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United States Nuclear Regulatory Commission
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Braidwood Station, Units 1 and 2
Facility Operating License Nos. NPF-72 and NPF-77
NRC Docket Nos. STN 50-456 and STN 50-457

Byron Station, Units 1 and 2
Facility Operating License Nos. NPF-37 and NPF-66
NRC Docket Nos. STN 50-454 and STN 50-455

Three Mile Island, Unit 1
Facility Operating License No. DPR-50
NRC Docket No. 50-289

Subject: Exelon/AmerGen Thirty-Day Response to NRC Bulletin 2002-02, "Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs"

On August 9, 2002, the NRC issued NRC Bulletin 2002-02, "Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs." The purpose of this bulletin is to learn what changes, if any, PWR licensees have made to their inspection programs for the reactor pressure vessel (RPV) head and vessel head penetration (VHP) nozzles, and their justification for reliance on visual examinations if that is their primary method to detect degradation.

In accordance with 10 CFR 50.54, "Conditions of licenses," paragraph (f), Attachments 1 and 2 to this letter provide the Exelon Generation Company, LLC 30-day bulletin response for Braidwood Station, Units 1 and 2, and Byron Station, Units 1 and 2, respectively. Attachment 3 provides the AmerGen Energy Company, LLC 30-day bulletin response for Three Mile Island, Unit 1. These responses are due to the NRC September 11, 2002, as clarified by the NRC at its public meeting held on August 23, 2002, on this subject.

A096

If you have any questions or desire additional information regarding this letter, please contact Don Cecchett at (630) 657-2826.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on this 11th day of September, 2002

Keith R. Jury

Keith R. Jury
Director - Licensing
Mid-West Regional Operating Group

Attachments: Attachment 1, Thirty-Day Response to NRC Bulletin 2002-02, Braidwood Station, Units 1 and 2
Attachment 2, Thirty-Day Response to NRC Bulletin 2002-02, Byron Station, Units 1 and 2
Attachment 3, Thirty-Day Response to NRC Bulletin 2002-02, Three Mile Island, Unit 1

cc: Regional Administrator – NRC Region I
Regional Administrator – NRC Region III

ATTACHMENT 1

Thirty-Day Response to NRC Bulletin 2002-02
"Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs "

Braidwood Station, Units 1 and 2

Exelon Generation Company, LLC

Attachment 1

Thirty-Day Response to NRC Bulletin 2002-02

Braidwood Station Units 1 and 2

Exelon Generation Company, LLC (Exelon) has evaluated the expected status of Braidwood Station, Units 1 and 2 with regard to accrued effective full power years (EFPY) and effective degradation years (EDY) calculated in accordance with Electric Power Research Institute (EPRI) Material Reliability Program (MRP) document, "PWR Materials Reliability Program Response to NRC Bulletin 2001-01 (MRP-48), 1006284 Final Report 2001," August 2001 (equation 2.1 and 2.2 respectively). The results are presented in the following table referenced to the next scheduled refueling outage for each unit:

Unit	Next Refueling Outage	EDY
1	April 2003	1.7
2	October 2003	1.7

The Exelon responses to NRC Bulletin 2002-01 addressed the adequacy of visual inspection for compliance with the design and licensing basis of the plants (Ref. 9). Those responses are still applicable with respect to the inspection adequacy and planned actions. Additional technical justification for the adequacy of the inspections is provided in this response to NRC Bulletin 2002-02.

The bare metal visual (BMV) inspection of the Braidwood Station, Unit 2 reactor pressure vessel (RPV) head was completed in April 2002 during the Spring refueling outage, as reported in References 10 and 11. No evidence of leakage or evidence of wastage was identified. The BMV inspection of the Braidwood Station, Unit 1 RPV head is scheduled for April 2003 during the Spring refueling outage, as reported in Reference 11.

The MRP Inspection Plan has been developed, reviewed, and approved by the PWR utilities (Refs. 1 and 2). It presents a technically credible inspection regimen that assures to a high degree of certainty, that leaks will be detected at an early stage long before wastage or circumferential cracking can challenge the structural integrity of the reactor coolant system (RCS) pressure boundary. Furthermore, implementation of the MRP Inspection Plan will assure continued compliance with the regulatory requirements cited within NRC Bulletin 2002-02.

Braidwood Station has implemented the MRP Inspection Plan and will continue to comply with its guidance with the conduct of the next planned BMV inspection of the Unit 1 RPV head in April 2003. The MRP Inspection Plan encompasses the inspection plans in our responses to NRC Bulletin 2001-01 and NRC Bulletin 2002-01, but is more rigorous.

Exelon provides the following justification for continued reliance on visual examinations as the primary method to detect degradation in the RPV head. Included in these responses are discussions on the reliability and effectiveness of visual examinations as they relate to the six concerns cited in NRC Bulletin 2002-02, and the basis for concluding that unacceptable wastage will not occur between refueling outages.

Concern 1: *"Circumferential cracking of CRDM nozzles was identified by the presence of relatively small amounts of boric acid deposits. This finding increases the need for more effective visual and non-visual NDE inspection methods to detect the presence of degradation in CRDM nozzles before nozzle integrity is compromised."*

Response: Since the initial industry discovery of circumferential cracks above the J-groove weld in 2001, visual inspection techniques and approaches employed have been dramatically improved and a heightened sense of awareness exists for the range in size and appearance of visual indications that must be further investigated. Non-visual techniques similarly continue to evolve to more effectively examine the penetration tube and associated welds for evidence of cracks. The recent events at Davis-Besse have not altered the fundamental inspection capability requirements previously established as necessary to identify the presence of primary water stress corrosion cracking (PWSCC) and subsequent associated wastage. The effectiveness of inspection techniques continues to be evaluated and improved.

The EPRI MRP has published detailed guidance for performing visual examinations of RPV heads (Ref. 2). A utility workshop was recently conducted to discuss this guidance and lessons learned from recent field experience, including Davis-Besse. An RPV head BMV inspection at Braidwood Station, Unit 2 was performed and documented in accordance with written procedures and acceptance criteria that met the guidance of the MRP Inspection Plan. As discussed in Reference 11, there were no corrective actions taken nor root cause investigations performed since no vessel head penetration (VHP) leakage was observed nor was there any RPV head wastage. A BMV inspection will be performed on the Braidwood Station, Unit 1 RPV head in the Spring of 2003. As was done for Braidwood Station, Unit 2, the inspection will be performed and documented in accordance with written procedures and acceptance criteria that comply with the guidance of the MRP Inspection Plan. Evaluations and corrective actions will be rigorous and thoroughly documented.

In order for outside diameter (OD) circumferential cracks above the J-groove weld to initiate and grow, a leak path must first be established to the control rod drive mechanism (CRDM) annulus region from the inner wetted surface of the reactor vessel head. If primary water does not leak to the annulus, the environment does not exist to cause circumferential OD cracking. Axial cracks in the CRDM nozzles or cracks in J-groove welds must first initiate and grow through-wall. Experience has shown that through-wall axial cracks will result in observable leakage at the base of the penetration on the outer surface of the vessel, even with interference fits. Alloy 600 steam generator drain pipes at Shearon Harris (1988) and pressurizer instrument nozzles at Nogent 1 and Cattenom 2 (1989) were all roll expanded but still developed leaks during operation (Ref. 3). Plant specific top head gap analyses have been performed for a large number of plants, with nozzle initial interference fits ranging from 0 to 0.0034 inches. These analyses have confirmed the presence of a physical leak path in essentially all nozzles under normal operating pressure and temperature conditions (Ref. 1).

