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NUCLEAR REGULATORY COMMISSION
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SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO THE HIGH PRESSURE INJECTION MAKEUP WATER NOZZLE FAILURE

TOLEDO EDISON COMPANY, ET AL.

DAVIS-BESSE NUCLEAR POWER STATION UNIT 1

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1.0 INTRODUCTION

During a combined ASME Section XI and prefueling visual inspection on July 2, 1988, several loose parts were found in the Davis-Besse Nuclear Power Station (DBNPS) Unit I reactor vessel. Among the loose parts were two metallic half cylinder pieces, later identified as parts from the high pressure injection (HPI) makeup water nozzle thermal sleeve. Approximately 3 inches of the thermal sleeve had broken off from the end of the sleeve, which protrudes into the reactor coolant system (RCS) cold leg, permitting cold water to impinge directly on the RCS cold leg cladding. Inspection of the HPI makeup nozzle showed linear indications throughout the area in the cladding where the thermal sleeve had failed.

Toledo Edison Company (the licensee) submitted, by letter dated September 15, 1988, the cause and analysis of the failure of the HPI makeup water nozzle thermal sleeve. The submittal was evaluated by the staff and a Safety Evaluation (SE) issued on Octob , 1988. The SE stated that, based on the results of the fracture mechanics analysis, the ultrasonic examination of the nozzle area, the revised design of the thermal sleeve, and the licensee's commitments to evaluate and monitor bypass flow, DBNPS could be operated through Cycle 6 without removing the cracks in the nozzle area. In the submittal, the licensee committed to provide the Commission with an update regarding the progress of evaluation of the failure and the progress for the preparation for action during the sixth refueling outage.

The current status of the HPI/Makeup water nozzle program at DBNPS was submitted in a letter from the licensee dated May 3, 1990 with the request for approval of plant operation for Cycle 7 and beyond. The purpose of this SE is to review the current status of the HPI/Makeup water nozzle program and to justify operation of DBNPS for Cycle 7 and beyond.

2.0 EVALUATION

Summary of Actions - In a letter dated June 19, 1989, the licensee described the planned program for the sixth refueling outage (6RFO). The actions were the following:

1) Modification of piping to reroute normal makeup flow through an alternate HPI nozzle;

2) Visual inspection of the HPI/Makeup nozzle thermal sleeve;

3) Enhanced ultrasonic (UT) examination of the HPI/Makeup nozzle (A1) from the outside diameter; and

4) Baseline enhanced UT examination of the alternate HPI nozzle (A2).

Additionally, a preliminary design and methodology for external weld overlay reinforcement of the nozzle, and means for removal and replacement of the thermal sleeve were developed in the event that the planned inspections had revealed additional defects.

Plant Modification rerouted the normal makeup flow path from HPI/Makeup nozzle A1 to HPI nozzle A2 on the adjacent RCS cold leg. The rerouting ensured that neither the thermal sleeve in nozzle A1 nor the nozzle itself will be subjected to thermal conditions related to normal makeup flow. Nozzle A1 will retain HPI duty and HPI nozzle A2 will become the combined HPI/Makeup nozzle. The nozzle A2 thermal sleeve was replaced during the fifth refueling outage (5RFO). The makeup flow path modification had no effect on HPI system operation or performance.

The inside diameter of the HPI/Makeup nozzle A1 thermal sleeve was visually inspected using fiberoptics. The inspection was similar to that performed during the 5RFO following discovery of the thermal sleeve failure. Indications found included scratches, which are believed to have resulted from attempts to insert tubing through the thermal sleeve to drain the RCS piping, and marks from the installation roll process. These indications have been evaluated, and determined not to be detrimental to the lifetime of the thermal sleeve. No indications of thermal fatigue cracks were found.

Toledo Edison Company in conjunction with B&W Nuclear Service Company developed the enhanced ultrasonic examination (enhanced UT) system which was used during the 6RFO to assure the structural integrity of the nozzle. Toledo Edison Company's submittals documented the development program and the capabilities of the enhanced UT system. The enhanced UT system utilizes automated scanning and an enhanced digital data acquisition and analysis system to examine the nozzle and adjacent reactor coolant piping from the outside diameter. The system was shown to be capable of detecting, locating and sizing thermal fatigue type flaws penetrating the inner clad surface into the base metal within the regions of the nozzle and adjacent RCS piping, which had been potentially affected by cold water following the thermal sleeve failure. The demonstrated ability to detect all flaws penetrating into the base metal by 0.125 inch or more ensured detection of flaws well below the depth where structural integrity of the nozzle would be compromised.

