handling and loading procedures were prepared by the licensee and reviewed by NRR staff. The procedures addressed initial loading, sampling and re-loading of the debris as well as a means to monitor and control debris concentration and fluid temperature. The licensee prepared a report on debris hideout, test fluid concentration and variation and other test system variables. The report was reviewed by the staff and found to adequately address test conditions.

Tests were run simulating a 250 gpm HPI pump flow rate. This flow rate is the post-LOCA, LTR flow rate specified in plant operating procedures and is therefore a reasonable test point. The test fluid was a conservative debris mixture and is evaluated in section 3.4

There were limitations on the mock-up testing such that the test did not fully represent HPI pump and system operation. For example, discharge from the wear ring and volute bushing were not modeled. Testing configuration was a single stage pump. The HPI pump is multiple stage. The licensee performed engineering evaluations to address these differences and to demonstrate that the mock-up testing fixtures were suitably representative of the HPI pump critical characteristics. The staff review found the evaluations to be thorough and reasonable. A review of the individual test loops is as follows:

3.5.1 Test Loops

Test Loop 1 - Suction Wear Ring Test - The licensee's stated objective was to obtain component specific wear rate data and hydraulic data to validate's analysis and confirm design. A review was performed of the critical characteristics. This test was a full scale mock-up. The only difference is a 'solid' impeller was used versus an actual impeller. The flow fields are similar and were validated by CFD analysis. Differential pressure and exit flow were monitored and trended. This mock-up accurately represented a suction wear ring in service.

Test Loop 2 - Discharge wear ring test fixture - The licensee stated objective was to obtain component specific wear rate data and hydraulic data to validate analysis and confirm design. A review was performed of the critical characteristics. This test was a full scale mock-up. The only difference is a 'solid' impeller was used versus a real impeller. The flow fields are similar and were validated by CFD analysis. Differential pressure and exit flow were monitored and trended. This mock-up accurately represented a discharge wear ring in service.

Test Loop 3 - Hydrostatic bearing test fixture - The licensee stated objective was to obtain component specific wear rate data and hydraulic data to validate analysis and confirm design and also to confirm that the bearing pockets would not adversely plug with debris. The test used a full scale bearing of same material and design as the modified bearing. Loading conditions i.e. weight, forces etc were not modeled. Fluid operating parameters were modeled after operating conditions at 250 gpm pump flow. Bearing flow and pressure drop were monitored and trended. This mock-up accurately represented a hydrostatic bearing in service.

Test Loop 4 - Central Volute Bushing - The licensee stated objective was to obtain component specific wear rate data and hydraulic data to validate analysis and confirm design. The mock-up test was 1/4 scale length and full scale diametral. The inboard clearances were 2 to 4 times actual and were thus determined to be not representative. The outboard clearances were 1 to 2 times actual pump clearance dimensions and were used in the wear rate prediction models. A 'solid' impeller was used versus a real impeller. The flow fields were modeled by CFD analysis. This analysis formed the basis for determination of test configuration versus actual pump. Pressure drop is proportional to length and was therefore assumed to be 1/4 of the design operating differential pressure. This assumption is reasonable for purposes of this test. Differential pressure and exit flow were monitored and trended. Initial exit flow was representative. Final exit flow was assumed in the hydraulic analysis to be split between the inboard and outboard sides of the test rig. This model is valid to predict full scale wear predictions.

Test Loop 5 - Strainer test fixture - The stated objective was to demonstrate the capability of the strainers to supply debris free water to the hydrostatic bearing under post LOCA conditions. The test also supplied a representative source of test fluid to test the new bearing design. The test fixture was a single stage volute v.s. a multiple stage as in an actual HPI pump. CFD analysis evaluated the flow fields and concluded that the similarities would allow for a valid evaluation of strainer design. The location of supply hole was in center of the screen. Final location was offset to the downstream side of the screen. CFD analysis concluded that the flow and pressure drop profile differences were not significant and therefore the test set-up reasonable. Strainer flow and pressure drop were monitored and trended.