The probability of detecting small CRDM leaks by visual inspections alone is high. Visual inspections of the RCS pressure boundary have been proven to be an effective method for identifying leakage from PWSCC cracks in Alloy 600 base material and Alloy 82/182 weld metal. Specifically, visual inspections have detected leaks in an RPV head CRDM nozzles, an RPV head thermocouple nozzles, pressurizer heater sleeves, pressurizer instrument nozzles, hot leg instrument nozzles, steam generator drain lines, a RPV hot leg nozzle weld, a power operated relief valve safe end and a pressurizer manway diaphragm plate (Ref. 3). To date, no leaking

CRDM nozzles have been discovered by non-visual NDE examinations except for the three nozzles at Davis-Besse where leakage would have been detected visually had there been good access for visual inspections and the head cleaned of pre-existing boric acid deposits from other sources (Ref. 1).

Finally, as described in our response to Concern 3 below, detailed probabilistic fracture mechanics (PFM) analyses have been performed to demonstrate the effectiveness of visual inspections in protecting the CRDM nozzles against failure due to circumferential cracking (Ref. 1). Even though the above discussion illustrates that visual inspections performed in accordance with MRP recommendations have a high probability of detecting through-wall leakage, a very low probability of detection was assumed in the PFM analyses. The PFM analyses assume only a 60% probability that leakage will be detected if a CRDM nozzle is leaking at the time a visual inspection is performed. Furthermore, if a nozzle has been inspected previously, and leakage was missed, subsequent visual inspections are assumed to have only a 12% probability of detecting the leak. Even with these conservative probabilities of detection assumptions, the PFM analyses show that visual inspection every outage reduces the probability of a nozzle ejection to an acceptable level for plants with 18 or more EDY. Visual inspections of plants with fewer than 18 EDY in accordance with the MRP Inspection Plan will maintain the probability of nozzle ejection for these plants more than an order of magnitude lower than that for the greater than 18 EDY plants.

In summary, the industry has responded to the need to detect small amounts of leakage by increased visual inspection sensitivity, increased inspection frequencies, and improved inspection capabilities. Small amounts of leakage can be detected visually and it has been shown that timely detection by visual examination will ensure the structural integrity of the RPV head penetrations with respect to circumferential cracking.

Concern 2: *"Cracking of 82/182 weld metal has been identified in CRDM nozzle J-groove welds for the first time and can precede cracking of the base metal. This finding raises concerns because examination of weld metal material is more difficult than base material."*

Response: Cracks in the J-groove weld do not pose an increased risk regarding nozzle ejection as compared to penetration base metal cracks. J-groove weld cracks that initiate and grow through-wall will leak the same as cracks in the penetration base metal. Therefore, weld cracks pose a similar risk as cracks in the base material and are equally detectable by visual examination. Although higher crack growth rates have been observed in laboratory testing of weld metal, the industry model of time-to-leakage includes plants that have had weld metal cracking as well as base metal cracking. The visual examination frequencies from the MRP Inspection Plan have been conservatively established based on the risk informed analyses considering leakage due to both weld metal and base metal cracking.

Concern 3: *"Through-wall circumferential cracking from the outside diameter of the CRDM nozzle has been identified for the first time. This raises concerns about the potential for failure of CRDM nozzles and control rod ejection, causing a LOCA."*

Response: PFM analyses using a Monte-Carlo simulation algorithm were performed to estimate the probability of nozzle failure and control rod ejection due to through-wall circumferential cracking (Ref. 1). The PFM analyses conservatively assume that, once a leak path has extended to the annulus region, an OD circumferential crack develops instantaneously, with a length encompassing 30° of the nozzle circumference. Fracture mechanics crack growth calculations are then performed for this initially assumed crack, using material crack growth rate data from EPRI Report MRP-55

(Ref. 4). The parameters used in the PFM model were benchmarked against the most severe cracking found to date in the industry (B&W Plants) and produced results that are in agreement with experience to date. The analyses were used to determine probability of nozzle failure versus EFPY for various head operating temperatures. Analyses were then performed to estimate the effect of visual and non-visual (NDE) inspections of the plants in the most critical inspection category, using the conservative assumption discussed above (see Concern 1 response) for probability of leakage detection by visual inspection. These analyses demonstrate that performing visual inspections significantly reduces the probability of nozzle ejection, and that performing such examinations on a regular basis, in accordance with the inspection schedule prescribed in the MRP Inspection Plan, effectively maintains the probability of nozzle ejection at an acceptably low level indefinitely.

In the extremely unlikely event that nozzle failure and rod ejection were to occur due to an undetected circumferential crack, an acceptable margin of safety would still be maintained (Ref. 5). The consequences of such an event are similar to that of a small-break loss of coolant accident, which is a design-basis event. The probability of core damage given a nozzle failure (assuming that failure leads to ejection of the nozzle from the head) has been estimated to be 1×10^{-3} per plant year. The PFM analyses demonstrate that periodic visual inspections are capable of maintaining the probability of nozzle failure due to circumferential cracking well below 1×10^{-3} per plant year. Therefore, the PFM analyses demonstrate that the resulting incremental change in core damage frequency due to CRDM nozzle cracking can be maintained at less than 1×10^{-6} (i.e., 1×10^{-3} times 1×10^{-3} equals 1×10^{-6}) per plant year, through a program of periodic visual examinations performed in accordance with the MRP Inspection Plan. This result is consistent with NRC Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk–Informed Decisions on Plant–Specific Changes to the Licensing Bases," that defines an acceptable change in core damage frequency (1×10^{-6} per plant year) for changes including plant design parameters, and technical specifications.

Concern 4: *"The environment in the CRDM housing/RPV head annulus will likely be more aggressive after any through-wall leakage because potentially highly concentrated borated primary water may become oxygenated. This raises concerns about the technical basis for current crack growth rate models."*

Response: Prior to the Davis-Besse incident, the MRP panel of international experts on stress corrosion cracking (SCC), including representatives from Argonne National Laboratory and the NRC Office of Research, gave extensive consideration to the likely environment in the annulus between a leaking CRDM nozzle and the RPV head and have subsequently re-evaluated this issue (Ref. 4). When re-evaluated, the relevant arguments remain valid for leak rates that are less than 1 liter/h or 0.004 gpm, which plant experience has shown to be the usual case. The conclusions were:

1. An oxygenated crevice environment is highly unlikely because:

- Back diffusion of oxygen is too low compared to counterflow of escaping steam (two independent assessments based on molecular diffusion models were examined).
- Oxygen consumption by the metal walls would further reduce its concentration.
- Presence of hydrogen from leaking water and diffusion through the upper head results in a reducing environment.
- Even if the concentration of hydrogen was depleted by local boiling, coupling between low alloy steel and Alloy 600 would keep the electrochemical potential low.

- Corrosion potential will be close to the Ni/NiO equilibrium, resulting in PWSCC susceptibility similar to normal primary water.

2. The most likely crevice environments are either hydrogenated steam or PWR primary water within normal specifications. Both of which would result in similar, i.e., non-accelerated, susceptibility of the Alloy 600 penetration material to PWSCC.

3. If the boiling interface happens to be close to the topside of the J-weld, itself a low probability occurrence, concentration of PWR primary water solutes, lithium hydroxide, and boric acid, can occur in principle. Of most concern, would be the accelerating effect of elevated pH on SCC, but calculations and experiments show that any changes are expected to be small, in part because of the buffering effects of precipitates. A factor of 2x on the crack growth rate (CGR) conservatively bounds possible acceleration of PWSCC up to a high-temperature pH of approximately 9.

   For larger leakage rates, which could lead to local cooling of the head, concentration of boric acid, and development of a sizeable wastage cavity adjacent to the penetration, the above arguments no longer directly apply. However, limited data (i.e., Berge et al., 1997) on SCC in concentrated boric acid solutions indicate that

   - Alloy 600 is very resistant to transgranular SCC (material design basis).
   - High levels of oxygen <u>and</u> chloride are necessary for intergranular cracking to occur.
   - The cracking is then worse at intermediate temperatures, suggesting that the mechanism is different from PWSCC.

