Duke Power®
A Duke Energy Company

R. A JONES
Vice President

Duke Power
29672 / Oconee Nuclear Site
7800 Rochester Highway
Seneca, SC 29672

864 885 3158
864 885 3564 fax

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Subject: Oconee Nuclear Station, Units 1, 2 and 3
Docket No. 50-269, 50-270, and 50-287
Bulletin 2002-02, Reactor Pressure Vessel Head and Vessel Head Penetration Nozzle Inspection Programs -
Response To Request For Information Concerning Recent Inspection Findings

On September 6, 2002, Duke Energy Corporation (Duke) provided its 30-day response to Bulletin 2002-02 for Oconee Nuclear Station, Units 1, 2 and 3. The response to the Bulletin provided a detailed response only for Oconee, Unit 2 (ONS-2) since it was the only one of the three Oconee units with a high susceptibility RVH for which the guidance provided by the bulletin would be applicable. The Oconee Units 1 and 3 RVHs are scheduled to be replaced at the end of their current refueling outage.

As a result of discussions between the NRC Staff and Duke concerning the impact to the ongoing ONS-2 RVH inspection of emerging information concerning RVHs at other nuclear power plants, additional information was requested by the Staff on October 7, 2002. The requested information is provided as Enclosure 1 to this letter.

Enclosure 2 provides the requested copy of Reference 13 from Duke's September 6, 2002 response entitled, "ONS-2 Risk Assessment For CRDM Nozzle PWSCC," dated September 2002.

There are no regulatory commitments contained in this letter or enclosures.

If you have questions are need additional information, please contact Robert Douglas at 864-885-3073.

Sincerely,

R. A. Jones,
Site Vice-president,
Oconee Nuclear Station

Enclosures

cc: L. A. Reyes
L. N. Olshan
M. C. Shannon

A096

AFFIDAVIT

R. A. Jones states that he is Site Vice President of Duke Energy Corporation; that he is authorized on the part of said corporation to sign and submit to the Nuclear Regulatory Commission this statement regarding Oconee Nuclear Station; and that all statements and matters set forth therein are true and correct to the best of his knowledge.

R. A. Jones, Site Vice President

Subscribed and sworn to me: 12-16-02
Date

Conice M. Breazeale, Notary Public

My Commission Expires: 2/12/03
Date

SEAL

ENCLOSURE 1

Oconee Unit 2
Docket Number 50-270

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION REACTOR PRESSURE VESSEL HEAD AND VESSEL HEAD PENETRATION INSPECTIONS RELATIVE TO RECENT INSPECTION FINDINGS

As a result of recent inspection findings, the NRC has two concerns about the combination and scope of inspection methods used during Reactor Pressure Vessel (RPV) head and RPV Head Penetration (RVHP) nozzle inspections implemented in response to Bulletin 2002-02. One concern is that through-weld cracks in the J-groove welds may provide the conditions that could lead to circumferential cracking in the nozzle base material at or above the J-groove weld with no visual indications of leakage deposits on the RPV head. The other concern is that cracks may develop in repaired nozzles within one operating cycle.

RAI - 1

North Anna 2 has identified circumferential cracks in nozzles examined with UT and indications were identified on the J-groove weld of a high percentage of the penetrations. According to the licensee for North Anna, there were no visual indications of boric acid deposits on the surface of the RPV head at all of these nozzles. This finding, if verified, indicates that cracks in the J-groove welds may provide the conditions that could lead to circumferential cracking in the nozzle base material at or above the J-groove weld with no visual indications of leakage deposits on the surface of the RPV head.

Considering the discussion above, please supplement your Bulletin 2002-02 response with a discussion of whether the findings at North Anna 2 alter your justification for continued reliance on visual examinations and the decision not to directly examine the J-groove welds.

Response to RAI - 1

Duke Energy Corporation (Duke) is aware of the information that is available on the North Anna 2 (NA-2) RPV head and RVHP nozzle inspection findings. Duke has reviewed the available information and concluded the inspection methods used for the Oconee Nuclear Station, Unit 2 (ONS-2) end-of-cycle 19 refueling outage were adequate to address the pertinent safety issues (nozzle ejection and head metal wastage). This included the potential that circumferential cracks could develop above the nozzle attachment welds (J-groove welds) without any visual indication of leakage on the head surface.

Weld metal cracking by itself, while not typically anticipated to be as prevalent as it was at NA-2, does not result in an immediate safety concern since cracking that is contained entirely within the weld metal, even if 360° around the nozzle, will not lead to nozzle ejection. The portion of the weld that is attached to the outside surface of the nozzle will not be able to pass through the tight annular fit. Additionally, outward distortion in the penetration from weld shrinkage would further prevent the nozzle from passing through the tight annular fit. Through-weld cracking to the annulus has the same consequence as a leaking nozzle in that it can result in a leak and wastage of the vessel steel and/or the initiation of a circumferential crack in the nozzle material. Therefore a weld metal examination is not needed to address the safety issues associated with Pressurized Water Stress Corrosion Cracking (PWSCC) of RVHP and welds if a bare metal visual (BMV) examination and ultrasonic testing (UT) of the nozzle material are performed. The benefits of each inspection type are discussed below.

Safety concerns associated with ejection of a RVHP during the next fuel cycle are addressed by performing UT of the RVHP nozzle material to detect circumferential cracking. A circumferential crack in a nozzle above the weld, takes several years to grow to a point of being an ejection concern even in the highest temperature plant with greater than 18 Effective Degradation Years (EDY). Therefore performing UT of the RVHP nozzle material will address the safety issue associated with OD circumferential cracking initiating above the weld, whether initiated by through-wall weld or nozzle cracks.

By performing a BMV inspection, any leakage that could cause wastage will be identified. In the event that a through-wall leak in the weld or nozzle does not result in visible leakage on top of the head, then no consequential wastage can occur. The inspection methods performed at ONS address the safety concerns associated with wastage of the vessel steel and nozzle ejection.

Duke believes that the graded RPVH inspection plan described in response to NRC Bulletin 2002-02 and those in response to NRC Bulletins 2001-01 and 2002-01, provide reasonable assurance that the ONS units are structurally sound and that all regulatory commitments are met. However, as additional conservative actions, Duke will conduct a volumetric inspection of the remaining nozzles using blade probe ultrasonic technology and incorporate lessons learned from the Davis Besse root cause report to evaluate conditions in containment for signs of leakage/wastage.

To summarize this approach, ONS-2 RPVH inspection plan is a graded or stepped process utilizing the following:

- 100% qualified visual inspection of all 69 Control Rod Drive Mechanism (CRDM) nozzles.
- Supplemental non-visual non-destructive examination (NDE) of masked nozzles including dye penetrant examination of the weld surface.
- Blade probe volumetric inspection of all remaining un-repaired nozzles to locate both ID and OD initiated axial and circumferential cracks and potential leak pathways.
- Ultrasonic inspection (using the post-repair technology) of the four previously repaired nozzles and PT examinations of two masked nozzles that had been previously repaired.
- Dye penetrant inspection of J-grove weld surface for nozzles with indeterminate blade probe UT inspection leak path results.