3.5.2 Conclusions

The staff concludes that while the component parts were tested separately, the operating conditions were adequately matched. The worst case wear of individual sub-components was used in the licensee analyses. This is conservative since it is expected that there would be some balancing of wear in a fully assembled pump. ASME OM Code testing and the 2x wear testing together with the component level testing provided a reasonable and conservative approach for pump evaluation.

The testing confirmed that fibrous debris can accumulate, forming a mat in critical areas within the pump such as within the hydrostatic bearing pads, serve to collect harder debris particles, potentially causing significant wear, loss of bearing cooling, or early pump failure. The testing also confirmed that small, hard debris can result in significant damage to other internal HPI pump components with critical clearances such as wear rings, shafts, and bushings.

The licensee performed mock-up testing to determine the wear rates for the HPI pump fine clearances when pumping debris-laden water. This information was used in analysis and evaluations of pump operating characteristics and hydraulic performance. The staff finds that the mock-up testing confirms that the proposed modifications to the HPI pumps will accomplish the intended function of preventing potentially damaging debris from reaching the hydrostatic bearing.

3.6 Other Considerations

During the course of pump dis-assembly, modification and re-assembly, the licensee found and corrected other material and configuration discrepancies. These discrepancies included slight dimensional inaccuracies, material differences and slight damage due to maintenance and operation activities. Data and results were documented in various design and field reports. The staff reviewed the licensee responses and found the evaluations and resolutions to be thorough, reasonable and conservative.

Changes to the HPI pump affected other plant equipment and analyses. Due to the physical changes, additional load is imposed on 4160 V Essential Buses during pump start and subsequent normal operation. Staff review found that the licensee identified the additional loads and has taken appropriate steps to update electrical load calculations and evaluations.

Testing was performed post-modification in accordance with the ASME OM Code to confirm as-modified performance and to provide a basis for future evaluation. This testing did show the pumps to be operating less efficiently than pre-modification. The licensee identified that these differences could affect maximum peak clad temperature in other SBLOCA scenarios. The SBLOCA analysis was revised with the net result of increase post LOCA peak clad temperatures. This result does not effect the assumptions, testing or analysis supporting operation with debris-laden fluid. The staff’s review of the licensee actions found that appropriate evaluations were performed and the post modification pump characteristics were adequately incorporated into plant calculations, specifications and other controlled documents plant design documents.

3.7 Post Modification Testing

Davis Besse HPI pump design change package ECR 03-0216-0, “HPI Pump Upgrade to Allow Operation with Debris-laden Water During Containment Recirculation,” defined the post modification testing requirements for the HPI pumps. The pumps were first aligned to the BWST and operated in recirculation mode. Pump flow was set and vibrations monitored.

Following operation in the recirculation mode, the pumps were aligned in piggyback with the low pressure injection (LPI) System. This alignment resembles the post accident alignment and allows for a full flow test of the HPI pumps.

Davis Besse is currently in its third 10-year inservice testing program interval. Surveillance testing and pre-service testing of the HPI pumps are required to be performed in accordance with ASME OM Code (1995 Edition with 1996 Addenda), Subsection ISTB. Operation in the piggyback mode allows this testing to be performed.

The staff reviewed the Davis Besse test procedures, witnessed the full flow and recirculation tests of HP-P1B, HPI Pump 2, and reviewed the test data from both pumps. The staff witnessed the first attempt to full flow test HP-P1A, HPI Pump 1.

Testing was performed post-modification in accordance with the ASME OM Code to confirm as-modified performance and to provide a basis for future evaluation. Pre-service / baseline testing showed the pumps to be operating well within expected vibration parameters, however less efficiently than pre-modification. The as-modified pumps were found to operate with a slightly different operating curve than previous. New pumps curves were generated, for future use in monitoring performance and degradation. The licensee compared the curves against the ASME OM Code criteria, the hydraulic criteria for long-term post LOCA operation, and with existing analysis using the pump curves as an input. Hydraulic and vibration criteria met the requirements of the ASME OM Code. Hydraulic performance validated the assumptions used in the evaluation of the HPI pumps for use with debris-laden water. The licensee identified that differences between the pre and post modified pump curves affected maximum peak clad temperature in other SBLOCA scenarios. The SBLOCA analysis was revised with the net result of increasing post LOCA peak clad temperatures.