The 6RFO inspection plan included repeating the 5RFO manual ultrasonic examination prior to the enhanced UT. If the enhanced UT detected flaws in the nozzle, the repeated manual UT would assist in dispositioning the flaw as pre-existing and not detectable by manual UT, or as new, developing since the 5RFO. As in the 5RFO, the manual detected no flaws.

The enhanced ultrasonic examinations detected no flaws in nozzle A1 or nozzle A2 either in the cladding or penetrating into the base metal. Longitudinal wave examinations of the clad layer, performed specifically for the purpose, did not detect any discernible flaw indications. This suggested that any cracks represented by the dye penetrant indications found in the 5RFO are confined to the clad layer and are most likely very shallow.

Based upon the enhanced UT results, the structural integrity of the nozzle was again reviewed for acceptability for the remainder of the plant design life. Toledo Edison Company contracted Structural Integrity Associates to perform a fracture mechanics evaluation based upon a 3-D finite-element analysis and an assumed flaw depth based upon the confirmed limits of detection of the enhanced UT system. The methodology is similar to that used to support Toledo Edison Company's request for NRC approval of weld overlay repair as a contingency.

The structural evaluation of HPI nozzle A1 considers those design transients that are consistent with HPI duty of the nozzle since makeup flow has been rerouted to an alternate HPI nozzle. It assumes an intact thermal sleeve and a pre-existing flaw penetration through the cladding and 0.125 inch into the base metal at the location of maximum stress. The evaluation concluded that the flaw will propagate less than 20 mils over an additional 40 years of service life. The ASME Code Section XI maximum flaw size was not challenged and ASME structural reinforcement requirements were met with margin.

In summary, Toledo Edison Company has addressed the implications of the failed HPI/Makeup nozzle thermal sleeve discovered during the 5RFO. The actions have eliminated cold makeup water as a potential driving force for thermal fatigue of the thermal sleeve in nozzle A1 and the nozzle itself by rerouting makeup flow to a previously unaffected nozzle. The increased minimum makeup flow is also expected to enhance the lifetime of the thermal sleeve in nozzle A2. Toledo Edison Company is confident that the improvements made to makeup flow control provide assurance that thermal sleeve life is greater than four operating cycles in makeup service.

Modification of Makeup Water Flow - The makeup water flow path was modified to eliminate any possibility of cold makeup flow effects upon the thermal sleeve in nozzle A1 or the nozzle itself. Nozzle A1 had served in combined makeup and HPI duty since plant operations began in 1977. The thermal sleeve in nozzle A1 was replaced during the 5RFO, and was exposed to only a single fuel cycle of operation in combined makeup/HPI duty. The modified flow path had no effect upon the high pressure injection system operation.

The physical rerouting of the 2½-inch schedule 160 piping involved the addition of approximately 7 feet of piping and fittings in Number 2 Mechanical Penetration Room. The makeup tie-in downstream of the valve HP2A was capped off and a new connection in the alternate HPI line downstream of valve HP2B was established. All work on this modification was completed prior to return to power from the 6RFO.

Thermal Sleeve Inspection - A visual inspection of the inside surface of the thermal sleeve installed in the HPI/Makeup nozzle A1 was performed during the 6RFO. The inspection was performed using fiberoptic viewing equipment with the results recorded on video tape. Review of the video tape records by B&W Nuclear Service Company concluded that:

1) The examination constituted a complete visual inspection of the inside diameter of the thermal sleeve, and

2) There are no abnormalities that could be interpreted as being deleterious to the continued service of the thermal sleeve.

Indications reported from this inspection included primarily longitudinal scratches plus marks from the rolling process used in installation. These marks included occasiona all gouges and small rounded depressions. The shallow scratches were believed to have been caused by attempts to force tubing through the thermal sleeve to drain a local section of the RCS piping. The indications were subjected to engineering review in accordance with Toledo Edison Company procedures. It was concluded that none of the indications were representative of, or precursors to, thermal fatigue cracking. Based upon these reviews, it was concluded that the thermal sleeve was suitable for return to service, and that a further dye penetrant examination was unnecessary.