The 100% qualified visual examination has proven to be a highly effective examination method to detect leaking nozzles on ONS RPV heads. Experience with five prior RPV head examinations has proved this method to be effective. The UT blade probe examination of the ONS Unit 3 RPV head in fall 2001 found no additional nozzles with leaks beyond those identified during the 100% qualified visual examinations. Further, the extent of condition NDE on ONS -1 and ONS-2 RPV heads performed during previous outages did not detect any leaking nozzles that had not previously identified as either masked or leaking.

The ONS-2 head was cleaned of all boron deposits to expose the nozzle to head interface and an additional visual inspection was performed. The additional inspection ensured that wastage of the low alloy head had not occurred at the nozzle to head interface.

Masked nozzles received the highest degree of inspection before being returned to service. Dye penetrant methods were deployed when necessary to evaluate "leak path" technology or to resolve questionable results provided by other NDE techniques. Dye penetrant is not deployed as a normal test method due to the high radiation exposures incurred when compared to the significantly lower exposures with use of the graded techniques described above.

Blade probe UT has demonstrated abilities to detect axial and circumferential cracking in the nozzle base material and has some capabilities to indicate a "leak path" for those nozzles with observed leakage. This capability was demonstrated by the EPRI MRP Inspection Committee and witnessed by the NRC. A demonstration of the "leak path" technology was made to the NRC on February 12, 2002. The presentation was supplemented by information provided to the NRC by Framatome letter to the NRC, "UT Inspection Technique," dated April 18, 2002. The "leak path" technology is not relied upon solely to determine the absence or presence of flaws in any given nozzle but is used along with visual and ultrasonic techniques to determine if a nozzle requires repair or additional inspection. Dye penetrant methods will be deployed when necessary to evaluate "leak path" technology or to disposition other NDE techniques that are questionable. Dye penetrant is not deployed as a normal test method.

ONS-2 is currently in the final cycle of operation with the current RPV head, which is scheduled to be replaced in the spring of 2004 or in approximately 18 months.

RAI - 2

Recent reactor pressure vessel head and vessel head penetration nozzle inspections have identified potential indications in previously repaired nozzles at multiple sites, including a recent UT inspection performed at NA-2 that identified indications in previously repaired nozzles after less than one year of operation. These findings indicate the possibility of rapid initiation of cracking in repaired nozzles and a need to include repaired nozzles within the scope of planned non-visual examinations.

Considering the discussion above, please supplement your Bulletin 2002-02 response with a discussion justifying the acceptability of excluding repaired nozzles from non-visual examination.

Response to RAI-2

It is our understanding that boric acid deposits indicative of thru-wall leakage on previously repaired CRDM nozzles have been found on top of the RV Head at NA-2 and another nuclear site. Since there is limited information regarding the original repair configuration at these nuclear plants, it is difficult to compare any similarities and/or differences to previously completed

Oconee repairs. Therefore this response focuses on the type of repairs that were completed at Oconee and Duke's actions to ensure the integrity of the repair for the final fuel cycle.

The ONS-2 refueling outage that began on October 12, 2002, was the sixth Oconee outage following the initial discovery of a leaking CRDM nozzle on ONS-1 in November of 2000. During the subsequent five outages, 23 CRDM nozzles and eight thermocouple (T/C) nozzles have been repaired at the three Oconee units. Of these repairs, all eight T/C nozzles and 10 of 23 repaired CRDM nozzles have been inspected with the top of head visual inspections with no evidence of RCS leaks found at these repaired locations. Nine repaired CRDM nozzle locations were visually inspected following nine months of full power operation on ONS-3. One CRDM nozzle location and 8 T/C nozzle locations were also inspected following approximately 14 months of full power operation on ONS-1. The completion of these visual inspections following a significant run time at full power operation is strong evidence of the integrity of the repairs previously completed at Oconee.

The repairs completed at Oconee contained repair attributes that may or may not exist at the other nuclear plants. The key attributes of the repairs that are believed to enhance the integrity of the repaired locations for Oconee are:

1. Removal of all flaws – No embedded flaw technique has been used at Oconee on any of the completed repairs. An inherent design criterion of both the manual and remote repair techniques to the pressure boundary was the removal of all identified flaws from both the weld and nozzle base materials.

2. Alloy 52/152 protective weld overlay – This overlay was completed on each of the manual repairs that isolated the remaining original Alloy 82/182 weld materials from the RCS Primary Water environment. This extra step was completed to minimize the susceptibility of the HAZ of a repaired Alloy 82/182 weld to any new cracking. The extent of the original 82/182 weld was confirmed during the repair execution.

3. Remediation Technique – For the remote ID Temper Bead repairs, a remediation technique – Water Jet Conditioning – was completed that imparted a compressive layer on the surface of the nozzle to inhibit future crack initiation.

4. All repaired locations received a final NDE, either PT and/or UT, to confirm the adequacy of the as left condition.

Repair service life calculations were also performed for each method of repair completed at Oconee that show service lives that extend beyond the time of RPV head replacement with significant margin. Framatome has been the repair vendor for each of the RPV head repair efforts at Oconee.

During the recently completed ONS-2 refueling outage, a visual inspection was completed on each of the four previously repaired CRDM locations. For these four repaired locations no leaking CRDM nozzles were identified, however, two of the four locations were considered masked by boron deposits from other sources. As planned in previous outages, any masked location will be dispositioned by removing the CRDM drive to complete additional inspection of the repaired location on the ID of the nozzle. This inspection contingency has been in each outage plan beginning with the first visual inspection of a repaired location on ONS-3. Because of the increased level of awareness regarding the integrity of the current and previous repairs, a conservative decision was made to remove the drives on all four of the previously repaired locations to complete additional inspections.

The additional inspections completed during this ONS-2 RFO included volumetric UT inspections on each of the four repaired locations and a dye penetrant exam on the two repaired locations that were considered masked. The inspection techniques used for both UT and PT were consistent with the post repair NDE required during the execution of the original repair process on these four locations. The inspections completed during the current RFO did not identify any flaws. As with the previous inspections of repaired locations, the NDE completed on these repaired CRDM locations followed a significant run time at full power operation (approximately 18 months) is additional strong evidence of the integrity of the repairs completed at Oconee.

Enclosure 2

Oconee Unit 2
Docket Number 50-270

ONS-2 Risk Assessment For CRDM Nozzle PWSCC, Framatome ANP, Inc. Document 51-5013694-04 September 2002

An AREVA and Siemens company

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September 2002

Oconee Nuclear Station

ONS-2 Risk Assessment For CRDM Nozzle PWSCC

FANP Job 4160188

Prepared by:

Framatome ANP, Inc.
Engineering & Licensing
Lynchburg, VA

FRAMATOME ANP

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FRAMATOME ANP

ENGINEERING INFORMATION RECORD

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Title ONS-2 SPECIFIC RISK ASSESSMENT FOR CRDM NOZZLE PWSCC

PREPARED BY:	REVIEWED BY:
Name ROBERT S. ENZINNA	Name STANLEY H. LEVINSON
Signature Robert S. Enzinna Date 9/30/02	Signature Date 9/30/02

Technical Manager Statement: Initials FOR CWT

Reviewer is Independent.