Staff review of the licensee post modification testing found that the testing was in accordance with design and Code requirements. Post test evaluations were appropriate and complete. Post modification pump characteristics were adequately incorporated into plant calculations, specifications and other controlled documents plant design documents. The post modification tests demonstrate that the modified pumps are capable of performing their design basis functions when called upon. The Code required baseline tests provide an adequate basis to assess future performance of the pumps.

4.0 On-site Reviews by NRC Staff

In the course of responding to this TIA, staff reviewed documents and observed testing at Wyle Testing Laboratory, MPR home offices and at the Davis-Besse site as discussed below.

4.1 Staff Reviews at Wyle Testing Laboratory

NRC staff visited the Wyle Testing Laboratory, located in Huntsville, Alabama, on two occasions, June 26 / 27, 2003 and September 30 / October 01, 2003. The purpose of the site visits was to review test procedures, observe the mock-up test set-up and to witness the results of the final testing.

During both site visits, the Wyle, FENOC, and MPR staffs were observed to be rigorously following the prescribed procedures. There was open discussion with regard to ongoing testing and test results.

During the June 2003 visit, following an unsuccessful design iteration, Test loops 3 and 5 were observed in their disassembled state. Loops 1, 2 and 5 were operating. The test (fluid) solution lab was observed as well as test facility adherence to test procedures.

During the September 30 - October 1, 2003 visit, the dis-assembly and recording of test measurements from Loops 2 and 4 were observed. Loop 1 was disassembled September 29 and the disassembled components observed. A review of ongoing Loop 3 and Loop 5 testing was also performed. Since June 2003, test loop set-up and test procedures had noticeably improved and much of the data acquisition had been automated. Test personnel demonstrated a high level of knowledge regarding component and test design, test methods and procedure.

FENOC staff responded to all NRC staff questions and followed up with direct communication as further test results and observations were obtained.

4.2 Staff Reviews at MPR Offices

Staff visited the MPR offices in Alexandria, Virginia on three occasions, August 28 / 29, 2003, October 9, 2003 and October 15, 2003. During these visits, staff met with FENOC and MPR personnel to review ongoing design and analysis. On all occasions, the licensee responded in an open, professional manner. A good questioning attitude and a rigorous design approach was noted. Licensee staff responded to all NRC staff questions and followed up with direct communication as further test results, observations and design analysis and evaluation were completed.

During the August 28-29, 2003 visit, staff observed the of the FENOC Engineering Review Board. This board was an independent review board assembled by the licensee to review the design and design approach taken by the licensee design team. The board was fully engaged and identified areas to be assessed in further detail by the design team. The staff views the assembly and use of this review board as a positive influence on the final design and disposition of the modifications to the HPI pumps.

4.3 Staff Reviews at Davis-Besse Site

The staff visited the Davis-Besse site from November 28 through December 2, 2003 to observe the post modification/pre-service and ASME OM Code testing of the HPI pumps. The staff also reviewed the completed, approved HPI pump design change package and referenced documentation. Final test documentation was forwarded to the staff following licensee test engineering review and concurrence in December 2003. During the site visit, the staff met with the licensee’s test coordinator, test technicians, operators and other licensee staff involved with the test evolutions. The test staff, in general, were knowledgeable of the test and test requirements. The licensee’s test staff maintained a questioning attitude and demonstrated conservative decision making.

The NRC staff met with the licensee’s engineering staff and plant management following review of the final design package. The staff questions were presented and responded to by the licensee’s engineering staff in the following days. During the course of the visit, the staff met and discussed the status of the design package review and the results of the post modification testing.