The above considerations show that there is no basis for assuming that any post-leakage, crevice environment in the CRDM housing/RPV head annulus would be significantly more aggressive with regard to SCC of the Alloy 600 penetration material than normal PWR primary water, irrespective of the assumed leakage rate and/or annulus geometry. The current industry model (Ref. 4), which includes a factor of 2x on CGR to cover residual uncertainty in the composition of the annulus environment, remains valid.

Concern 5: *"The presence of boron deposits or residue on the RPV head, due to leakage from mechanical joints, could mask pressure boundary leakage. This raises concerns that a through-wall crack may go undetected for years."*

Response: The experience at Davis-Besse has clearly demonstrated that effective visual inspection for leakage from CRDM nozzle and weld PWSCC requires unobstructed inspection access and that the head surface be free of pre-existing boric acid deposits. Accumulations of debris and boric acid deposits from other sources can interfere with a determination as to the presence or absence of boric acid deposits extruding from the tube-to-head annulus. Therefore, to effectively perform a visual examination of the RPV head outer surface for penetration leakage, such deposits and debris accumulations must be carefully inspected, removed, and the area re-inspected. Evaluation may show that it is necessary to perform a non-visual examination to establish the source of the leakage.

Accordingly, each inspection at Braidwood Station, Units 1 and 2 has been, and will continue to be conducted with a questioning attitude and any boric acid deposit on the vessel head will be evaluated to determine its source in accordance with existing industry guidance, supplemented by the most recent industry experience at the time of the inspection. These requirements are incorporated in the visual inspection guidance contained in the MRP Inspection Plan. Implementation of these requirements will preclude the condition of a through-wall crack remaining undetected for years.

As reported in Reference 11, the BMV inspection of the Braidwood Station, Unit 2 RPV head identified evidence of previous leakage from thermocouple/ reactor vessel level instrumentation system bolted connections. Boric acid staining was seen on several penetration housings. However, there were no fixed boric acid deposits on the RPV head surface. Loose deposits of boric acid trailing down from the penetration housings were negligible and were cleaned as part of the examination process. Post-cleaning examinations did not reveal evidence of any carbon steel head wastage. In addition, debris accumulated around the VHPs that could interfere with leakage detection was vacuumed and a post cleaning examination was performed. There was not evidence of any active leakage or leakage from any VHP.

Based on history of boric acid leakage reported in Reference 12 and considering that at Braidwood Station all the CRDM housing to VHP connections are welded connections, the condition of the Braidwood Station, Unit 1 RPV head is expected to also be free of fixed boric acid deposits.

Concern 6: *"The causative conditions surrounding the degradation of the RPV head at Davis-Besse have not been definitively determined. The staff is unaware of any data applicable to the geometries of interest that support accurate predictions of corrosion mechanisms and rates."*

Response: Exelon considers the causes of the Davis-Besse degradation to be sufficiently well known to avoid significant wastage. The root cause evaluation performed by the utility (Ref. 6) identifies the root cause as PWSCC of CRDM nozzles followed by boric acid corrosion. The large extent of degradation has been attributed to failure of the utility to address evidence that had been accumulating over a five year period of time (Figure 26 of Ref. 6).

The industry has provided utilities with guidance for vessel top head visual inspections to ensure that conditions approaching that which existed at Davis-Besse will not occur. Visual inspection guidelines have been provided (Ref. 2), and a workshop was conducted to thoroughly review industry experience, regulatory requirements, leakage detection, and analytical work performed to understand the causes of high wastage rates (Ref. 7).

Subsequent to significant wastage being discovered on the Davis-Besse RPV head, the industry has performed analyses to determine how a small leak such as seen at several plants can progress to the significant amounts of wastage discovered at Davis-Besse. These analyses are referenced within the basis for the MRP Inspection Plan (Ref. 1) and was previously presented to the NRC (Ref. 8).

The analyses show that the corrosion rate is a strong function of the leakage rate. Finite element thermal analyses show that leak rates must reach approximately 0.1 gpm for there to be sufficient cooling of the RPV top head surface to support concentrated liquid boric acid that will produce high corrosion rates. The leak rate is in turn a strong function of the crack length. The effect of crack length above the J-groove weld on crack opening displacement and area has been confirmed by finite element modeling of nozzles, including the effects of welding residual stresses and axial cracks. Leak rates have been calculated using crack opening displacements and areas determined by the finite element analyses, and leak rate models based on PWSCC cracks in steam generator tubes.

Cracks that just reach the annulus through the base metal or weld metal will result in small leaks such as those that produced small volumes of boric acid deposits on several vessel heads at locations where the CRDM nozzles penetrate the RPV head outside surface. These leaks are typically on the order of 10^{-6} to 10^{-4} gpm. There is no report of any of these leaks resulting in significant corrosion. A leak rate of 10^{-3} gpm will result in the release of about 500 in^3 of boric acid deposits in an 18-month operating cycle, which will be detectable by visual inspections.

The time for a crack to grow from a length that will produce a leak rate of 10^{-3} gpm to a leak rate of 0.1 gpm has been estimated by deterministic analyses based on the MRP crack growth models to be 1.7 years for plants with 602°F head temperatures. Probabilistic analyses show that there is less than a 1×10^{-3} probability that corrosion will proceed to the point that the inside surface cladding of the head would be uncovered over a significant area before the wastage would be detected by supplemental visual inspections as required under the MRP Inspection Plan. During the transition from leak rates of 10^{-3} gpm to 0.1 gpm, loss of material will be by relatively slow processes (Ref. 1).

The ability to detect leakage prior to the risk of structural failure is illustrated by Figure 26 of the Davis-Besse root cause analysis report. There was visual evidence of boric acid deposits on the vessel head for five years prior to the degradation being detected. Guidance provided in the MRP Inspection Plan would not permit these conditions to exist without determining the source of the leak, including non-destructive examinations if necessary.

Therefore, while the exact timing of the event progression at Davis-Besse cannot be definitively established, the probable durations can be predicted with sufficient certainty to conclude that a visual inspection regimen can ensure continued structural integrity of the RCS pressure boundary.

REFERENCES

1. Letter from Christine King (MRP) to Alex Marion (NEI), "PWR Reactor Pressure Vessel (RPV) Upper Head Penetrations Inspection Plan (MRP-75), Revision 1, EPRI Technical Report 1007337," dated September 2002
2. EPRI Technical Report 1006899, "Visual Examination for Leakage of PWR Reactor Head Penetrations on Top of the RPV Head: Revision 1," March 2002
3. EPRI Technical Report 103696, "PWSCC of Alloy 600 Materials in PWR Primary System Penetrations," July 1994
4. EPRI Document MRP-55, "Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Material," July 2002
5. Walton Jensen, NRC, Reactor Systems Branch, Division of Systems Safety and Analysis (DSSA), "Sensitivity Study of PWR Reactor Vessel Breaks," memo to Gary Holahan, NRC, DSSA, May 10, 2002
6. Davis-Besse Nuclear Power Station Report CR2002-0891, "Root Cause Analysis Report – Significant Degradation of the Reactor Pressure Vessel Head," April 2002
7. EPRI Technical Report 1007336, "Proceedings of the EPRI Boric Acid Corrosion Workshop, July 25-26, 2002 (MRP-77)," September 2002
8. Glenn White, Chuck Marks and Steve Hunt, "Technical Assessment of Davis-Besse Degradation," Presentation to NRC Technical Staff, May 22, 2002

9. Letter from J. A. Benjamin (Exelon Generation Company, LLC) to NRC," Exelon/AmerGen Sixty-Day Response to NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated May 17, 2001
10. Letter from J. D. von Suskil (Exelon Generation Company, LLC) to NRC, "Braidwood Station Unit 2 Response to Requested Action 5 of NRC Bulletin 2001-01,"Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles," dated June 11, 2002
11. Letter from J. D. von Suskil (Exelon Generation Company, LLC) to NRC, "Braidwood Station Unit 2 Thirty-Day Response to NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated June 11, 2002
12. Letter from J. A. Benjamin (Exelon Generation Company, LLC) to NRC, "Exelon/AmerGen Response to NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated April 1, 2002