Remarks:

This revision provides an ONS-2 specific risk assessment to quantify the core damage frequency associated with potential CRDM nozzle cracks in the final fuel cycle (cycle 20) before planned replacement of the reactor vessel head. This revision of the risk assessment includes refinements in the risk assessment methodology and conservative assumptions that have evolved due to interactions with the NRC staff and with EPRI's Material Reliability Program (MRP). This revision includes the impact of volumetric inspections planned on the ONS-2 nozzles prior to cycle 20 startup. The incremental core damage frequency from potential CRDM nozzle cracks growing to failure prior to replacement of the ONS-2 reactor vessel head is 4.93×10^{-7} per reactor year for the time period covering ONS-2 cycle 20 (approximately November 2002 to March 2004). This is a very small change in risk.

Revision History

Rev. 01 – This revision totally supersedes Rev. 00.

Rev. 01 was prepared to:

- account for the latest identification of OD-initiated above-the-weld CRDM nozzle circumferential cracks, namely cracks in nozzle 23 at Oconee 3 and in nozzle 18 at Oconee 2. These are in addition to similar OD-initiated circumferential cracks identified in nozzles 50 and 56 at Oconee 3.

- account for all portions of the original analysis that would be affected based on the Oconee shortened time-horizon (resulting from Duke Energy Corporation's commitment to install new reactor heads). The original analysis estimated the risk by simply truncating the appropriate branches of the event tree.

Rev. 02 – This revision updates the value of the conditional core damage probability for medium break LOCA. The value used is $3.5x10^{-3}$ and is based directly on the Oconee PRA (which is reflected in the Reference section). As a result of this change, the CDF drops from $9.3x10^{-8}$/reactor-year to $6.0x10^{-8}$/reactor-year.

Rev. 03 – This revision totally supersedes Rev. 02. This revision provides an ONS-3 specific risk assessment to quantify the CDF associated with potential CRDM nozzle cracks in the final fuel cycle (cycle 20) before planned replacement of the reactor vessel head. This revision of the risk assessment includes refinements in the risk assessment methodology and assumptions that have evolved since Revision 2 due to interactions with the NRC staff during technical meetings between Davis-Besse and NRC. This revision also includes the impact of volumetric inspections performed on the ONS-3 nozzles prior to cycle 20 startup.

Rev. 04 – This revision provides an ONS-2 specific risk assessment to quantify the CDF associated with potential CRDM nozzle cracks in the final fuel cycle (cycle 20) before planned replacement of the reactor vessel head. This revision of the risk assessment includes some assumptions that are more conservative than used in Rev. 3. This revision includes the impact of volumetric inspections to be performed on the ONS-2 nozzles prior to cycle 20 startup.

1.0 Introduction

At the request of Duke Energy Corporation (Duke), Framatome ANP has performed an Oconee Unit 2 (ONS-2) specific estimation of the core damage frequency (CDF) associated with potentially undetected control rod drive mechanism (CRDM) nozzle cracks. The ONS-2 risk evaluation addresses the period of operation from the start of cycle 20 (estimated November 2002) through the end of cycle 20 (estimated March 2004), when reactor vessel head replacement is scheduled

The ONS-2 specific risk evaluation is based upon the methodology of the B&W Owners Group (B&WOG) generic risk assessment (Reference 1). The B&WOG generic risk assessment includes refinements in the methodology made as a result of several technical meetings between individual B&WOG members and the Nuclear Regulatory Commission (NRC), as well as interactions with EPRI's Materials Reliability Program (MRP).

2.0 Scope of Risk Analysis

This analysis estimates the incremental CDF during the next ONS-2 fuel cycle (cycle 20) due to a LOCA that may be caused by CRDM nozzle failure. The scope of this analysis is the risk associated with potentially undiscovered circumferential cracks that may be located in CRDM nozzles above the J-groove weld. A circumferential crack of sufficient extent may cause a large leak or a LOCA due to gross structural failure (net-section collapse) of the CRDM nozzle pressure boundary. The outside diameter (OD) of the CRDM nozzle just above the J-groove weld (which is normally dry) is the only region on the CRDM nozzle pressure boundary where there is high axial stress relative to hoop stress. This region is susceptible to circumferential PWSCC cracks only if there is a source of primary water to the nozzle penetration annulus, such as might occur if there is a pressure boundary leak via a separate ID-initiated through-wall (TW) axial crack or a crack in or under the J-groove weld.

Therefore this risk analysis includes:

- the frequency of weld or nozzle leakage that wets the OD of CRDM nozzle(s) in the susceptible location,
- the probability that CRDM nozzle leakage is undetected by visual and/or volumetric exams,
- the time-dependent probability of CRDM nozzle net-section failure due to undetected circumferential crack initiation and growth on the nozzle OD, and
- the probability of core damage from the resulting LOCA.

Estimates of these probabilities and frequencies are provided in the following sections, and are used to determine the CDF for CRDM nozzle failure occurring during the next fuel cycle (cycle 20). A spectrum of scenarios is included in the risk analysis for different leak initiation times that may result in nozzle failure during the next fuel cycle. These scenarios address the possibility of cracks developing from new leaks in the next fuel cycle, as well as the possibility that leaking CRDM nozzles from previous fuel cycles were inadvertently left in service. The mechanism for quantification of the event scenarios is to use an Excel spreadsheet (see Section 8) that accounts for the staggered timing of leaks that initiate in different past and future fuel cycles.

3.0 Frequency of Weld or Nozzle Leak

In this section, the frequency of CRDM nozzle leaks that may wet the OD above the weld is estimated. It is assumed there may be some probability that some CRDM nozzles may be in service with near-TW nozzle cracks or weld cracks that may surface in the next fuel cycle. The CRDM nozzle cracks of interest are those above weld axial cracks and weld cracks that may leak primary water to the exterior of the CRDM nozzle in the annulus region of the RV head penetration.

Recent B&WOG experience has included several axial cracks propagating through the J-groove weld or the area of the CRDM nozzle near the weld. The table below summarizes the experience to date.

B&WOG CRDM Nozzle Leakage Experience as of August 2002		
B&W Plant	Number of Nozzles with External Leakage	Nozzles with External OD Circumferential Cracks
Oconee-1	2	0
Oconee-2	4	1
Oconee-3	14	4
ANO-1	1	0
Crystal River-3	1	1
TMI-1	5	0
Davis-Besse	3	1
Total	**30**	**7**

The leak initation frequency is a time-dependent function using a two-parameter Weibull distribution recommended by Dr. W. J. Shack (Reference 2). Using the Weibull distribution below, the cumulative probability of a CRDM nozzle leak can be estimated.

$$F(x) = 1 - \exp(-\left(\frac{x}{\alpha}\right)^{\beta})$$

where x is the effective degradation years (EDY, which is EFPY corrected to 600°F), α is the scale parameter, and β is the shape parameter.

The Weibull distribution used in this analysis is similar to Shack's recommended upper bound (i.e., 5th percentile) curve that used a shape parameter (β) of 3.0. Shack suggested either a shape parameter of 1.5 or 3.0, and the steeper sloped curve ($\beta = 3.0$) was used here because it more closely matched expert judgement as to when leaks may have first appeared at B&WOG plants. The scale parameter used in the analysis was changed from Shack's recommendation to a more conservative value to match the updated experience of the most limiting B&WOG plant. The resulting Weibull curve (see Figure 1) is slightly more conservative than Shack's upper bound curve and is conservative for ONS-2.

