DEGRADATION OF THE DAVIS-BESSE NUCLEAR POWER STATION REACTOR PRESSURE VESSEL HEAD LESSONS-LEARNED REPORT

EXECUTIVE SUMMARY

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Objective and Scope

The U.S. Nuclear Regulatory Commission (NRC) has conducted a number of lessons-learned reviews to assess its regulatory processes as a result of significant plant events or plant safety issues. Consistent with this practice, the NRC's Executive Director for Operations (EDO) directed the formation of an NRC task force in response to the issues associated with the extensive degradation of the pressure boundary material of the Davis-Besse Nuclear Power Station (DBNPS) reactor pressure vessel (RPV) head. The degraded RPV head was identified by the FirstEnergy Nuclear Operating Company (FENOC), the licensee for DBNPS, on March 5, 2002. The objective of this task force was to independently evaluate the NRC's regulatory processes related to assuring RPV head integrity in order to identify and recommend areas for improvement that may be applicable to either the NRC or the nuclear industry.

Consistent with its charter, the task force reviewed five general areas, including: (1) reactor oversight process issues; (2) regulatory process issues; (3) research activities; (4) international practices; and (5) the NRC's Generic Issues Program. In reviewing these areas, the task force used processes and techniques that were similar to those used in NRC Incident Investigation Team and Diagnostic Evaluation Team reviews. A representative from the State of Ohio observed selected task force review activities. The task force conducted fact finding at DBNPS, which consisted of a review of the RPV head degradation condition and related issues. The task force conducted review activities at NRC regional and headquarters offices, which consisted of assessments of several NRC programs and functional areas. The task force held discussions with representatives from a number of external organizations.

Background

On March 12, 2002, the NRC dispatched an Augmented Inspection Team (AIT) to gather facts surrounding the circumstances associated with the March 5, 2002, discovery of a cavity in the DBNPS RPV head. The discovery of the cavity occurred following a plant shutdown for a refueling outage, during which the licensee was conducting inspections for reactor pressure vessel head penetration (VHP) nozzle cracking due to primary water stress corrosion cracking (PWSCC). These inspections were being conducted in response to an NRC bulletin. During these inspections, the licensee discovered cracks in several VHP nozzles. Subsequent to the machining process to repair VHP Nozzle 3, the nozzle was observed to displace, or tip in the downhill direction as the machining apparatus was withdrawn. The displacement led DBNPS personnel to examine the region adjacent to VHP Nozzle 3. The licensee discovered a cavity with a surface area of approximately 20-30 square inches. Upon further examination, the licensee identified that the cavity extended completely through the 6.63 inch thick carbon steel RPV head down to a thin internal liner of stainless steel cladding. In this case, the cladding withstood the primary system pressure over the cavity region during operation. However, the cladding is not designed to perform this function. Boric acid corrosion of the carbon steel RPV head was the primary contributor to the RPV head degradation.

The VHP nozzles, which are made from a nickel based alloy, are part of the reactor coolant pressure boundary (RCPB) in pressurized water reactor (PWR) plants. The VHP nozzles are highly resistant to general corrosion, but can be susceptible to PWSCC. Borated water is used in PWR plants as a reactivity control agent to aid in control of the nuclear reaction. If leakage occurs from the reactor coolant system (RCS), the escaping coolant flashes to steam and leaves behind a concentration of impurities, including boric acid. Under certain conditions, boric acid can cause extensive and rapid degradation of carbon steel components. If undetected and uncorrected, VHP nozzle leakage could potentially propagate to a failure of a nozzle and result in a loss-of-coolant accident (LOCA). In addition, boric acid-induced material wastage of the RPV head could result in a LOCA independent of catastrophic failure of a VHP nozzle.