5.0 Overall Conclusions

The staff has completed its review of the HPI pump modifications and concludes the following:

(1) The licensee has performed sufficient design, analysis and testing to demonstrate the ability of the pump strainers in their location on the fourth stage volute to perform the function of eliminating particles greater than 0.050 inches while continuing to provide adequate flow to the hydrostatic bearing. The mock-up testing adequately demonstrated the self-cleaning design of the strainer i.e., that it would not fully plug with debris thus limiting bearing supply flow. The strainer design was shown to be robust and will not fail due to flow-induced erosion.

(2) The licensee has performed sufficient design, analysis and testing to demonstrate the ability of the as-designed bearing to operate with no plugging of the orifices or bearing pads with debris-laden water.

(3) The licensee’s design, analysis and testing demonstrate that fine clearance components such as wear ring and shaft sleeves may experience wear while operating with debris-laden water during plant recirculation. However, the proposed hard facing of pump critical components minimizes wear such that operations near pump critical speed is not adversely affected. The modifications to the fine clearance components provide reasonable assurance that these critical components will not fail due to excessive abrasive wear or flow-induced erosion.

(4) The licensee’s design, analysis and testing provide reasonable assurance that the HPI pump will be able to perform its safety function under design basis conditions and that the hydraulic performance of the HPI pump will be maintained even with wear of the fine clearance components such as the wear rings and shaft sleeves while operating with debris-laden water during plant recirculation. The proposed hard facing of pump critical components minimizes wear such that the hydraulic capability is not adversely affected. The design modifications were found to meet design requirements and the testing provides reasonable assurance that critical components will not fail due to excessive abrasive wear or flow induced erosion.

(5) In-plant, post-modification, pre-service testing performed in accordance with the ASME Code for Operation and Maintenance of Nuclear Power Plants (OM Code) provides assurance of the pump’s operational readiness and that any hydraulic degradation will be identified and monitored.

(6) The approach taken by the licensee in their calculations for debris generation, transport, and characterization was a valid approach. The staff finds that reasonable assumptions based on engineering judgement and appropriate conservatism were utilized where necessary to account for inherent uncertainties in the prediction of debris generation or impracticalities associated with modeling actual containment debris. The staff therefore concludes that the use of commercially available materials, i.e. "engineered debris" as practical substitutes for actual containment debris in the Davis Besse HPI pump mock-up tests is acceptable.

The staff, therefore, concludes that the licensee's overall approach to the modification of the high pressure injection pumps is acceptable and provides reasonable assurance that they will perform their required functions when called upon.

6.0 Documents Reviewed

Title 10 CFR 50.46 Acceptance Criteria for Emergency Core Cooling Systems for Light Water Nuclear Power Reactors

Title 10 CFR 50, Appendix A, General Design Criterion (GDC) 35, Emergency Core Cooling

Title 10 CFR 50, Appendix K, ECCS Evaluation Models

NRC Bulletin 2003-01, Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized Water Reactors

NUREG/CR 2792, An Assessment of Residual Heat Removal and Containment Spray Pump Performance Under Air and Debris Ingesting Conditions, September 1982

NUREG/CR 6762, Volume 4, Technical Assessment: Development of Debris Transport Fractions in Support of Parametric Evaluation, August 2002

NUREG/CR 6808, Knowledge Base for the Effect of Debris on Pressurized Water Reactor Emergency Core Cooling Sump Performance, February 2003

Letter dated March 28, 2003, USNRC to Mr. L. W. Meyers, FENOC entitled Davis Besse Nuclear Power Station, Unit 1 - Requests for Relief from the Third 10-Year Pump and Valve Inservice Testing (IST) Program (TAC No. MB3909)

American Society of Mechanical Engineers (ASME) Code for Operation and Maintenance of Nuclear Power Plants (OM Code), 1995 Edition with 1996 Addenda

Davis Besse Nuclear Power Station Unit 1, UFSAR, Section 6.3 Emergency Core Cooling Systems

Davis Besse Nuclear Power Station Unit 1, Safety Technical Specifications, Section 3/4.5 Emergency Core Cooling Systems