ATTACHMENT 2

**Thirty-Day Response to NRC Bulletin 2002-02
"Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs "**

Byron Station, Units 1 and 2

Exelon Generation Company, LLC

Attachment 2

Thirty-Day Response to NRC Bulletin 2002-02
Byron Station Units 1 and 2

Exelon Generation Company (Exelon) has evaluated the expected status of Byron Station, Units 1 and 2 with regard to accrued effective full power years (EFPY) and effective degradation years (EDY) calculated in accordance with Electric Power Research Institute (EPRI) Material Reliability Program (MRP) document "PWR Materials Reliability Program Response to NRC Bulletin 2001-01 (MRP-48), 1006284 Final Report 2001," August 2001 (equation 2.1 and 2.2 respectively). The results are presented in the following table referenced to the next scheduled refueling outage for each unit:

Unit	Next Refueling Outage	EDY
1	September 2003	2.0
2	September 2002	1.8

The Exelon responses to NRC Bulletin 2002-01 addressed the adequacy of visual inspection for compliance with the design and licensing basis of the plants (Ref. 10). Those responses are still applicable with respect to the inspection adequacy and planned actions. Additional technical justification for the adequacy of the inspections is provided in this response to NRC Bulletin 2002-02.

The bare metal visual (BMV) inspection of the Byron Station, Unit 2 reactor pressure vessel (RPV) was committed to in Reference 11. The BMV inspection of Byron Station, Unit 2 is scheduled for September 2002 during the fall refueling outage as reported in Reference 11.

The MRP Inspection Plan has been developed, reviewed, and approved by the PWR utilities (Refs. 1 and 2). It presents a technically credible inspection regimen that assures to a high degree of certainty, that leaks will be detected at an early stage long before wastage or circumferential cracking can challenge the structural integrity of the reactor coolant system (RCS) pressure boundary. Furthermore, implementation of the MRP Inspection Plan will assure continued compliance with the regulatory guidance cited within NRC Bulletin 2002-02.

Byron Station will implement the MRP Inspection Plan and will comply with its guidance beginning with the conduct of the next planned BMV inspection of Unit 2 in September 2002, and Unit 1 in September 2003. The MRP Inspection Plan encompasses the inspection commitments made in our responses to NRC Bulletin 2001-01 and NRC Bulletin 2002-01, but is more rigorous.

Exelon provides the following justification for continued reliance on visual examinations as the primary method to detect degradation in the RPV head. Included in these responses are discussions on the reliability and effectiveness of visual examinations as they relate to the six concerns cited in NRC Bulletin 2002-02, and the basis for concluding that unacceptable wastage will not occur between refueling outages.

Concern 1: *"Circumferential cracking of CRDM nozzles was identified by the presence of relatively small amounts of boric acid deposits. This finding increases the need for more effective visual and non-visual NDE inspection methods to detect the presence of degradation in CRDM nozzles before nozzle integrity is compromised."*

Response: Since the initial industry discovery of circumferential cracks above the J-groove weld in 2001, visual inspection techniques and approaches employed have been dramatically improved and a heightened sense of awareness exists for the range in size and appearance of visual indications that must be further investigated. Non-visual techniques similarly continue to evolve to more effectively examine the penetration tube and associated welds for evidence of cracks. The recent events at Davis-Besse have not altered the fundamental inspection capability requirements previously established as necessary to identify the presence of primary water stress corrosion cracking (PWSCC) and subsequent associated wastage. The effectiveness of inspection techniques continues to be evaluated and improved.

The EPRI MRP has published detailed guidance for performing visual examinations of RPV heads (Ref. 2). A utility workshop was recently conducted to discuss this guidance and lessons learned from recent field experience, including Davis-Besse. An RPV head bare metal visual inspections at Byron Station, Units 1 and 2 will be performed and documented in accordance with written procedures and acceptance criteria that met the guidance of the MRP Inspection Plan. Evaluations and corrective actions will be rigorous and thoroughly documented.

In order for outside diameter (OD) circumferential cracks above the J-groove weld to initiate and grow, a leak path must first be established to the control rod drive mechanism (CRDM) annulus region from the inner wetted surface of the reactor vessel head. If primary water does not leak to the annulus, the environment does not exist to cause circumferential OD cracking. Axial cracks in the CRDM nozzles or cracks in J-groove welds must first initiate and grow through-wall. Experience has shown that through-wall axial cracks will result in observable leakage at the base of the penetration on the outer surface of the vessel, even with interference fits. Alloy 600 steam generator drain pipes at Shearon Harris (1988) and pressurizer instrument nozzles at Nogent 1 and Cattenom 2 (1989) were all roll expanded but still developed leaks during operation (Ref. 3). Plant specific top head gap analyses have been performed for a large number of plants, with nozzle initial interference fits ranging from 0 to 0.0034 inches. These analyses have confirmed the presence of a physical leak path in essentially all nozzles under normal operating pressure and temperature conditions (Ref.1).

The probability of detecting small CRDM leaks by visual inspections alone is high. Visual inspections of the RCS pressure boundary have been proven to be an effective method for identifying leakage from PWSCC cracks in Alloy 600 base metal and Alloy 82/182 weld metal. Specifically, visual inspections have detected leaks in RPV head CRDM nozzles, RPV head thermocouple nozzles, pressurizer heater sleeves, pressurizer instrument nozzles, hot leg instrument nozzles, steam generator drain lines, an RPV hot leg nozzle weld, a power operated relief valve safe end and a pressurizer manway diaphragm plate (Ref. 3). To date, no leaking CRDM nozzles have been discovered by non-visual NDE examinations except for the three nozzles at Davis-Besse where leakage would have been detected visually had there been good access for visual inspections and the head cleaned of pre-existing boric acid deposits from other sources (Ref. 1).

Finally, as described in our response to Concern 3 below, detailed probabilistic fracture mechanics (PFM) analyses have been performed to demonstrate the effectiveness of visual inspections in protecting the CRDM nozzles against failure due to circumferential cracking (Ref. 1). Even though the above discussion illustrates that visual inspections performed in accordance with MRP recommendations have a high probability of detecting through-wall leakage, a very low probability of detection was assumed in the PFM analyses. The PFM analyses assume only a 60% probability that leakage will be detected if a CRDM nozzle is leaking at the time a visual inspection is performed. Furthermore, if a nozzle has been inspected previously, and leakage was missed, subsequent visual inspections are assumed to have only a 12% probability of detecting the leak. Even with these conservative probability of detection assumptions, the PFM analyses show that visual inspection every outage reduces the probability of a nozzle ejection to an acceptable level for plants with 18 or more EDY. Visual inspections of plants with fewer than 18 EDY in accordance with the MRP Inspection Plan will maintain the probability of nozzle ejection for these plants more than an order of magnitude lower than that for the greater than 18 EDY plants.

In summary, the industry has responded to the need to detect small amounts of leakage by increased visual inspection sensitivity, increased inspection frequencies, and improved inspection capabilities. Small amounts of leakage can be detected visually and it has been shown that timely detection by visual examination will ensure the structural integrity of the RPV head penetrations with respect to circumferential cracking.

Concern 2: *"Cracking of 82/182 weld metal has been identified in CRDM nozzle J-groove welds for the first time and can precede cracking of the base metal. This finding raises concerns because examination of weld metal material is more difficult than base metal."*

Response: Cracks in the J-groove weld do not pose an increased risk regarding nozzle ejection as compared to penetration base metal cracks. J-groove weld cracks that initiate and grow through-wall will leak the same as cracks in the penetration base metal. Therefore, weld cracks pose a similar risk as cracks in the base material and are equally detectable by visual examination. Although higher crack growth rates have been observed in laboratory testing of weld metal, the industry model of time-to-leakage includes plants that have had weld metal cracking as well as base metal cracking. The visual examination frequencies from the MRP Inspection Plan have been conservatively established based on the risk informed analyses considering leakage due to both weld metal and base metal cracking.