A conservative Weibull curve was created by adjusting the scale parameter (α) to increase the number of predicted leaks until it matched the number of leaking CRDM nozzles found to date at the most limiting plant. The most limiting plant is ONS-3, which has had 14 leaking CRDM nozzles. This reference point was increased from 14 to 14.75 leaks to account for an estimated human error probability associated with leak detection. The curve was adjusted (via the scale parameter) until it passed through this reference point (i.e., 14.75 leaks) at the end of the last ONS-3 fuel cycle (22.2 EDY) (Reference 1).

For example, applying this leak distribution to ONS-2 for x = 23.53 EDY at the beginning of cycle 20 and an estimated 24.75 EDY at the end of cycle 20, with $\beta = 3.0$ and $\alpha = 35.6$, the cumulative leak probability is $F(x) = 0.250$ and 0.285 respectively. Therefore, the incremental leak initiation probability during fuel cycle 20 is $0.285 - 0.250 = 3.5\text{x}10^{-2}$ per nozzle. Similar calculations produce incremental leak probabilities for the previous fuel cycles.

Since the leakage frequency estimate is based upon the most susceptible B&WOG plant, it is conservative for ONS-2. The estimated leak frequency using this method is conservative for ONS-2 because the 14 leaking nozzles at ONS-3 are from the same Alloy-600 heat (M3935), which except for the center five nozzles at Davis-Besse and one nozzle at ANO-1, is not used elsewhere in B&WOG plants. The other Alloy-600 heats used in the B&WOG plants have experienced a much less percentage of leaks for the equivalent age. Figure 1 also shows the nozzle leak experience to date for all of the B&WOG plants, and it can be seen that the curve, which is based on the ONS-3 CRDM nozzle leakage experience, is conservative with respect to ONS-2.

For the probabilistic fracture mechanics (PFM) analysis, any leak that may occur during the fuel cycle is conservatively assumed to start at the beginning of the cycle.

4.0 Probability that CRDM Nozzle Leakage is Undetected

Detection of nozzle leakage and subsequent circumferential cracking by visual and volumetric inspection methods is evaluated in the risk analysis. The risk analysis credits bare metal visual exams on all of the nozzles except three nozzles where the interference fit of the penetration has been identified as being greater than 2 mils. In addition, the risk analysis credits UT exams to be performed prior to fuel cycle 20 on all of the nozzles except the four that were previously repaired. The risk analysis considers new leaks that initiate after the inspections as well as the potential that the inspections may miss an existing leak and any subsequent circumferential cracking.

4.1 Estimate of Human Error Probability for Visual Inspections

A human reliability analysis has been performed to estimate the human error probability (HEP) for the inspection personnel failing to detect CRDM nozzle leakage. CRDM nozzle leakage will be detectable through the accumulation of boron crystal deposits on the top of the RV head around the base of the affected CRDM nozzles.

For failure of an inspector to observe boron crystals via visual inspection, a conservative HEP has been estimated using the Human Cognitive Reliability (HCR) model developed by EPRI (Reference 3). This screening model uses four parameters, which are provided below with the "value" assumed:

- Time frame/window: intermediate (approximately 1 to 4 hour window to make decision)
- Training/practice: yes (training and/or practice for this task is available)
- Task complexity: simple
- Environmental conditions: poor

Using the above values for these parameters, the HEP is estimated to be $5x10^{-2}$ by the HCR model.

This HEP is conservative considering the increased current emphasis on effective visual inspections of the reactor vessel head penetrations. For past inspections, where sensitivity to boron deposits may not have been as great, a more conservative base HEP of 0.1 is assumed. Only one past visual inspection is credited in this analysis (corresponding to refueling outage in April 2001). In addition, if a leak was "new" (i.e., less than one cycle old) at the time of a past visual inspection then 1.0 is assumed for the HEP.

Conservative HEPs have been used to encompass the uncertainty that is generally present in HEP estimates. Sensitivity cases were also run to ensure that the risk analysis is not sensitive to the assumptions used with respect to the HEP for visual inspections. For the HEP sensitivity, the base probability of missing a nozzle penetration leak in a visual inspection was increased from 0.05 to 0.2 for current or future inspections, and from 0.1 to 0.4 for past inspections.

4.2 Probability that Circumferential Crack is Undetected by Volumetric Exam

The risk analysis considers the potential for the UT exam to find or miss a circumferential crack. Since above-the-weld OD circumferential cracks can only occur in CRDM nozzles that are already leaking, the UT exam may also find the crack that is the source of the leak.

For UT exams, the crucial parameter for predicting the likelihood of crack detection is the crack depth. Although there is evidence that previous UT exams have detected CRDM nozzle circumferential cracks of various depths, specific data for probability of detection (POD) of circumferential cracks in this application are limited. Therefore, engineering judgement was used to postulate a crude but conservative distribution for POD as a function of crack depth. It is assumed that the UT process would have a 0.01 probability of error (99% POD) for a circumferential crack depth that is through-wall (TW), and a 0.03 error probability (97% POD) for all other leaking nozzles, including circumferential crack depths less than TW and their precursor leaking axial cracks. A conservatism in the model is that no credit is taken for detection of cracks prior to nozzle leakage. These crack depth/POD assumptions are subjective, but are considered conservative in light of the observed experience.

A sensitivity study was performed to determine the impact of the UT resolution upon risk. The POD was changed to 95% for a TW circumferential crack and to 50% for other leaks. The results ensure that the risk analysis is not sensitive to the assumptions used with respect to the crack depth sensitivity of the volumetric inspection methods.

5.0 Probability of OD Crack Initiation

The probability that a CRDM nozzle leak will initiate an exterior outside diameter circumferential nozzle crack was determined from B&WOG field experience. A total of 30 leaking CRDM nozzle penetrations have been found in B&WOG plants as of mid 2002. Only seven of these CRDM nozzles had indications of OD circumferential cracking above the weld. It is unknown specifically how long each of these CRDM nozzles had been leaking or whether OD cracks would have initiated on the others if leakage had continued undetected. Therefore, since a valid time-dependent model for OD PWSCC crack initiation is unavailable, it is assumed that the probability of OD crack initiation is 0.23 (seven circumferential cracks out of 30 leaking nozzles = 0.23) if the CRDM nozzle has leakage into the annular region above the weld. For those that initiate circumferential cracks, the time to initiation after the exterior surface of the nozzle is wetted is assumed to be zero.

6.0 Crack Growth to Failure of CRDM Nozzle

The probability of net-section failure was estimated for representative CRDM nozzles at ONS-2 through the development of a probabilistic fracture mechanics (PFM) model

(Reference 4). This model estimated the probability of net-section failure of representative CRDM nozzles experiencing OD-initiated circumferential flaws above the partial penetration (J-groove) weld by varying the defining parameters of flaw geometry and growth rate in a Monte Carlo subroutine. The PFM model used in this plant-specific analysis was originally developed around a deterministic fracture mechanics model. It employs the Peter Scott crack growth model in a Monte Carlo simulation to estimate the probability distribution for time-to failure. The PFM analysis was performed for two nozzle heats of material, corresponding to yield strengths of 55.2 ksi and 64.4 ksi, to account for the specificity of the ONS-2 stress profiles. Industry data were used to define distributions for other key variables, with conservatism employed when substantial data were not available.