Davis Besse Nuclear Power Station, Unit 1, Third 10-Year Pump and Valve Inservice Testing (IST) Program, January 11, 2002

Davis Besse CR 02-08492 HPI Pump Internal Clearances may be Inadequate for Emergency Sump Operation, October 22, 2002

Davis Besse Action Plan Number SH-IAP-2e-01, Revision 0, High Pressure Injection Pump Internal Clearance / Debris Resolution - Implementation Action Item

Davis Besse HPI Pump Design Change Package ECR 03-0216-0, HPI Pump Upgrade to Allow Operation with Debris-laden Water During Containment Recirculation, November 26, 2003, Revision 0

Davis Besse HPI Pump Design Change Package ECR 03-0216-01 Inputs, Revision 0

Davis Besse 10 CFR 50.59 Evaluation, ECR 03-216-01, HPI Pump Upgrade to Minimize Debris Damage during Suction from the Containment Sump. Revision 0

Equivalency Evaluation of Central Volute Bushing Redesign in Support of Davis Besse ECR No. 03-0216, Material Engineering Evaluation (MEE), Davis Besse Form ED 7593-6 and 7593B-1

Equivalency Evaluation of Front Wear Ring Redesign in Support of Davis Besse ECR No. 03-0216, Material Engineering Evaluation (MEE), Davis Besse Form ED 7593-6 and 7593B-1

Equivalency Evaluation of Back Wear Ring Redesign in Support of Davis Besse ECR No. 03-0216, Material Engineering Evaluation (MEE), Davis Besse Form ED 7593-6 and 7593B-1

Equivalency Evaluation of Head Plate Wear Ring Redesign in Support of Davis Besse ECR No. 03-0216, Material Engineering Evaluation (MEE), Davis Besse Form ED 7593-6 and 7593B-1

Equivalency Evaluation of Outboard Bearing Sleeve Redesign in Support of Davis Besse ECR No. 03-0216, Material Engineering Evaluation (MEE), Davis Besse Form ED 7593-6 and 7593B-1

Equivalency Evaluation of Central Shaft Sleeve Redesign in Support of Davis Besse ECR No. 03-0216, Material Engineering Evaluation (MEE), Davis Besse Form ED 7593-6 and 7593B-1

Davis Besse Nuclear Power Station Emergency Procedure DB-OP-02000, RPS, SFAS, SFRCS Trip, or SG Tube Rupture, Revision 7, June 24, 2003

Davis Besse Nuclear Power Station Surveillance Test Procedure DB-PF-03218, HPI Train 1 Pump and Valve Test, Revision 6, August 30, 2003

Davis Besse Nuclear Power Station Surveillance Test Procedure DB-PF-03407, HPI Pump 1 Mode 5 Baseline Test in Piggyback Mode, Revision 5, November 25, 2003

Davis Besse Nuclear Power Station Surveillance Test Procedure DB-PF-03408, HPI Pump 2 Mode 5 Baseline Test in Piggyback Mode, Revision 2, November 25, 2003

Babcock and Wilcox Canada, LTD Curve 7134.5004, Pump Performance Chart, Pump HMBS 4x6x9 - 11 Stage, Serial # 068981, January 17, 1973

Babcock and Wilcox Canada, LTD Drawing 643065, Sectional Arrangement High Pressure Injection Pump, Revision K, November 28, 1972

Framatome Report No. 51-5035650-00, Davis Besse HPI Pump Post LOCA Mission Time, Revision 0

MPR HPI Pump Mockup Testing - Debris Characterization Summary, August 22, 2003

MPR -2543, Davis Besse HPI Post LOCA Debris Operation Issue Resolution Physical Modification Report, November 2003, Revision 1

MPR -2546, Davis Besse HPI Pump Post LOCA Debris Operation Issue Resolution Qualification Mock-up Testing Final Report, November 2003, Revision 0

MPR -2547, Davis Besse HPI Pump Post LOCA Debris Operation Issue Resolution Final Summary Report, November 2003, Revision 0