Concern 3: *"Through-wall circumferential cracking from the outside diameter of the CRDM nozzle has been identified for the first time. This raises concerns about the potential for failure of CRDM nozzles and control rod ejection, causing a LOCA."*

Response: PFM analyses using a Monte-Carlo simulation algorithm were performed to estimate the probability of nozzle failure and control rod ejection due to through-wall circumferential cracking (Ref. 1). The PFM analyses conservatively assume that, once a leak path has extended to the annulus region, an OD circumferential crack develops instantaneously, with a length encompassing 30° of the nozzle circumference. Fracture mechanics crack growth calculations are then performed for this initially assumed crack, using material crack growth rate data from EPRI Report MRP-55 (Ref. 4). The parameters used in the PFM model were benchmarked against the most severe cracking found to date in the industry (B&W Plants) and produced results that are in agreement with experience to date. The analyses were used to determine probability of nozzle failure versus EFPY for various head operating temperatures. Analyses were then performed to estimate the effect of visual and non-visual (NDE) inspections of the plants in the most critical inspection category, using the conservative assumption discussed above (see Concern 1 response) for probability of leakage detection by visual inspection. These analyses demonstrate that performing visual inspections significantly reduces the probability of nozzle ejection, and that performing such examinations on a regular basis, in accordance with the inspection schedule prescribed in the MRP Inspection Plan, effectively maintains the probability of nozzle ejection at an acceptably low level indefinitely.

In the extremely unlikely event that nozzle failure and rod ejection were to occur due to an undetected circumferential crack, an acceptable margin of safety would still be maintained (Ref. 5).

The consequences of such an event are similar to that of a small-break loss of coolant accident, which is a design-basis event. The probability of core damage given a nozzle failure, assuming that failure leads to ejection of the nozzle from the head, has been estimated to be 1×10^{-3} per plant year. The PFM analyses demonstrate that periodic visual inspections are capable of maintaining the probability of nozzle failure due to circumferential cracking well below 1×10^{-3} per plant year. Therefore, the PFM analyses demonstrate that the resulting incremental change in core damage frequency due to CRDM nozzle cracking can be maintained at less than 1×10^{-6} (i.e., 1×10^{-3} times 1×10^{-3} equals 1×10^{-6}) per plant year, through a program of periodic visual examinations performed in accordance with the MRP inspection plan. This result is consistent with NRC Regulatory Guide 1.174,"An Approach for Using Probabilistic Risk Assessment in Risk–Informed Decisions on Plant–Specific Changes to the Licensing Bases," that defines an acceptable change in core damage frequency (i.e.,1×10^{-6} per plant year) for changes including plant design parameters, and technical specifications.

Concern 4: *"The environment in the CRDM housing/RPV head annulus will likely be more aggressive after any through-wall leakage because potentially highly concentrated borated primary water may become oxygenated. This raises concerns about the technical basis for current crack growth rate models."*

Response: Prior to the Davis-Besse incident, the MRP panel of international experts on stress corrosion cracking (SCC), including representatives from Argonne National Laboratory and the NRC Office of Research, gave extensive consideration to the likely environment in the annulus between a leaking CRDM nozzle and the RPV head and have subsequently re-evaluated this issue (Ref. 4). When re-evaluated, the relevant arguments remain valid for leak rates that are less than 1 liter/h or 0.004 gpm, which plant experience has shown to be the usual case. The conclusions were:

1. An oxygenated crevice environment is highly unlikely because:
   - Back diffusion of oxygen is too low compared to counterflow of escaping steam (two independent assessments based on molecular diffusion models were examined).
   - Oxygen consumption by the metal walls would further reduce its concentration.
   - Presence of hydrogen from leaking water and diffusion through the upper head results in a reducing environment.
   - Even if the concentration of hydrogen was depleted by local boiling, coupling between low alloy steel and Alloy 600 would keep the electrochemical potential low.
   - Corrosion potential will be close to the Ni/NiO equilibrium, resulting in PWSCC susceptibility similar to normal primary water.

2. The most likely crevice environments are either hydrogenated steam or PWR primary water within normal specifications. Both of which would result in similar, i.e., non-accelerated, susceptibility of the Alloy 600 penetration material to PWSCC.

3. If the boiling interface happens to be close to the topside of the J-weld, itself a low probability occurrence, concentration of PWR primary water solutes, lithium hydroxide, and boric acid, can occur in principle. Of most concern, would be the accelerating effect of elevated pH on SCC, but calculations and experiments show that any changes are expected to be small, in part because of the buffering effects of precipitates. A factor of 2x on the crack growth rate (CGR) conservatively bounds possible acceleration of PWSCC up to a high-temperature pH of approximately 9.

For larger leakage rates, which could lead to local cooling of the head, concentration of boric acid, and development of a sizeable wastage cavity adjacent to the penetration, the above arguments no longer directly apply. However, limited data (i.e.,Berge et al., 1997) on SCC in concentrated boric acid solutions indicate that

- Alloy 600 is very resistant to transgranular SCC (material design basis).
- High levels of oxygen <u>and</u> chloride are necessary for intergranular cracking to occur.
- The cracking is then worse at intermediate temperatures, suggesting that the mechanism is different from PWSCC.

The above considerations show that there is no basis for assuming that any post-leakage, crevice environment in the CRDM housing/RPV head annulus would be significantly more aggressive with regard to SCC of the Alloy 600 penetration material than normal PWR primary water, irrespective of the assumed leakage rate and/or annulus geometry. The current industry model (Ref. 4), which includes a factor of 2x on CGR to cover residual uncertainty in the composition of the annulus environment, remains valid.

Concern 5: *"The presence of boron deposits or residue on the RPV head, due to leakage from mechanical joints, could mask pressure boundary leakage. This raises concerns that a through-wall crack may go undetected for years."*

Response: The experience at Davis-Besse has clearly demonstrated that effective visual inspection for leakage from CRDM nozzle and weld PWSCC requires unobstructed inspection access and that the head surface be free of pre-existing boric acid deposits. Accumulations of debris and boric acid deposits from other sources can interfere with a determination as to the presence or absence of boric acid deposits extruding from the tube-to-head annulus. Therefore, to effectively perform a visual examination of the RPV head outer surface for penetration leakage, such deposits and debris accumulations must be carefully inspected, removed, and the area re-inspected. Evaluation may show that it is necessary to perform a non-visual examination to establish the source of the leakage.

Accordingly, each inspection at Byron Station, Units 1 and 2, will be conducted with a questioning attitude and any boric acid deposit on the vessel head will be evaluated to determine its source in accordance with existing industry guidance, supplemented by the most recent industry experience at the time of the inspection. These requirements are incorporated in the visual inspection guidance contained in the MRP Inspection Plan. Implementation of these requirements will preclude the condition of a through-wall crack remaining undetected for years.

On March 18, 2002, the NRC issued NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity." This bulletin required that within 30 days after plant restart following the next inspection of the RPV head, information regarding the inspection scope, results, and corrective actions taken be provided to the NRC. Byron Station provided this information for Unit 1 to the NRC (Ref. 9). The results of the pre-outage and post-outage VT-2 examinations performed on the accessible areas on top of the RPV head (i.e., control rod drive mechanism housings) at normal reactor coolant system pressure, showed no evidence of leakage, boric acid residue, or material wastage. Inspections for Byron Station, Unit 2 are yet to be performed and the results will be provided to the NRC in accordance with the Bulletin requirements.

Concern 6: *"The causative conditions surrounding the degradation of the RPV head at Davis-Besse have not been definitively determined. The staff is unaware of any data applicable to the geometries of interest that support accurate predictions of corrosion mechanisms and rates."*

Response: Exelon considers the causes of the Davis-Besse degradation to be sufficiently well known to avoid significant wastage. The root cause evaluation performed by the utility (Ref. 6) identifies the root cause as PWSCC of CRDM nozzles followed by boric acid corrosion. The large extent of degradation has been attributed to failure of the utility to address evidence that had been accumulating over a five year period of time (Figure 26 of Ref. 6).