Nozzle Inspections - Volumetric inspections of the HPI/Makeup nozzle A1 and the HPI nozzle A2 were made during the 6RFO using the enhanced ultrasonic examination system. The enhanced UT system employs automated scanning using a Puma Model 262 robot to manipulate the transducer along predetermined scanning trajectories. The ultrasonic data were collected and displayed for analysis using the B&W Nuclear Service Company ACCUSONEX data acquisition and imaging system.

The capabilities of the system were improved during the development program which selected the scanning techniques and confirmed the required resolution. The resolution was demonstrated by using a series of test blocks and a replica mockup of the nozzle in which both cracks and narrow notches simulating cracks were installed. Blind tests were also incorporated in the development program. The development program proved the system's capability to detect, locate, and size flaws in the zone of concern in the HPI/Makeup nozzle and in adjacent parts of the reactor coolant pipe. This zone encompassed the regions potentially exposed to cold makeup water following the thermal sleeve failure discovered during the 5RFO.

The enhanced UT system was demonstrated to have high resolution for the detection of small flaws penetrating into the base metal. The system can reliably detect and locate flaws within the zone which penetrate into base metal by 0.125 inch or more. The detection capability is below the depth where structural integrity of the nozzle would be compromised.

Manual Scanning of Nozzle A1 - Prior to conducting the automated scanning, a manual examination was made in an attempt to duplicate the manual examination performed during the 5RFO. No recordable indications were detected during this repeat examination, matching the results of the last examination. All of the manual scans were performed in the same manner as the previous scans with the exception of the 35 degree longitudinal wave scan from the outside diameter blend radius. This particular scan was omitted because it had been determined during the enhanced UT development program to be ineffective for detecting cracking in the nozzle inside blend radius region.

Enhanced UT of Nozzle A1 - The examinations performed on nozzle A1 using the enhanced UT system were organized in several different scanning patterns. These patterns were designed to detect both radial and circumferential cracking in the zone of concern in the nozzle bore, including the inner radius and extending around the reactor coolant pipe to a distance of 8 inches from the nozzle centerline. The scan types included axial scans from the nozzle taper, and radial, circular, and tangent scans from the reactor coolant piping surface. During the automated scanning, the transducer was indexed approximately every 0.050 inch between traverses.

The axial taper scans were capable of detecting circumferential flaws in the nozzle bore. These scans were performed in segments that together extended 360 degrees around the nozzle for complete coverage. A 45-degree shear wave, 1.5 MHz, 0.375-inch transducer was used for this examination. An examination with a 45-degree longitudinal wave, 1.5 MHz, 0.375-inch transducer was used to supplement the shear wave examination in order to enhance detection of flaws contained in the cladding.

The radial scans performed from the reactor coolant pipe surface were capable of detecting circumferentially oriented flaws on the pipe inside surface. These scans were performed in segments that together extended 360 degrees around the nozzle for complete coverage. A 45-degree shear wave, 1.5 MHz, 0.375-inch diameter transducer was used for this examination. These scans covered the region extending from the nozzle inside blend radius back to 8 inches from the nozzle centerline.

The circular scans performed from the reactor coolant pipe surface were capable of detecting radially oriented flaws on the pipe inside surface. These scans were performed in segments that together extended 360 degrees around the nozzle for complete coverage. A 45-degree shear wave, 1.5 MHz, 0.375-inch diameter transducer was used for this examination. These scans cover an area extending from slightly under the O.D. blend radius to 8 inches from the nozzle centerline.

The tangent scans performed from the reactor coolant pipe surface are capable of detecting circumferentially and radially oriented flaws on the pipe inside surface extending from the nozzle inside blend radius to a point beneath the tangency point of the outside blend radius back to 8 inches from the nozzle centerline. In addition, this scan is capable of detecting axial flaws in the nozzle bore.