MPR -2562, Davis Besse HPI Pump Post LOCA Debris Operation Issue Resolution, Developmental Testing Final Report, November 2003, Revision 0

MPR -2573, Davis Besse HPI Pump Post-LOCA Debris Operation Issue Resolution, Wear, Rotordynamic, and Hydraulic Analysis, November 2003, Revision 1

MPR -2574, Davis Besse HPI Pump Post-LOCA Debris Operation Issue Resolution Mockup Test Fixture Equivalency Evaluation, November 2003, Revision 0

MPR -2577, Davis Besse HPI Pump Post-LOCA Debris Operation Issue Resolution In Plant Testing, November 2003, Revision 0

MPR -2578, Davis Besse HPI Post LOCA Debris Operation Issue Resolution, Mock-up Testing Debris Summary, November 2003, Revision 0

MPR -2598, Davis Besse HPI Pump Post-LOCA Debris Operation Issue Resolution, Pump P58-2M Modification Records, November 2003, Revision 1

MPR -2602, Davis Besse HPI Pump Post-LOCA Debris Operation Issue Resolution, Pump P58-1M Modification Records, November 2003, Revision 0

MPR -2603, Davis Besse HPI Pump Post-LOCA Debris Operation Issue Resolution, Supporting Documentation for Pump Modifications, November 2003, Revision 0

MPR Specification 0200-0060-00-01, Structural Design for Davis Besse Nuclear Power High Pressure Injection Pump Strainer Modification, November 2003, Revision 4

MPR Specification 0200-0060-00-27, Material Requirements for Davis Besse Nuclear Power High Pressure Injection Pump Bearing Parts, July 2003, Revision 1

MPR Specification 0200-0060-00-28, Fabrication Specification for Davis Besse Nuclear Power High Pressure Injection Pump Hardfaced Parts, July 2003, Revision 1

MPR Specification 0200-0060-00-29, Design Requirements for the Hydrostatic Bearing in the Davis Besse Nuclear Power High Pressure Injection Pump, November 2003, Revision 1

MPR Specification 0200-0060-00-31, Davis Besse High Pressure Injection Pump Modifications, Failure Modes and Effects Analysis, November 17, 2003, Revision 1

Davis-Besse Calculation No. C-NSA-049.02-028, Davis-Besse Debris Transport Logic Trees for Emergency Sump Strainer Loadings

Davis-Besse Calculation No. C-NSA-052.01-003, Davis-Besse HPI Pump Acceptance Criteria, Revision 7

MPR Calculation 0200-0060-00-01, Post LOCA Containment Debris Characterization for HPI Pump Test, August 19, 2003, Revision 4

MPR Calculation 0200-0060-00-03, Evaluation of Debris Transport to Containment Sump for Refinement of Debris Source for HPI Pump Testing, August 21, 2003, Revision 0

MPR Calculation 0200-0060-01-03, Debris Loading Procedures for the Davis-Besse HPI Pump Mock-up Testing, August 30, 2003, Revision 3

MPR Calculation 0200-0060-00-06, HPI Pump Debris Characteristics, August 30, 2003, Revision 6

MPR Calculation 0200-0058-jlh05,Leak Rate at Wear Ring and Throttle Bushing, April 29, 2003, Revision 0

MPR Calculation 0200-0060-ASL-01, Suction and Wear Ring Differential Head Calculation for 1X Design Clearance across the Wear Rings, September 29, 2003, Revision 1

MPR Calculation 0200-0060-ASL-02, Suction and Wear Ring Differential Head Calculation for 2X Design Clearance across the Wear Rings, September 30, 2003, Revision 0

MPR Calculation 0200-0060-ASL-03, Flow through the Hydrostatic Bearing, October 01, 2003, Revision 0

MPR Calculation 0200-0060-ASL-05, Pressures in Hydrostatic Bearing Flow Path at Different Stages of Performance Degradation, November 18, 2003, Revision 1

MPR Calculation 0200-0060-EBB-1, Strainer Finite Element Analysis, November 6, 2003, Revision 2