The industry has provided utilities with guidance for vessel top head visual inspections to ensure that conditions approaching that which existed at Davis-Besse will not occur. Visual inspection guidelines have been provided (Ref. 2), and a workshop was conducted to thoroughly review industry experience, regulatory requirements, leakage detection, and analytical work performed to understand the causes of high wastage rates (Ref. 7).

Subsequent to significant wastage being discovered on the Davis-Besse RPV head, the industry has performed analyses to determine how a small leak such as seen at several plants can progress to the significant amounts of wastage discovered at Davis-Besse. These analyses are referenced within the basis for the MRP Inspection Plan (Ref. 1) and was previously presented to the NRC (Ref. 8).

The analyses show that the corrosion rate is a strong function of the leakage rate. Finite element thermal analyses show that leak rates must reach approximately 0.1 gpm for there to be sufficient cooling of the RPV top head surface to support concentrated liquid boric acid that will produce high corrosion rates. The leak rate is in turn a strong function of the crack length. The effect of crack length above the J-groove weld on crack opening displacement and area has been confirmed by finite element modeling of nozzles, including the effects of welding residual stresses and axial cracks. Leak rates have been calculated using crack opening displacements and areas determined by the finite element analyses and leak rate models based on PWSCC cracks in steam generator tubes.

Cracks that just reach the annulus through the base metal or weld metal will result in small leaks such as those that produced small volumes of boric acid deposits on several vessel heads at locations where the CRDM nozzles penetrate the RPV head outside surface. These leaks are typically on the order of 10^{-6} to 10^{-4} gpm. There is no report of any of these leaks resulting in significant corrosion. A leak rate of 10^{-3} gpm will result in the release of about 500 in^3 of boric acid deposits in an 18-month operating cycle, which will be detectable by visual inspections.

The time for a crack to grow from a length that will produce a leak rate of 10^{-3} gpm to a leak rate of 0.1 gpm has been estimated by deterministic analyses based on the MRP crack growth models to be 1.7 years for plants with 602°F head temperatures. Probabilistic analyses show that there is less than a 1×10^{-3} probability that corrosion will proceed to the point that the inside surface cladding of the head would be uncovered over a significant area before the wastage would be detected by supplemental visual inspections as required under the MRP Inspection Plan. During the transition from leak rates of 10^{-3} gpm to 0.1 gpm, loss of material will be by relatively slow processes (Ref. 1).

The ability to detect leakage prior to the risk of structural failure is illustrated by Figure 26 of the Davis-Besse root cause analysis report. There was visual evidence of boric acid deposits on the vessel head for five years prior to the degradation being detected. Guidance provided in the

MRP Inspection Plan would not permit these conditions to exist without determining the source of the leak, including non-destructive examinations if necessary.

Therefore, while the exact timing of the event progression at Davis-Besse cannot be definitively established, the probable durations can be predicted with sufficient certainty to conclude that a visual inspection regimen can ensure continued structural integrity of the RCS pressure boundary.

1. Letter from Christine King (MRP) to Alex Marion (NEI), "PWR Reactor Pressure Vessel (RPV) Upper Head Penetrations Inspection Plan (MRP-75), Revision 1, EPRI Technical Report 1007337," dated September 2002
2. EPRI Technical Report 1006899, "Visual Examination for Leakage of PWR Reactor Head Penetrations on Top of the RPV Head: Revision 1," March 2002
3. EPRI Technical Report 103696, "PWSCC of Alloy 600 Materials in PWR Primary System Penetrations," July 1994
4. EPRI Document MRP-55, "Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Material," July 2002
5. Walton Jensen, NRC, Reactor Systems Branch, Division of Systems Safety and Analysis (DSSA), "Sensitivity Study of PWR Reactor Vessel Breaks," memo to Gary Holahan, NRC, DSSA, May 10, 2002
6. Davis-Besse Nuclear Power Station Report CR2002-0891, "Root Cause Analysis Report – Significant Degradation of the Reactor Pressure Vessel Head," April 2002.
7. EPRI Technical Report 1007336, "Proceedings of the EPRI Boric Acid Corrosion Workshop, July 25-26, 2002 (MRP-77)," September 2002
8. Glenn White, Chuck Marks and Steve Hunt, "Technical Assessment of Davis-Besse Degradation," Presentation to NRC Technical Staff, May 22, 2002
9. Letter from R. P. Lopriore (Exelon Generation Company, LLC) to NRC, "Byron Station Unit 1 Response to NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated April 26, 2002
10. Letter from J. A. Benjamin (Exelon Generation Company, LLC) to NRC," Exelon/AmerGen Sixty-Day Response to NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated May 17, 2002
11. Letter from R. P. Lopriore (Exelon Generation Company, LLC) to NRC, "Response to Request for Additional Information Regarding Inspection Plans for the Byron Station Unit 2 Reactor Vessel Head During the Fall 2002 Refueling Outage in Support of NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated July 26, 2002

ATTACHMENT 3

Thirty-Day Response to NRC Bulletin 2002-02
"Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs "

Three Mile Island, Unit 1

AmerGen Energy Company, LLC (AmerGen)

Attachment 3

Thirty-Day Response to NRC Bulletin 2002-02

Three Mile Island (TMI), Unit 1

The AmerGen response to NRC Bulletin 2002-01 addressed the adequacy of visual inspection for compliance with the design and licensing basis of TMI Unit 1 (Ref. 9). Those responses are still applicable with respect to inspection adequacy and planned actions. Additional technical justification for the adequacy of the inspections is provided in this response to NRC Bulletin 2002-02.

AmerGen previously committed to perform a qualified bare metal visual inspection to detect leakage/boric acid deposits on all reactor vessel head thermocouple (TC) nozzles and control rod drive mechanism (CRDM) nozzles, and ultrasonic testing (UT) examination in the nozzle and penetrant testing (PT) examination on the associated J-groove weld for any CRDM nozzle found leaking for TMI Unit 1 (Ref. 10). The last inspection of the TMI Unit 1 reactor pressure vessel (RPV) head penetration nozzles was completed following the October 9, 2001, shutdown in support of the planned refueling outage as reported in References 11 and 12. As stated in Reference 12, TMI Unit 1 is planning to replace the RPV head in the next refueling outage scheduled for Fall of 2003. The replacement RPV head will contain Alloy 690 nozzles and equivalent weld metal that will significantly reduce susceptibility to primary water stress corrosion cracking (PWSCC) in the head penetrations. Industry guidance is being developed for the inspection criteria of replacement RPV heads. AmerGen will develop inspection plans based on the Electric Power Research Institute (EPRI) Materials Reliability Program (MRP) guidance and industry standards. AmerGen will provide inspection plans for the replacement RPV head to the NRC prior to reaching the three and five year inspection intervals delineated in NRC Bulletin 2002-02 for low susceptibility RPV heads (i.e.,< 8 EDY), or provide an alternative inspection plan if industry guidance has not been finalized at that time.

AmerGen provides the following justification for continued reliance on visual examinations as the primary method to detect degradation in the RPV head. Included in these responses are discussions on the reliability and effectiveness of visual examinations as they relate to the six concerns cited in Bulletin 2002-02 and the basis for concluding that significant RPV head wastage will not occur between refueling outages.

Concern 1: *"Circumferential cracking of CRDM nozzles was identified by the presence of relatively small amounts of boric acid deposits. This finding increases the need for more effective visual and non-visual NDE inspection methods to detect the presence of degradation in CRDM nozzles before nozzle integrity is compromised."*

Response: Since the initial industry discovery of circumferential cracks above the J-groove weld in 2001, visual inspection techniques and approaches employed have been dramatically improved and a heightened sense of awareness exists for the range in size and appearance of visual indications that must be further investigated. Non-visual techniques similarly continue to evolve to more effectively examine the penetration tube and associated welds for evidence of cracks. The recent events at Davis-Besse have not altered the fundamental inspection capability requirements previously established as necessary to identify the presence of primary water stress corrosion cracking (PWSCC) and subsequent associated wastage. The effectiveness of inspection techniques continues to be evaluated and improved.