The PFM model considers the growth of semi-elliptical surface flaws within the CRDM nozzle base metal. A distribution for the initial flaw geometry was conservatively postulated to represent the B&WOG plant experience. For example, UT exams of the seven OD-initiated circumferential flaw indications identified in CRDM nozzles above the weld at ONS-2, ONS-3, CR-3, and Davis-Besse, indicate circumferential extents varying from 33° to 165°. These were "as-found" crack sizes (i.e., after growth), which started from smaller initiation sites. Since it is not possible to determine the initial flaw geometry, the PFM analysis considered OD-initiated flaws that could potentially grow to the extent observed at the B&W plants. The PFM analysis assumed the potential for multiple small circumferential cracks to initiate and link together along the OD-surface to form a circumferential flaw of appreciable length. The PFM analysis also considered a flaw configuration resulting from an axial flaw that branches circumferentially as it transitions through-wall; however, the results for this configuration were determined to be less conservative relative to the postulated multiple linked initiation sites. Consequently, the initial flaw distribution was approximated with a shallow semi-elliptical surface flaw with a radial extent varying between 0° and 180°. The lognormal distributional parameters for the initial flaw length were conservatively derived from the "as-found" flaw extents, and correspond to a median circumferential extent of 66°. The initial flaw depth is also treated with a degree of variability. The initial flaw depth is modeled as 20 mils (0.51mm), with a uniform uncertainty of ±10 mils (0.25 mm to 0.76 mm).

A practical upper limit for the initial flaw length is a circumferential extent of 180°, which is related to the nature of the stresses on the CRDM nozzle surface above the weld. On the nozzle OD above the weld, crack initiation in the circumferential direction may be driven by the axial bending stresses that are related to the proximity of the weld and shrink fit zones, and different on the uphill and downhill side of the nozzles. The approach of postulating an initial flaw as long as 180° in circumferential extent bounds the uncertainty from scarcity of PFM data for OD flaw distributions and multiple initiation sites.

Another parameter of the crack growth model is the crack growth rate (CGR). The CGR coefficient, A_0, is considered as a random variable represented by a lognormal distribution in the PFM model. This choice of distribution is more conservative than the log-triangular used in earlier work by EPRI (Reference 5). The difference in distributions is that the lognormally distributed CGR coefficient is not bounded at the upper end, and therefore sampled values in the distribution's tail can be significantly worse than the known data points from which it was derived.

The flaw growth rate distribution used in the Monte Carlo simulation is based upon industry data collected for PWSCC. The parameters used for the lognormal distribution of the CGR coefficient correspond to data from heat of material 91069, which is one of the 22 Alloy 600 heats evaluated by the EPRI Materials Reliability Program (MRP) (Reference 6). Since "heat 69" is a known bad heat of material, it provides a conservative CGR distribution to use for the CRDM nozzle heats at ONS-2. The heat 69 CGR coefficient parameters are conservative relative to those recommended recently by the MRP (Reference 7), which are based on all 22 of the evaluated Alloy 600 heats. The parameters for the lognormal distribution of the CGR coefficient used in the PFM model are provided in the table below.

Crack Growth Coefficient for Heat of Material 90169 (Log-normal distribution with parameters $\mu = -26.334$ and $\sigma = 0.564$)	
Median	**95th Percentile**
$3.66\mathrm{x}10^{-12}$	$9.26\mathrm{x}10^{-12}$

This Monte Carlo analysis considers stresses contributing to flaw growth by PWSCC as a combination of sustained stresses due to shrink fit of the nozzle during installation, shrinkage of the partial penetration attachment weld (residual stresses), and steady state pressure and thermal loads. Nozzle stresses were developed by Dominion Engineering, Inc. (DEI) considering an extreme "hillside" CRDM nozzle (i.e., nozzle with the largest angle of penetration with the head) for two heats of material, with corresponding yield strengths of 55.2 ksi and 64.4 ksi. These stress results (as inputs) provide representative stress distributions for ONS-2. The stresses are considered conservative since the stresses corresponding to the nozzles with the largest angle of penetration (i.e., "worst case" stresses) were applied unilaterally to all nozzles in the vessel head model. Since the stress profile varies around the nozzle circumference, the PFM analysis assumes that the circumferential flaw initiated on the downhill side of the nozzle since the OD tensile stresses are larger on the outside surface of the downhill side than on the uphill side.

For this analysis, failure is defined as net-section failure of the nozzle. Net-section failure is defined as a circumferential crack extent equal to the critical crack size (330° circumferential extent). The critical crack length is determined assuming a circular cross section of the nozzle (i.e., no credit is taken for the additional distance associated with the crack growth on a path following the oval cross-section on the hill side nozzles). No credit is taken for the Technical Specification required 1 gpm leak detection capability, which may occur at a somewhat smaller crack extent than failure depending upon the radial clearance in the penetration annulus.

Sensitivity studies were performed on the PFM evaluation to investigate the effect of varying the critical modeling parameters. The sensitivity cases performed investigate the effect on the failure probability of the CRDM nozzles assuming:

- 25% increase in the CGR coefficient parameters,
- log-triangular CGR coefficient distribution,
- elevated reactor vessel head temperature representative of the most limiting head temperature of any B&W plant, and
- reduced critical flaw size (293° circumferential extent), which corresponds to an insufficient nozzle ligament to meet ASME Code primary stress limits with a safety factor of three (and 1.5 for emergency and faulted conditions).

The results of the PFM analysis are illustrated by the histograms shown in Figure 2 and 3. The histograms illustrate the probability versus time for an OD-initiated circumferential flaw in the nozzle body above the weld to reach failure due to net-section collapse in a 55.2 ksi and a 64.4 ksi nozzle, respectively. After the start of the annular leakage, an OD-initiated circumferential nozzle flaw above the weld in a 55.2 ksi nozzle would take a mean time of 4.78 years to grow to a through-wall state and a mean time of 15.81 years to reach net-section failure. For the 64.4 ksi nozzle, it would take a mean time of 4.16 years to grow through-wall and a mean time of 14.32 years to reach net-section failure. The histogram partitions the failure probabilities into time intervals corresponding to fuel cycle lengths, which represent the inspection intervals available to ONS-2. The Figures show the probability that an OD-initiated circumferential flaw will grow to failure within the time indicated assuming there is no detection by inspection. The opportunities for detection are considered in the quantification of the event scenarios (see Section 8.0, Figure 4), which represents the probability of leaks starting at various intervals in the past and reaching failure in fuel cycle 20, with the appropriate inspection probabilities in between.

7.0 Probability of Core Damage

The most likely consequence of CRDM nozzle failure (critical size crack) is leakage that is within the capacity of the makeup system. If a complete severance of the CRDM nozzle occurs, the break size will be within the range of what the Oconee PRA identifies as a medium break LOCA. However, a smaller break size could result if there is a partial failure of the nozzle.