The cracking of Alloy 600 nozzles was first discovered in the late 1980s. The cracking of VHP nozzles was first observed at a French PWR, Bugey, Unit 3 in 1991. As a result of the Bugey experience, the NRC implemented an action plan to address PWSCC of VHP nozzles fabricated from Alloy 600. This action plan included an NRC staff review of safety assessments conducted by the PWR owners groups. These owners group reports addressed VHP nozzle cracking and the potential for boric acid degradation of RPV heads from leakage through the VHP nozzle cracks. The U.S. industry reports concluded that axial cracking, even if through-wall, was not highly safety significant. These owners group reports also concluded that circumferential cracking of VHP nozzles was improbable and boric acid attack of the RPV head, if it were to occur, would be discovered through boric acid walkdown inspections well before safety margins would be compromised. In a safety evaluation dated November 19, 1993, the NRC agreed with this assessment, but reserved judgment regarding circumferential cracking on a case-by-case basis, and encouraged the industry to develop enhanced VHP nozzle leakage monitoring techniques.

In 1997, continued NRC concern with this issue led the NRC to issue a generic letter which requested PWR plant licensees to inform NRC of their plans to monitor and manage cracking in VHP nozzles and their intentions, if any, to perform non-visual, volumetric examinations of their VHP nozzles. Also, this NRC generic letter requested information regarding the occurrence of resin bead intrusions in PWR plants because of the concern that such intrusions could result in circumferential intergranular attack of VHP nozzles. In July 1997, the owners groups submitted their generic responses to the NRC on behalf of their members. The generic responses ranked the potential for the VHP nozzles of their member plants to develop PWSCC.

Subsequently, inspections conducted in response to the generic letter led to the discovery of extensive circumferential cracking of several VHP nozzles at Oconee Nuclear Station (ONS), Unit 3 in the spring of 2001. Circumferential cracking in VHP nozzles is more safety significant than axial cracking since it creates the potential for separation of the nozzle if the cracking is severe enough. As a result of the ONS cracking experience, the NRC issued a bulletin which requested licensees to address the potential for similar cracking at their plants and to discuss their plans for VHP nozzle inspections. The Electric Power Research Institute/Materials Reliability Project took the lead for the industry in "binning" plants by susceptibility relative to ONS. The Babcock & Wilcox (B&W) plants, such as ONS and DBNPS, were all considered to be highly susceptible to the potential for circumferential cracking. By the end of November 2001, all but one of the other B&W units had identified circumferential cracking of VHP nozzles, while the remaining unit had identified VHP nozzle axial cracking. For highly susceptible plants, the bulletin recommended that VHP nozzle inspections be performed by December 31, 2001.

The licensee believed that it was safe to operate the plant until the next scheduled refueling outage in the spring of 2002 before conducting the VHP nozzle inspections recommended by the bulletin. Because FENOC did not intend to perform the inspections recommended in the bulletin by the requested date, the NRC initiated action to prepare an immediately effective order to require DBNPS to cease power operations by December 31, 2001. Subsequently, the licensee provided additional information to the NRC. The NRC accepted FENOC's justification to operate DBNPS only until February 16, 2002, provided that DBNPS implement compensatory measures to reduce the risk of VHP nozzle failure and perform volumetric examinations of 100 percent of the VHP nozzles. During subsequent inspections, DBNPS discovered VHP nozzle cracking, including through-wall cracking of several VHP nozzles. The licensee discovered a long axial crack in VHP Nozzle 3. This crack was the source of the leakage that was likely the most significant contributor to the RPV head degradation.

Observations and Conclusions

About 10 years ago, the NRC and industry recognized the potential for an event such as the one that occurred at DBNPS. In spite of the wealth of information, which includes extensive foreign and domestic PWR plant operating experience, as well as research activities involving tests and engineering analyses, the DBNPS event occurred. Events involving the material wastage of components stemming from primary system leaks have been reported for more than 30 years. For more than 15 years, Alloy 600 nozzle leakage events in U.S. PWR plants have been reported. In 1993, the industry and NRC specifically addressed the possibility of extensive RPV head wastage stemming from undetected VHP nozzle leaks involving axial cracking caused by PWSCC. The industry and the NRC concluded that the likelihood of such an event was low because VHP nozzle leaks would be detected before significant RPV head degradation could occur.