The EPRI MRP has published detailed guidance for performing visual examinations of RPV heads (Ref. 2). A utility workshop was recently conducted to discuss this guidance and lessons learned from recent field experience, including Davis-Besse. An RPV head bare metal visual inspections at TMI Unit 1 have been performed and documented in accordance with written procedures and acceptance criteria that met with the guidance of the MRP Inspection Plan. Evaluations and corrective actions have been rigorously and thoroughly documented in Reference 13.

In order for outside diameter (OD) circumferential cracks above the J-groove weld to initiate and grow, a leak path must first be established to the control rod drive mechanism (CRDM) annulus region from the inner wetted surface of the reactor vessel head. If primary water does not leak to the annulus, the environment does not exist to cause circumferential OD cracking. Axial cracks in the CRDM nozzles or cracks in J-groove welds must first initiate and grow through-wall. Experience has shown that through-wall axial cracks will result in observable leakage at the base of the penetration on the outer surface of the vessel, even with interference fits. Alloy 600 steam generator drain pipes at Shearon Harris (1988) and pressurizer instrument nozzles at Nogent 1 and Cattenom 2 (1989) were all roll expanded but still developed leaks during operation (Ref. 3). Plant specific top head gap analyses have been performed for a large number of plants, with nozzle initial interference fits ranging from 0 to 0.0034 inches. These analyses have confirmed the presence of a physical leak path in essentially all nozzles under normal operating pressure and temperature conditions (Ref. 1).

The probability of detecting small CRDM leaks by visual inspections alone is high. Visual inspections of the RCS system pressure boundary have been proven to be an effective method for identifying leakage from PWSCC cracks in Alloy 600 base metal and Alloy 82/182 weld metal. Specifically, visual inspections have detected leaks in an RPV head CRDM nozzles, RPV head thermocouple nozzles, pressurizer heater sleeves, pressurizer instrument nozzles, hot leg instrument nozzles, steam generator drain lines, an RPV hot leg nozzle weld, a power operated relief valve safe end and a pressurizer manway diaphragm plate (Ref. 3). To date, no leaking CRDM nozzles have been discovered by non-visual NDE examinations except for the three nozzles at Davis-Besse where leakage would have been detected visually had there been good access for visual inspections and the head cleaned of pre-existing boric acid deposits from other sources (Ref. 1).

Finally, as described in our response to Concern 3 below, detailed probabilistic fracture mechanics (PFM) analyses have been performed to demonstrate the effectiveness of visual inspections in protecting the CRDM nozzles against failure due to circumferential cracking (Ref. 1). Even though the above discussion illustrates that visual inspections performed in accordance with MRP recommendations have a high probability of detecting through-wall leakage, a very low probability of detection was assumed in the PFM analyses. The PFM analyses assume only a 60% probability that leakage will be detected if a CRDM nozzle is leaking at the time a visual inspection is performed. Furthermore, if a nozzle has been inspected previously, and leakage was missed, subsequent visual inspections are assumed to have only a 12% probability of detecting the leak. Even with these conservative probabilities of detection assumptions, the PFM analyses show that visual inspection every outage reduces the probability of a nozzle ejection to an acceptable level for plants with 18 or more EDY. Visual inspections of plants with fewer than 18 EDY in accordance with the MRP Inspection Plan will maintain the probability of nozzle ejection for these plants more than an order of magnitude lower than that for the greater than 18 EDY plants.

In summary, the industry has responded to the need to detect small amounts of leakage by increased visual inspection sensitivity, increased inspection frequencies, and improved inspection capabilities. Small amounts of leakage can be detected visually and it has been shown that timely detection by visual examination will ensure the structural integrity of the RPV head penetrations with respect to circumferential cracking.

Concern 2: *"Cracking of 82/182 weld metal has been identified in CRDM nozzle J-groove welds for the first time and can precede cracking of the base metal. This finding raises concerns because examination of weld metal material is more difficult than base material."*

Response: Cracks in the J-groove weld do not pose an increased risk regarding nozzle ejection as compared to penetration base material cracks. J-groove weld cracks that initiate and grow through-wall will leak the same as cracks in the penetration base material. Therefore, weld cracks pose a similar risk as cracks in the base material and are equally detectable by visual examination. Although higher crack growth rates have been observed in laboratory testing of weld metal, the industry model of time-to-leakage includes plants that have had weld material cracking as well as base metal cracking. The visual examination frequencies from the MRP Inspection Plan have been conservatively established based on the risk informed analyses considering leakage due to both weld metal and base material cracking.

Concern 3: *"Through-wall circumferential cracking from the outside diameter of the CRDM nozzle has been identified for the first time. This raises concerns about the potential for failure of CRDM nozzles and control rod ejection, causing a LOCA."*

Response: PFM analyses using a Monte-Carlo simulation algorithm were performed to estimate the probability of nozzle failure and control rod ejection due to through-wall circumferential cracking (Ref. 1). The PFM analyses conservatively assume that, once a leak path has extended to the annulus region, an OD circumferential crack develops instantaneously, with a length encompassing 30° of the nozzle circumference. Fracture mechanics crack growth calculations are then performed for this initially assumed crack, using material crack growth rate data from EPRI Report MRP-55 (Ref. 4). The parameters used in the PFM model were benchmarked against the most severe cracking found to date in the industry (B&W Plants) and produced results that are in agreement with experience to date. The analyses were used to determine probability of nozzle failure versus EFPY for various head operating temperatures. Analyses were then performed to estimate the effect of visual and non-visual (NDE) inspections of the plants in the most critical inspection category, using the conservative assumption discussed above (see Concern 1 response) for probability of leakage detection by visual inspection. These analyses demonstrate that performing visual inspections significantly reduces the probability of nozzle ejection, and that performing such examinations on a regular basis, in accordance with the inspection schedule prescribed in the MRP Inspection Plan, effectively maintains the probability of nozzle ejection at an acceptably low level indefinitely.

In the extremely unlikely event that nozzle failure and rod ejection were to occur due to an undetected circumferential crack, an acceptable margin of safety would still be maintained (Ref. 5). The consequences of such an event are similar to that of a small-break loss of coolant accident, which is a design-basis event. The probability of core damage given a nozzle failure, assuming that failure leads to ejection of the nozzle from the head, has been estimated to be 1×10^{-3} per plant year. The PFM analyses demonstrate that periodic visual inspections are capable of maintaining the probability of nozzle failure due to circumferential cracking well below 1×10^{-3} per plant year. Therefore, the PFM analyses demonstrate that the resulting incremental change in core damage frequency due to CRDM nozzle cracking can be maintained at less than 1×10^{-6} (i.e., 1×10^{-3} times 1×10^{-3} equals 1×10^{-6}) per plant year, through a program of periodic visual examinations performed in accordance with the MRP Inspection Plan. This result is consistent with NRC Regulatory Guide 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk–Informed

Decisions on Plant–Specific Changes to the Licensing Bases," that defines an acceptable change in core damage frequency (1 x 10^{-6} per plant year) for changes including plant design parameters, and technical specifications.