The conditional probability of core damage given a small- or medium-sized LOCA can be readily determined from the Oconee PRA (Reference 8). In the Oconee PRA, the conditional core damage probability (CCDP) for a medium break LOCA is greater than for a small break LOCA. Therefore, as a representative value, the risk assessment uses the average CCDP for a medium break LOCA from the Oconee PRA, which is approximately 3.5×10^{-3}. Use of this CCDP is conservative because plant mitigation response will be better for a break at the top of the vessel than for the LOCAs typically considered in the PRAs.

ECCS effectiveness for a break on top of the vessel is better than for the typical LOCA that is assumed in the safety analyses and the PRAs. That is because the postulated accident does not involve a break in the RCS piping between the injection location and the core. Since the break is located on top of the reactor vessel, it is on the hot side of the core and none of the (borated) ECCS fluid bypasses the core. The full capacity of the ECCS is available to compensate for the RCS inventory loss, which is better than the standard LOCA analysis assumption. In addition, standard LOCA analysis assumptions do not credit insertion of the control rod with the greatest reactivity worth. For long-term shutdown, LOCA analyses credit only 50% of the available control rod worth. The shutdown margin is such that several CRDM failures to trip could be tolerated before the risk would increase over that of a single CRDM trip failure. Even in the very unlikely event that the detached CRDM nozzle prevents adjacent rods from dropping, the reactor can be safely shutdown. For example, an analysis of a specific core at another B&W plant assumed that a cluster of five control rods failed to insert in addition to the control rod of maximum worth (Reference 9). That analysis showed that the shutdown margin was sufficient even with a cluster of five failed control rods. While this type of analysis is core-specific, it demonstrates that the shutdown margin is generous. Therefore, it is concluded that the CCDP for the medium LOCA is representative of the risk from CRDM nozzle failure.

8.0 Risk Analysis Results for OD PWSCC

The estimated frequency and probabilities in the preceding sections are used to quantify the overall risk from outside diameter PWSCC. This quantification is accomplished in a spreadsheet (Figure 4) so that the start times (leak initiation) can be staggered. The spreadsheet indicates the probability of leaks starting at various intervals in the past and ultimately reaching failure in fuel cycle 20, with appropriate inspection failure probabilities interspersed between leak initiation and failure. Scenarios that result in nozzle failure and subsequent core damage during the fuel cycle 20 are quantified. Thus, postulated nozzle failures that occur in the next fuel cycle may have originated with leaking nozzles during that cycle or any one of several past fuel cycles. The sum of the staggered sequence frequencies provides an estimate of the CDF due to OD PWSCC of the CRDM nozzles. This incremental CDF has a mean value of 4.93×10^{-7} per reactor-year for the next fuel cycle (cycle 20). The tables below summarize these results along with various sensitivity studies.

Incremental Core Damage Frequency from Potential CRDM Nozzle Cracks for ONS-2 Fuel Cycle 20			
Number of nozzles	**Nozzle group**	**Inspection assumed during upcoming outage**	**Incremental CDF during fuel cycle 20 due to CRDM nozzle failure (per year)**
2	64.4 ksi stress	BM visual and UT	1.11E-8
60	55.2 ksi or less	BM visual and UT	2.30E-7
3	55.2 ksi or less	UT (no credit for visual)	2.52E-7
4	previously repaired	BM visual	negligible
69	**Total**		**4.93e-7**

Uncertainty in the results has been addressed by using conservative inputs for the most important PFM parameters. In particular, uncertainties in crack growth rate and initial flaw size were addressed by using very conservative probability distributions. In addition, conservative inputs were used for nozzle leak frequency, and nozzle stresses. As shown in the table below, sensitivity studies were performed for important PFM variables including crack growth rate and distributional form, head temperature, net-section failure definition, and crack propagation path (multiple crack initiation sites versus axial crack that branches). The sensitivity studies show that the results are robust.

The tables below also show the sensitivity to assumptions regarding method of inspection and probability of inspection error. It can be seen from the inspection sensitivities that the specific POD assumptions for the volumetric or visual inspection methods affect the risk somewhat, and it is apparent from the results that the performance of effective inspections is important for managing the risk from this issue. These inspection sensitivities demonstrate that the risk is acceptable for a range of inspection assumptions.

The estimated core damage frequency compares favorably to the risk acceptance guidelines contained in Regulatory Guide 1.174 (Reference 10) for core damage frequency. Although Regulatory Guide 1.174 addresses permanent changes to the licensing basis, and the issue here is temporarily (until head replacement), it still provides a useful guideline for acceptability of the incremental risk. Per these guidelines, the risk of operation with potentially undiscovered CRDM nozzle cracks is categorized as "very small" for the next fuel cycle.

Sensitivity to PFM Assumptions				
Case	**64.4 ksi nozzles with visual and UT exams (2)**	**55.2 ksi nozzles with visual and UT exams (60)**	**55.2 ksi nozzles with UT exam only (3)**	**Total incremental CDF for fuel cycle 20 (per year)**
Base Case • multiple linked initiation sites • heat 69 CGR • log-normal CGR • 602 °F • Failure = critical crack size (330°)	1.11E-8	2.30E-7	2.52E-7	**4.93e-7**
Branched axial flaw	3.17E-9	6.99E-8	2.25E-7	**2.98E-7**
CGR increased 25%	3.17E-8	5.20E-7	3.23E-7	**8.75E-7**
Log-triangular (i.e., truncated) CGR	1.07E-9	2.69E-8	2.45E-7	**2.73E-7**
Elevated operating temp. (605 °F)	1.33E-8	2.94E-7	2.74E-7	**5.81E-7**
Safety factor 3 (i.e., failure = allowable crack size)	2.25E-8	4.16E-7	2.92E-7	**7.31E-7**

Sensitivity to Inspection Assumptions				
Case	**64.4 ksi nozzles with visual and UT exams (2)**	**55.2 ksi nozzles with visual and UT exams (60)**	**55.2 ksi nozzles with UT exam only (3)**	**Total incremental CDF for fuel cycle 20 (per year)**
Base Case • POD for visual =95% new inspection =90% old inspection • POD for UT =99% for TW circ. =97% for leaker	1.11E-8	2.30E-7	2.52E-7	**4.93e-7**
POD for visual =80% for new inspection =60% for old inspection (HEPs x4)	2.60E-8	6.24E-7	2.52E-7	**9.02E-7**
POD for UT = 95% for TW circ. crack = 50% for leaking nozzle	1.99E-8	4.34E-7	1.26E-6	**1.71E-6**

9.0 References

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Figure 1 CRDM Nozzle Leak Probability versus EDY based on Most Limiting B&WOG Plant with Weibull Shape Parameter = 3 and Scale Parameter = 35.6