The task force concluded that DBNPS VHP nozzle leakage and RPV head degradation event was preventable. The task force focused on understanding why the event was not prevented. While this focus was primarily introspective, this question could not be answered without considering industry activities and DBNPS's performance. The task force concluded that the event was not prevented because: (1) the NRC, DBNPS, and the nuclear industry failed to adequately review, assess, and followup on relevant operating experience; (2) DBNPS failed to assure that plant safety issues would receive appropriate attention; and (3) the NRC failed to integrate known or available information into its assessments of DBNPS's safety performance.

Because the NRC and nuclear industry concluded that Alloy 600 VHP nozzle cracking was not an immediate safety concern, the NRC and the industry's efforts to further evaluate this issue became protracted. Also, the NRC and industry continued to rely on visual inspections of VHP nozzles. These inspections are incapable of characterizing the extent of nozzle cracking and damage. While the industry initiated actions to improve non-visual inspection capabilities, the requirements governing inspections remained unchanged.

The NRC recognized that some affected PWR plants could potentially operate with small leaks which would not be detected by boric acid corrosion control walkdown inspections. Rather than adopt an approach of leakage prevention, the NRC focused on measures intended to enhance licensee capabilities to detect small VHP nozzle leaks. Because of this, the NRC believed it was prudent for the industry to consider implementing an enhanced leakage detection method for detecting small leaks during plant operation. Leakage detection would serve as a means of providing defense-in-depth to account for any potential uncertainties in the industry analysis that boric acid corrosion walkdown inspections would be an effective means of detecting VHP nozzle leaks before significant degradation could occur. However, PWR plant licensees have not installed enhanced leakage detection systems designed to detect VHP nozzle leaks.

The licensee for DBNPS, as well as the NRC, failed to learn a key lesson from boric acid leakage and corrosion operating experience. Specifically, predictions regarding boric acid-induced corrosion rates, for in-plant boric acid leaks, have not been reliable in all cases. Operating experience reveals instances in which corrosion rates were significantly underestimated for identified boric acid leaks because of erroneous assumptions regarding the nature of the leakage, environmental conditions, the relationship between the actual leakage and experimental data, or other factors. As a consequence, in some instances, carbon steel components have been corroded to a much greater extent than anticipated. A number of these events occurred even though the underlying leakage had been previously identified by licensees, as they deferred material wastage assessments and repairs on the basis of the assumption that the corrosion rates would be inconsequential. At least two such events occurred at DBNPS prior to the discovery of the RPV head degradation.

The NRC and the industry regarded boric acid deposits on the RPV head as an issue that required attention; however, the NRC and industry did not regard the presence of the boric acid deposits on the RPV head as a significant safety concern because they expected that boric acid crystals would form from flashing steam and such crystals would not cause significant corrosion of RPV heads. For example, the NRC and industry were concerned that the presence of boric acid deposits, from CRDM flange leakage in the case of B&W PWR plants, could obscure the indications of VHP nozzle leakage. While dry boric acid crystals would not be expected to result in significant corrosion rates, representative testing of nozzle leakage indicated that corrosion rates from boric acid solutions could be in the range of 4 inches per year. These rates of corrosion could occur at primary system leakage rates that are significantly lower than the typical PWR plant technical specification limit, namely, at a rate too small to directly measure with the current leakage detection systems. Even at somewhat lower rates of corrosion, properly implemented boric acid corrosion control programs may not lead licensees to detect VHP nozzle leaks before significant RPV head degradation could occur. The results of these tests, while known within the NRC, were not widely recognized by the NRC staff.