MPR Calculation 0200-0060-EBB-2, Volute Finite Element Analysis, November 18, 2003, Revision 2

MPR Calculation 0200-0060-EBB-3, CFD Analysis of HPI and Generic Mock-up Pumps, November 18, 2003, Revision 0 (Note: This calculation will be re-numbered and re-issued. Davis Besse Corrective Action CA 03-10410-1)

MPR Calculation 0200-0060-EBB-3, Rotor Dynamic Analysis, November 21, 2003, Revision 1

MPR Calculation 0200-0060-EBB-4, Rotor Dynamic Analysis Without Inlet Suction Wear Ring, November 13, 2003, Revision 0

MPR Calculation 0200-0060-JLH-04, HPI Pump Head-flow Performance Acceptance Criterion to Prevent Boron Precipitation, November 10, 2003, Revision 0

MPR Calculation 0200-0060-PCC-01, Hydraulic Performance Degradation Due to Increased Leakage, November 18, 2003, Revision 1

MPR Calculation 0200-0060-RCS10, Wear Ring Estimates for the Suction Wear Ring, Discharge Wear Ring, Hydrostatic Bearing, and Central Volute Bushing, November 17, 2003, Revision 1

MPR Calculation 0200-0060-SDK-1, Wear Model for HPI Pump Test, September 30, 2003, Revision 1

MPR Calculation 0200-0060-SDK-2, Heterogeneous Debris Mixture Wear Model for HPI Pump Tests, September 2003, Revision 0

MPR Calculation 0200-0060-SDK-3, Wear Ring Resistance for Chrome Plating, November 12, 2003, Revision 0

MPR Calculation 0200-0060-SDK-4, Service Wear Ring for the Suction Wear Ring, Discharge Wear Ring, Hydrostatic Bearing, and Central Volute Bushing, November 17, 2003, Revision 1

MPR Calculation 0200-0060-SRH-02, Hydrostatic Bearing Rotordynamic Coefficients - Original Bearing, November 20, 2003, Revision 1

MPR Calculation 0200-0060-SRH-03, Hydrostatic Bearing Rotordynamic Coefficients at 1X and 2X Design Clearances - Modified Bearing Design, November 20, 2003, Revision 1

MPR Calculation 0200-0060-SRH-04, Hydrostatic Bearing Rotordynamic Coefficients at Different Stages of Performance Degradation - Modified Bearing Design, November 20, 2003, Revision 1

MPR, Davis Besse High Pressure Injection Pump Strainer Location CFD Analysis, September 23, 2003, Revision 0

Davis Besse VDWG M-518-00119-1, Sheet 1, Weld Plug, Revision B

Davis Besse VDWG M-518-00120-1, Sheet 1, Short Radius Bearing Strainer, Revision A

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Davis Besse VDWG M-518-00127-1, Pump Modification Central Shaft Sleeve, Revision B

Davis Besse VDWG M-518-00128-1, Pump Modification Head Plate Wear Ring, Revision B

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Davis Besse VDWG M-518-00130-1, Pump Modification Back Wear Ring, Revision B

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MPR Drawing 1200-058-05, Suction Wear Ring Mockup Assembly, Revision B

MPR Drawing 1200-058-06, Hydrostatic Bearing Mockup Assembly, Revision B

MPR Drawing 1200-058-07, Central Volute Mockup Assembly, Revision B

MPR Drawing 1200-058-111, Hydrostatic Bearing Mockup Assembly, Revision A

MPR Drawing 1200-060-05, Hydrostatic Bearing Strainer Volute Modification Assembly, Revision C

MPR Drawing 1200-060-06, Volute Modified Fourth Stage, Revision C

MPR Drawing 1200-060-48, Short Radius Bearing Strainer, Revision A

MPR Procedure 0200-0060-00-10, Debris Receipt Inspection Procedure, September 2003, Revision 3

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MPR Procedure 0200-0060-01-03, Debris Loading Procedures for the Davis Besse HPI Mock-up Testing, September 2003, Revision 3