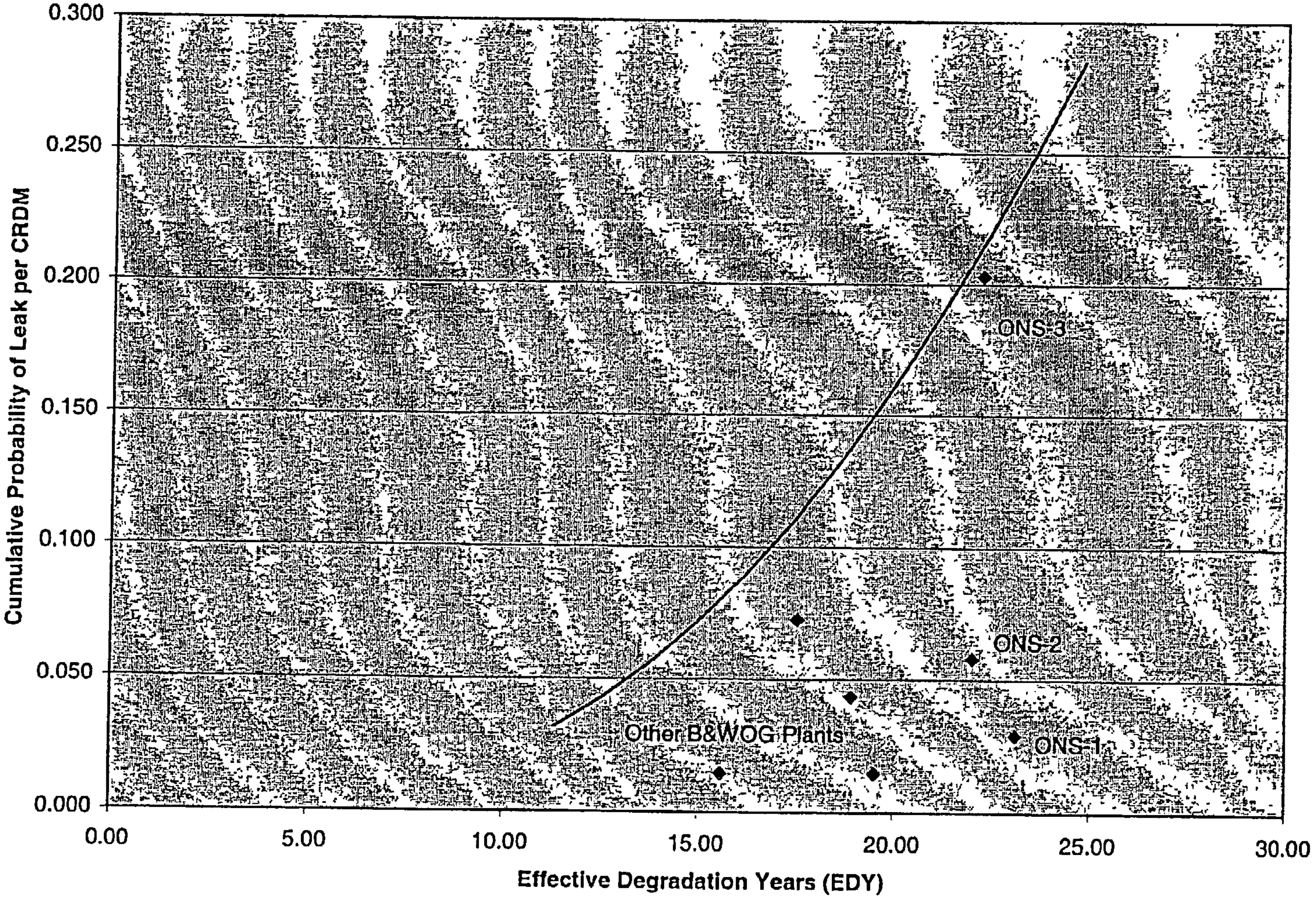

Figure 2 Probability of Net-Section Failure vs. Time after Initiation of Circumferential Crack due to Outside Diameter PWSCC for 55.2ksi CRDM Nozzle

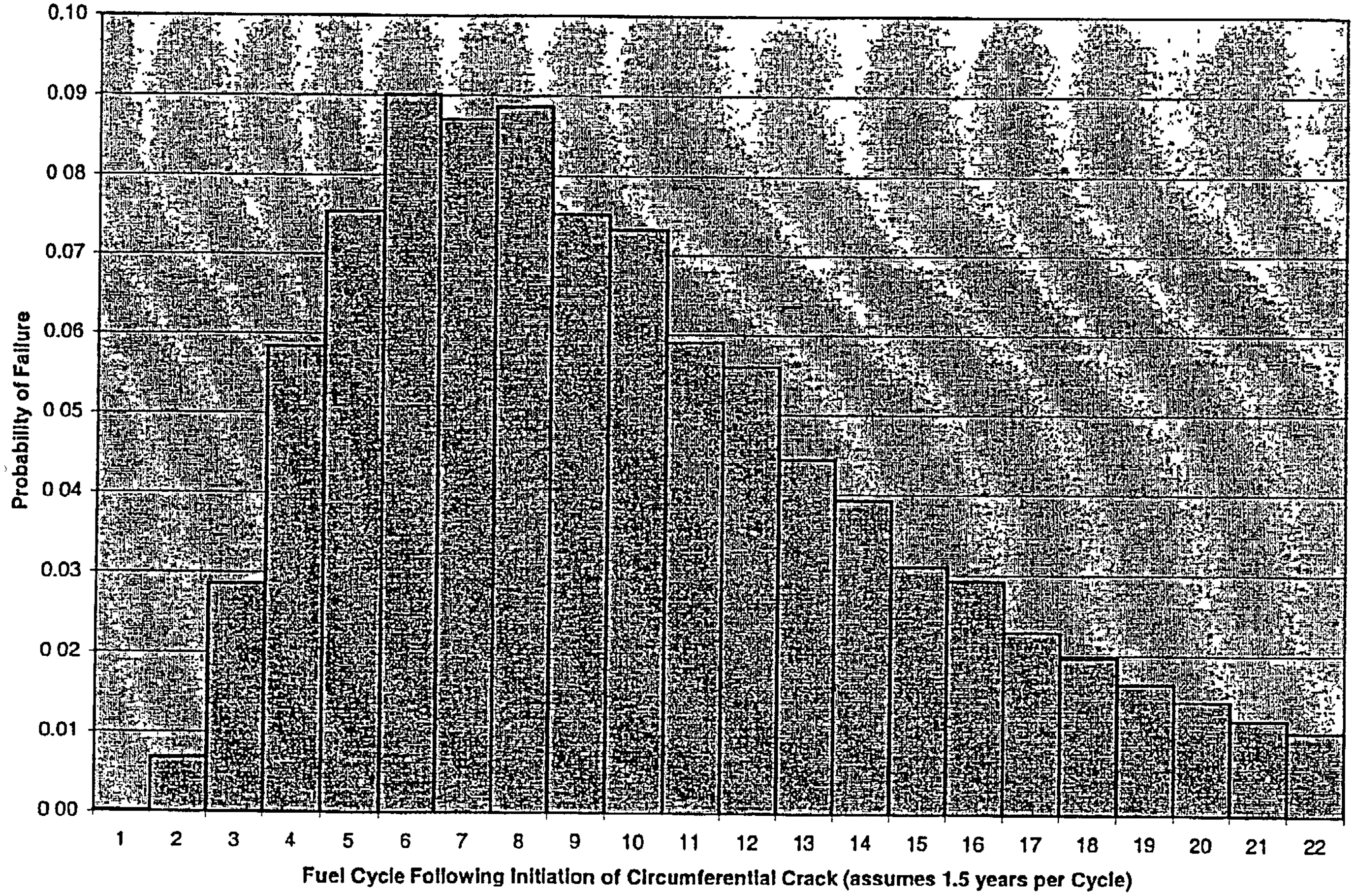

Figure 3 Probability of Net-Section Failure vs. Time after Initiation of Circumferential Crack due to Outside Diameter PWSCC for 64.4ksi CRDM Nozzle