The tangent scans were performed by directing the transducer along parallel paths which are tangent to the nozzle bore at increments of 30 degrees. Three different transducer angles were required at each rotation angle for maximum coverage. These angles include 56, 66, and 75 degrees. The transducer angles were generally used with the shear wave mode at each rotation angle around the nozzle. The 240-degree angle proved the exception since access was restricted due to interferences with the reactor coolant pipe whip restraint and the HPI/Makeup line check valve. For this case, the scan plan was modified by performing a radial scan using a 66-degree shear wave over the range of 220 to 225 degrees to detect circumferentially oriented flaws on the pipe side in this region. The scan plan was also modified to ensure detection of axial flaws in the nozzle, which would otherwise have been detected using the tangent scan. To provide the required coverage, the 57, 66, and 75 degree transducers were scanned at the 60-degree rotation angle with the scan offset to cover the 330-degree side of the nozzle. These supplemental scans provide the same coverage and detection capabilities that the tangent scan at the 240-degree angle was intended to provide.

In addition to the shear wave scans, the downstream half of the nozzle (relative to reactor coolant flow) was examined using tangent scans with 57, 66 and 75 degree longitudinal waves to enhance detection of flaws contained in the cladding layer. This region was believed to have the highest probability of having any significant cracking due to the interaction of hot reactor coolant and cold makeup flow. The longitudinal wave examination did not detect any discernible flaw indications. Therefore, the flaws previously identified by dye penetrant testing during the 5RFO are believed to be confined to the clad layer and are most likely very shallow.

Results of Enhanced UT of Nozzle A1 - There were no indications detected with any of the scans which are considered to be service induced. This applies to both the examinations with the shear wave and longitudinal wave modes.

The only significant indications detected were in the nozzle-to-reactor coolant pipe weld. These were small and volumetric in nature. Of these, there were three weld indications which exceeded 20% Distance Amplitude Correction (DAC) level based upon the calibrations established on the ASME calibration block for the reactor coolant piping. The ASME Section XI recording threshold is 50% of DAC. These indications had peak amplitude readings of 23%, 27% and 82% of DAC and were determined to be acceptable.

One of the segments in the axial taper scans which was scanned with the 45-degree longitudinal wave did show indications at the clad layer. However, these indications were determined to be non-planar and were actually detected with the 22-degree shear wave which accompanies the 45-degree longitudinal wave. These indications are typical of those from the clad layer detected with shallow angle shear waves at high gain levels. While the exact source of the reflections is unknown, possibilities include small inclusions in the clad layer, the metallurgical interface between the base metal and the clad layer, or acoustic variations in the clad layer itself. It is noteworthy that these indications are located several inches from and are unrelated to the cladding flaws detected by dye penetrant testing in the 5RFO. The reason that the indications only appeared in one scan segment is that a higher gain setting was used to acquire data for this segment than for the other segments.

It was concluded that any indications in the cladding discovered during the 5RFO following failure of the HPI/Makeup thermal sleeve had not reached the clad-base metal interface in the regions examined. The use of the enhanced ultrasonic examination techniques show that there has been no significant growth of flaws which might have been initiated following the thermal sleeve failure. The ability of the enhanced UT system to resolve any flaws penetrating more than 0.125 inch into the base metal offers a conservative bound for an assumed flaw depth for re-evaluation of flaw growth potential in future operation.

Baseline Examination of Nozzle A2 - HPI nozzle A2 will become the normal makeup flow path following 6RFO as a result of the modification to reroute the normal makeup path. A baseline examination of this nozzle was performed using the enhanced UT system in a manner similar to that performed for nozzle A1. As for nozzle A1, no service-related indications were detected in nozzle A2.

Nozzle Structural Reviews - Although the enhanced ultrasonic examination showed no evidence of flaws penetrating into the nozzle or reactor coolant pipe base metal, a conservative review of the potential crack growth rate was made using fracture mechanics techniques.

The analytical methods used were improved over those used in the evaluations submitted following discovery of the thermal sleeve failure in 1988. The new considerations include the following:

- The HPI/Makeup nozzle A1 will no longer serve the combined functions for makeup and high pressure injection. Due to the rerouting of the normal makeup flow path, the nozzle will serve in HPI duty only. The evaluation of future flaw growth takes into account the functional transients associated with this duty.

- The geometry of the nozzle was determined to be slightly different than shown on the original B&W drawing. As part of the development of the enhanced ultrasonic examination system, the cladding was found to be thicker in some locations and to have a sharper inside blend radius. These cladding dimensional changes have been taken into account.