The recurring nature of boric acid leakage and corrosion events generally indicates a lack of effectiveness of industry corrective actions in these areas. This event also indicates that DBNPS failed to effectively implement its operating experience review program. Also, the NRC failed to adequately review, assess, and followup on relevant operating experience to bring about the necessary industry and plant specific actions to prevent this event. While much was known within the NRC about nozzle cracking and boric acid corrosion, other important details associated with these two issues, such as the number of nozzle cracking events, as well as insights from foreign operating experience and domestic research activities, were not widely recognized or were viewed as not being applicable. The NRC accepted industry positions regarding the nature and significance of VHP nozzle cracking without having independently verified a number of key assumptions, including the implementation effectiveness of boric acid corrosion control programs and enhanced visual inspections of RPV heads. None of the NRC's previously identified generic issues pertained directly to either VHP nozzle cracking or boric acid corrosion; although, there was one generic issue that pertained, in part, to boric acid corrosion of fasteners. This generic issue was classified as resolved in 1991.

The task force identified multiple DBNPS performance problems that indicated DBNPS's failure to assure that plant safety issues would receive appropriate attention. Specifically, the licensee failed to: (1) resolve long-standing or recurring primary system component leaks; (2) establish and effectively implement a boric acid corrosion control program; and (3) adequately implement industry guidance and NRC recommendations intended to identify VHP nozzle leakage. Collectively, these and other performance issues involved: (1) strained engineering resources; (2) an approach of addressing the symptoms of problems as a means of minimizing production impacts; (3) a long-standing acceptance of degraded equipment; (4) a lack of management involvement in important safety significant work activities and decisions, including a lack of a questioning attitude by managers; (5) a lack of engineering rigor in the approach to problem resolution; (6) a lack of awareness of internal and external operating experience, including the inability to implement effective actions to address the lessons-learned from past events; (7) ineffective and untimely corrective actions, including the inability to recognize or address repetitive or recurring problems; (8) ineffective self-assessments of safety performance; (9) weaknesses in the implementation of the employee concerns program; and (10) a lack of compliance with procedures.

For a number of years, the NRC was aware of the symptoms and indications of active RCS leakage. The NRC even reviewed some of these individual symptoms during routine inspections; however, the NRC failed to integrate this information into its assessments of DBNPS's safety performance. As a result, the NRC failed to perform focused inspections of these symptoms. If focused inspections had been performed, then the NRC may have ultimately discovered the VHP nozzle leaks and RPV head degradation. The former senior resident inspector became aware of boric acid deposits on the RPV head at the onset of the spring 2000 refueling outage; however, he did not inform his supervisor and did not perform inspection followup. There were other licensee performance data that were available for review, in the context of the NRC's inspection program, but the NRC did not review or assess this information. Actual and perceived weaknesses with inspection, enforcement, and assessment guidance, as well as inadequate VHP nozzle and RPV head inspection requirements, contributed to the NRC's failure to identify the problem. During the period in which the symptoms and indications of RCS leakage were visible, the managers and staff members of the NRC's regional office responsible for DBNPS oversight were more focused on other plants that were the subject of increased regulatory oversight. This distracted management attention and contributed to staffing and resource challenges impacting the regulatory oversight of DBNPS. The dissemination of some licensee information resulted in actual and potential missed opportunities for the NRC to have identified the problem. Also, there were a number of licensing process issues that contributed to the NRC's failure to identify the problem.

Recommendations

As a result of its review, the task force determined that the NRC should take specific actions directed toward areas it considered contributors to the DBNPS event.

The task force's recommendations are addressed in Section 3 of the report. Appendix A provides a consolidated listing of these recommendations. The recommendations involve the following areas: (1) inspection guidance; (2) NRC and industry processes to assess operating experience; (3) industry code inspection requirements for RCPB components (ASME requirements); (4) assessment of NRC programs, processes, and capabilities; (5) NRC staff training and experience; (6) technical specification requirements related to RCPB integrity; (7) reactor coolant system leakage monitoring practices and capabilities; (8) stress corrosion cracking and boric acid corrosion technical information and guidance; (9) NRC licensing process guidance development and implementation; and (10) previous NRC lessons-learned reviews.