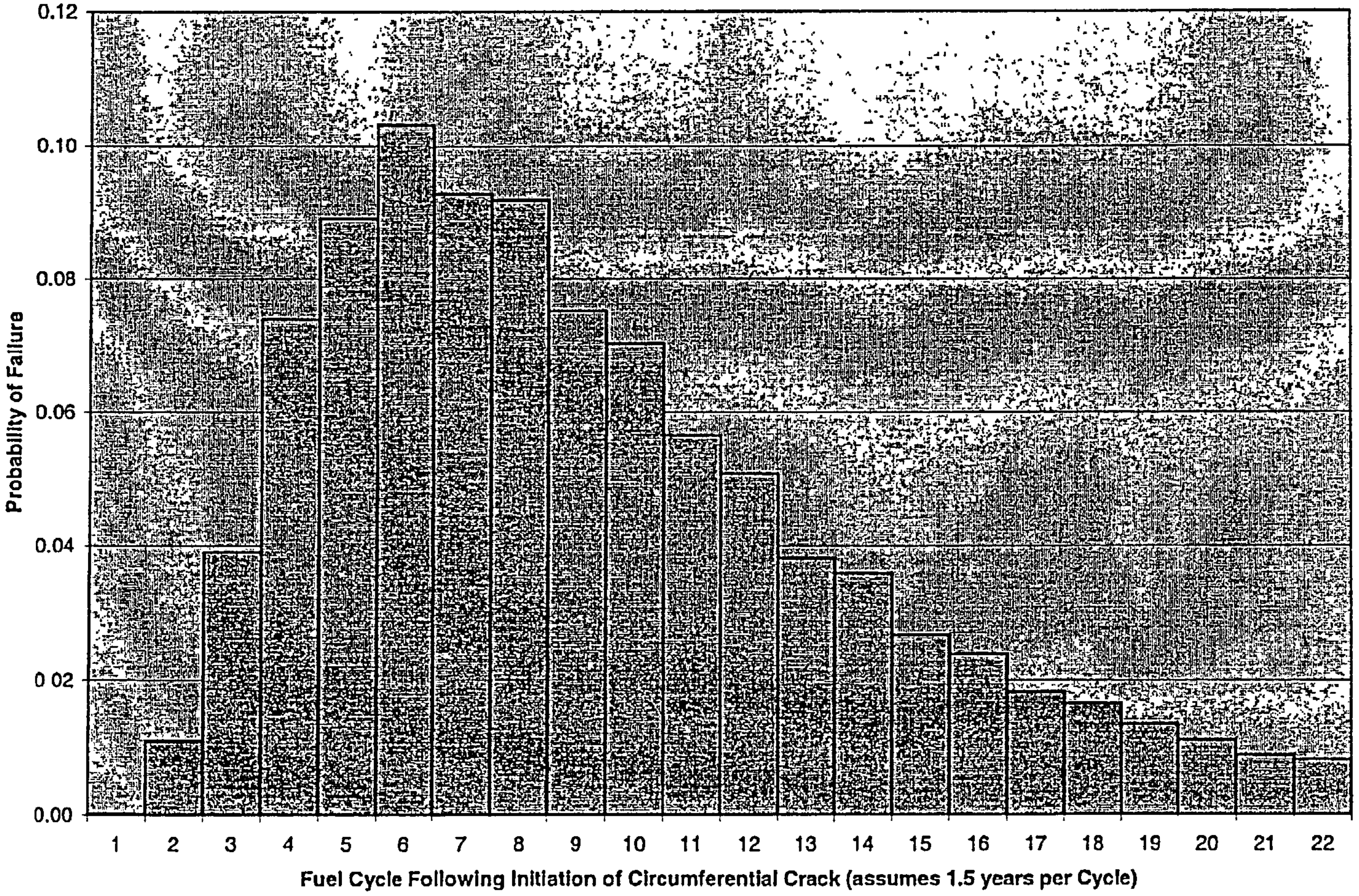

Figure 4 Representative Spreadsheet for Core Damage Frequency from CRDM Nozzle Circumferential Cracking (Base Case 55.2 ksi Nozzle with Visual and UT Inspections)

Leaks Initiating in Cycle:	Weibull Leak Probability	CRDMs in Group	Leak Frequency (leaks/yr)	VI leak non-detection Probability		Probability Circ Crack Initiates	Max Age of Leak at EOC 20 (yrs)	Cycle 20 Failure Probability no insp.	UT non-detect Probability (before cycle 20)	Cycle 20 Failure Frequency (/yr)	CCDP	CDF (/yr)
				before Cycle 19	before Cycle 20							
20 (upcoming cycle)	3.45E-02	60	1.38E+00	N/A	N/A	0.23	1.5	1.67E-04	N/A	5.37E-05	3.50E-03	1.88E-07
19	3.26E-02	60	1.30E+00	N/A	0.05	0.23	3.0	6.80E-03	0.02	1.61E-06	3.50E-03	5.64E-09
18	3.04E-02	60	1.22E+00	1.00	0.05	0.23	4.5	2.86E-02	0.01	4.06E-06	3.50E-03	1.42E-08
17	2.81E-02	60	1.12E+00	0.10	0.05	0.23	6.0	5.84E-02	0.01	7.64E-07	3.50E-03	2.68E-09
16	2.56E-02	60	1.03E+00	0.10	0.05	0.23	7.5	7.54E-02	0.01	9.02E-07	3.50E-03	3.16E-09
15	2.31E-02	60	9.25E-01	0.10	0.05	0.23	9.0	9.01E-02	0.01	9.72E-07	3.50E-03	3.40E-09
14	2.06E-02	60	8.24E-01	0.10	0.05	0.23	10.5	8.70E-02	0.01	8.37E-07	3.50E-03	2.93E-09
13	1.81E-02	60	7.25E-01	0.10	0.05	0.23	12.0	8.87E-02	0.01	7.49E-07	3.50E-03	2.62E-09
12	1.57E-02	60	6.27E-01	0.10	0.05	0.23	13.5	7.52E-02	0.01	5.50E-07	3.50E-03	1.92E-09
11	1.33E-02	60	5.34E-01	0.10	0.05	0.23	15.0	7.32E-02	0.01	4.55E-07	3.50E-03	1.59E-09
10	1.11E-02	60	4.45E-01	0.10	0.05	0.23	16.5	5.91E-02	0.01	3.07E-07	3.50E-03	1.07E-09
9 or earlier	3.17E-02	60	1.27E+00	0.10	0.05	0.23	18.0	5.60E-02	0.01	8.29E-07	3.50E-03	2.90E-09
										6.57E-05		2.30E-07