- The development of the enhanced UT system resulted in an improved resolution of small flaws penetrating the cladding into the base metal. Although no flaws were detected in the base metal in nozzle A1, the initial flaw depth assumed was that depth at which there is full confidence of detection (flaw depth extending 0.125 inch into the base metal).

Stress Analysis - A fracture mechanics analysis based upon a finite element stress analysis of the nozzle was performed by Structural Integrity Associates (SIA). Through-wall stresses were determined using the finite element model and the appropriate combination of internal pressure and HPI initiation thermal transients.

The fracture mechanics evaluation was performed using the linear elastic fracture mechanics option of the pc-Crack computer code. The two aspects of the evaluation include allowable flaw size determination and crack growth evaluation.

Minimum Flaw Size - The allowable flaw size evaluation was based upon a fracture mechanics model of the nozzle assuming a semicircular flaw penetrating 0.125 inch into the base metal at the location of maximum stress. The material fracture toughness for the ASTM A105 Carbon Steel nozzle base material was taken to be 200 ksi-inch divided by a safety factor of square root of 10 or 63.2 ksi-inch. Based upon this material fracture toughness, the allowable flaw depth in all cases was found to be through wall.

Fatigue Crack Growth - Fatigue crack growth analysis was also provided using pc-CRACK and the bilinear law in Appendix A, ASME Code Section XI, 1977 Edition, Summer 1978 Addenda. An initial crack size conservatively representing the maximum cladding thickness plus 0.125-inch base metal crack penetration, was assumed for the analysis. The number of startup and shutdown cycles for the 40-year design life was assumed to be 240, and the number of HPI injection transients was assumed to be 80. The resultant crack growth at the most structurally limiting location was determined to be less than 20 mils for an additional 40-years of life.

Structural Review Conclusions - The fracture mechanics analysis results show that flaws substantially larger than those conservatively assumed can be tolerated without challenging the ASME Code, Section XI, allowable flaw size. Additionally, a very large margin remains for flaw growth before the minimum nozzle reinforcement requirement required by ASME Code, Section III, would be reached.

The ASME Code, Section III, reinforcement requirements are based solely upon the carbon steel base metal. (Cladding is not considered part of the Code pressure boundary.) The initial flaw depth appropriate to this concern is therefore just the 0.125 inch assumed penetration into the base metal. On this basis, reviews of the HPI nozzle have shown that a fracture zone defined within the carbon steel base metal is acceptable without challenging minimum reinforcement requirements. With less the 20 mils growth projected for an additional 40 years of life, a very substantial margin remains before the ASME Code reinforcement limit could be reached. Thus, the calculated flaw growth rate shows large structural margins remain to accommodate operation for the remainder of the plant operating lifetime.

Review of HPI/Makeup Nozzle Program - On May 10, 1990 the licensee and its consultants, Babcock and Wilcox Nuclear Service Company (BWNS) and Structural Integrity Associates (SIA), met with the staff to review the HPI/Makeup Nozzle Program as described in the preceding section of this SE. The staff concluded that the licensee has taken adequate actions to address the HPI/Makeup nozzle thermal sleeve failure. There were no additional activities required from the licensee prior to restart of operation of DBNPS in refueling cycle 7 and subsequent cycles. However, the licensee agreed to continue to investigate mechanisms affecting the life of the thermal sleeve and to provide an answer to the concern regarding the conservatism afforded by the pc-CRACK nozzle corner flaw model. The follow-up activities will be completed after restart from the sixth refueling outage (6RFO).

3.0 CONCLUSION

The makeup water flow path was modified from nozzle A1 to nozzle A2 to eliminate the possibility of an effect of cold water flow on nozzle A1. Volumetric examination during refueling Cycle 6 indicated no growth of the service induced flaws in nozzle A1 and no flaws in nozzle A2. The Toledo Edison Company plans to volumetrically examine nozzle A1 at the next refueling outage. If this examination shows no growth of the flaws, the nozzle will be subsequently examined in compliance with ASME Code requirement.

We conclude from our review and evaluation of the High Pressure Injection Makeup Water Nozzle and Thermal Sleeve Program at the Davis-Besse Nuclear Power Station Unit 1 that approval of operation for Cycle 7 and beyond is justified. Approval of operation for Cycle 7 and beyond is granted as requested.

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