Concern 4: *"The environment in the CRDM housing/RPV head annulus will likely be more aggressive after any through-wall leakage because potentially highly concentrated borated primary water may become oxygenated. This raises concerns about the technical basis for current crack growth rate models."*

Response: Prior to the Davis-Besse incident, the MRP panel of international experts on stress corrosion cracking (SCC), including representatives from Argonne National Laboratory and the NRC Office of Research, gave extensive consideration to the likely environment in the annulus between a leaking CRDM nozzle and the RPV head and have subsequently re-evaluated this issue (Ref. 4). When re-evaluated, the relevant arguments remain valid for leak rates that are less than 1 liter/h or 0.004 gpm, which plant experience has shown to be the usual case. The conclusions were:

1. An oxygenated crevice environment is highly unlikely because:

   - Back diffusion of oxygen is too low compared to counterflow of escaping steam (two independent assessments based on molecular diffusion models were examined).
   - Oxygen consumption by the metal walls would further reduce its concentration.
   - Presence of hydrogen from leaking water and diffusion through the upper head results in a reducing environment.
   - Even if the concentration of hydrogen was depleted by local boiling, coupling between low alloy steel and Alloy 600 would keep the electrochemical potential low.
   - Corrosion potential will be close to the Ni/NiO equilibrium, resulting in PWSCC susceptibility similar to normal primary water.

2. The most likely crevice environments are either hydrogenated steam or PWR primary water within normal specifications. Both of which would result in similar, i.e., non-accelerated, susceptibility of the Alloy 600 penetration material to PWSCC.

3. If the boiling interface happens to be close to the topside of the J-weld, itself a low probability occurrence, concentration of PWR primary water solutes, lithium hydroxide, and boric acid, can occur in principle. Of most concern, would be the accelerating effect of elevated pH on SCC, but calculations and experiments show that any changes are expected to be small, in part because of the buffering effects of precipitates. A factor of 2x on the crack growth rate (CGR) conservatively bounds possible acceleration of PWSCC up to a high-temperature pH of approximately 9.

   For larger leakage rates, which could lead to local cooling of the head, concentration of boric acid, and development of a sizeable wastage cavity adjacent to the penetration, the above arguments no longer directly apply. However, limited data (i.e., Berge et al., 1997) on SCC in concentrated boric acid solutions indicate that:

   - Alloy 600 is very resistant to transgranular SCC (material design basis).
   - High levels of oxygen <u>and</u> chloride are necessary for intergranular cracking to occur.
   - The cracking is then worse at intermediate temperatures, suggesting that the mechanism is different from PWSCC.

The above considerations show that there is no basis for assuming that any post-leakage, crevice environment in the CRDM housing/RPV head annulus would be significantly more aggressive with regard to SCC of the Alloy 600 penetration material than normal PWR primary water, irrespective of the assumed leakage rate and/or annulus geometry. The current industry model (Ref. 4), which includes a factor of 2x on CGR to cover residual uncertainty in the composition of the annulus environment, remains valid.

Concern 5: *"The presence of boron deposits or residue on the RPV head, due to leakage from mechanical joints, could mask pressure boundary leakage. This raises concerns that a through-wall crack may go undetected for years."*

Response: The experience at Davis-Besse has clearly demonstrated that effective visual inspection for leakage from CRDM nozzle and weld PWSCC requires unobstructed inspection access and that the head surface be free of pre-existing boric acid deposits. Accumulations of debris and boric acid deposits from other sources can interfere with a determination as to the presence or absence of boric acid deposits extruding from the tube-to-head annulus. Therefore, to effectively perform a visual examination of the RPV head outer surface for penetration leakage, such deposits and debris accumulations must be carefully inspected, removed, and the area re-inspected. Evaluation may show that it is necessary to perform a non-visual examination to establish the source of the leakage.

Accordingly, each inspection at TMI Unit 1 has evaluated any boric acid deposit on the vessel head to determine its source in accordance with existing industry guidance, supplemented by the most recent industry experience at the time of the inspection. These requirements are incorporated in the visual inspection guidance contained in the MRP Inspection Plan. Implementation of these requirements has precluded the condition of a through-wall crack remaining undetected for years.

Detailed results of the last TMI Unit 1 RPV head inspection in refueling outage 1R14 were submitted to the NRC in AmerGen letters dated January 7, 2002 and April 1, 2002. No evidence of head wastage was observed.

Concern 6: *"The causative conditions surrounding the degradation of the RPV head at Davis-Besse have not been definitively determined. The staff is unaware of any data applicable to the geometries of interest that support accurate predictions of corrosion mechanisms and rates."*

Response: AmerGen considers the causes of the Davis-Besse degradation are sufficiently well known to avoid significant wastage. The root cause evaluation performed by the utility (Ref. 6) identifies the root cause as PWSCC of CRDM nozzles followed by boric acid corrosion. The large extent of degradation has been attributed to failure of the utility to address evidence that had been accumulating over a five-year period of time (Figure 26 of Ref. 6).

The industry has provided utilities with guidance for vessel top head visual inspections to ensure that conditions approaching that which existed at Davis-Besse will not occur. Visual inspection guidelines have been provided (Ref. 2), and a workshop was conducted to thoroughly review industry experience, regulatory requirements, leakage detection, and analytical work performed to understand the causes of high wastage rates (Ref. 7).

Subsequent to significant wastage being discovered on the Davis-Besse RPV head, the industry has performed analyses to determine how a small leak such as seen at several plants can progress to the significant amounts of wastage discovered at Davis-Besse. These analyses are referenced within the basis for the MRP Inspection Plan (Ref. 1) and was previously presented to the NRC (Ref. 8).

The analyses show that the corrosion rate is a strong function of the leakage rate. Finite element thermal analyses show that leak rates must reach approximately 0.1 gpm for there to be sufficient cooling of the RPV top head surface to support concentrated liquid boric acid that will produce high corrosion rates. The leak rate is in turn a strong function of the crack length. The effect of crack length above the J-groove weld on crack opening displacement and area has been confirmed by finite element modeling of nozzles, including the effects of welding residual stresses and axial cracks. Leak rates have been calculated using crack opening displacements and areas determined by the finite element analyses and leak rate models based on PWSCC cracks in steam generator tubes.

Cracks that just reach the annulus through the base material or weld metal will result in small leaks such as those that produced small volumes of boric acid deposits on several vessel heads at locations where the CRDM nozzles penetrate the RPV head outside surface. These leaks are typically on the order of 10^{-6} to 10^{-4} gpm. There is no report of any of these leaks resulting in significant corrosion. A leak rate of 10^{-3} gpm will result in the release of about 500 in^3 of boric acid deposits in an 18-month operating cycle, which will be detectable by visual inspections.

The time for a crack to grow from a length that will produce a leak rate of 10^{-3} gpm to a leak rate of 0.1 gpm has been estimated by deterministic analyses based on the MRP crack growth models to be 1.7 years for plants with 602°F head temperatures. For plants that operate with two-year fuel cycles (approaching 2.0 EFPYs), the potential 0.3 EFPY of operation with rapid corrosion will not exhaust the American Society of Mechanical Engineers Code (ASME) stress margins as is apparent considering an upper bound corrosion rate of 5 in/yr based on the available test data for aerated, concentrated boric acid solutions and the approximate 150 in^3 volume of allowable wastage. Up to 150 in^3 can be lost without the relevant stresses exceeding the ASME Code allowable stress values. The model shows that the probability of the wastage cavity size exceeding the allowable wastage volume of about 150 in^3 is less than 1×10^{-3} for both 1.5 and 2.0 EFPY cycles given a head temperature of 602°.

Probabilistic analyses show that there is less than a 1×10^{-3} probability that corrosion will proceed to the point that the inside surface cladding of the head would be uncovered over a significant area before the wastage would be detected by supplemental visual inspections as required under the MRP Inspection Plan. During the transition from leak rates of 10^{-3} gpm to 0.1 gpm, loss of material will be by relatively slow processes (Ref. 1).

The ability to detect leakage prior to the risk of structural failure is illustrated by Figure 26 of the Davis-Besse root cause analysis report. There was visual evidence of boric acid deposits on the vessel head for five years prior to the degradation being detected. Guidance provided in the MRP Inspection Plan would not permit these conditions to exist without determining the source of the leak, including nondestructive examinations if necessary.

Therefore, while the exact timing of the event progression at Davis-Besse cannot be definitively established, the probable durations can be predicted with sufficient certainty to conclude that a visual inspection regimen can ensure continued structural integrity of the RCS pressure boundary.

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