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MRP **Materials Reliability Program** MRP 2011-034

(via email)

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Subject: T_{cold} RV Closure Head Nozzle Inspection Impact Assessment

References:

1. *Materials Reliability Program:* Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking (MRP-105), EPRI, Palo Alto, CA: 2004. 1007834.

The current inspection requirements for CRDM and other reactor vessel top head nozzles, contained within ASME CC N-729-1, were developed in part on the basis of plant experience with PWSCC of these components. Indications of primary water stress corrosion cracking (PWSCC) have now been identified in Alloy 600 CRDM penetration tubes in two domestic PWR vessel top heads that operate at reactor coolant system cold leg temperature (T_{cold}), commonly referred to as "cold heads". EPRI MRP routinely considers the impact of such operating experience on existing guidance and determined this extension of PWSCC experience to cold heads in the U.S. fleet warranted a detailed assessment of the implications on the technical basis for the inspection requirements. Specifically, this assessment reviewed the technical basis for ASME Code Case N-729-1, with particular emphasis on the re-inspection intervals it establishes, to determine whether recent apparent PWSCC indications in two cold heads (plus other top head plant experience to date) are consistent with that technical basis. This review has been completed and the NRC Staff was briefed on the assessment approach and the associated conclusions during a conference call held September 16, 2011. At that time, the Staff requested that the detailed assessment report be provided for information and this letter hereby transmits the final report as two attachments.

The original technical basis incorporated plant PWSCC experience through a Weibull approach considering all relevant data available at the time of publication in 2004. The additional accumulated inspection data and operating experience has been incorporated into an updated Weibull analysis described in Attachment 2 to this letter and is the key input to the assessment. This update addresses both the recent Tcold head inspection results as well as the determination that a slightly higher representative temperature should be considered for a subset of the plant population.

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The assessment process then steps through the original MRP-105 analysis, and evaluates the impact if the updated Weibull results had been used. This process and the conclusions that were obtained are described in detail in Attachment 1 to this letter. Key conclusions are as follows:

- The current inspection requirements have been effective in detecting the PWSCC degradation reported in a timely fashion, before the degradation produces flaws of safety significance. No nozzle leaks have been detected in a head after a first in-service volumetric/surface examination was performed of all its CRDM or CEDM nozzles.
- Plant experience to date indicates a somewhat higher probability of crack initiation for cold heads than that calculated per the original set of MRP-105 Weibull crack initiation inputs. However, this is concluded to have an acceptably small effect on the probability of nozzle ejection calculations in MRP-105 for cold heads. The required volumetric/surface inspection intervals for cold heads are concluded still to be appropriate and conservative.
- Plant experience continues to support the adequacy of the current requirements for top heads to perform periodic visual inspections for evidence of leakage in order to protect against structurally significant boric acid corrosion.

In summary, the inspection requirements for PWR reactor vessel top heads with Alloy 600 nozzles per ASME Code Case N-729-1 are still concluded to be conservative and adequate to ensure nuclear safety with respect to the PWSCC degradation concern. There is no need to revise the technical safety assessments or inspection requirements for the reactor vessel top head nozzles.

MRP will continue to monitor operating experience and inspection results associated with these PWSCC-susceptible materials and repeat this assessment process any time such action may again be warranted.[1]

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[1] Attachment 1 to this letter includes a series of sensitivity cases that investigate hypothetical detection of additional PWSCC in cold heads. Based on the results of these cases, it is concluded that the technical basis for the N-729-1 volumetric/surface inspection intervals would continue to remain valid if additional PWSCC were to be detected in other cold heads, to an extent similar to the sensitivity cases assumed, in terms of the numbers of affected heads and nozzles and EDY values at time of detection.

If you have any questions or concerns, please contact Craig Harrington (charrington@epri.com, 817-897-1433).

Best Regards,

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Attachment 1: Assessment of Implications of Recent Cold Head CRDM Nozzle PWSCC Experience

Attachment 2: 2011 Update of Weibull Statistical Assessment of U.S. Alloy 600 CRDM/CEDM Nozzle Inspection Experience

Cc: Craig Harrington, EPRI
PMMP EC
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ATTACHMENT 1
ASSESSMENT OF IMPLICATIONS OF RECENT COLD HEAD CRDM NOZZLE PWSCC EXPERIENCE

1 *Introduction*

1.1 Recent Cold Head PWSCC Experience

Indications of primary water stress corrosion cracking (PWSCC) have been identified in Alloy 600 CRDM penetration tubes in two domestic PWR vessel top heads that operate at reactor coolant system cold leg temperature (Tcold), commonly referred to as "cold heads." PWSCC indications were identified in a single CRDM nozzle at one plant in 2007 ([1], [2]), and in four CRDM nozzles at another in 2011 [3]. The indication detected in 2007 was concluded to have initiated at a subsurface location that was wetted through lack-of-fusion fabrication defects [1], whereas the experience reported in 2011 included PWSCC flaws that were not connected to the attachment weld [3] and hence are concluded to have initiated on the wetted surface of the Alloy 600 tube.

As discussed below, the current inspection requirements for CRDM and other reactor vessel top head nozzles were developed in part on the basis of plant experience with PWSCC of these components. Because the PWSCC experience has recently extended to cold heads in the U.S. fleet, it is appropriate to assess the implications of this experience on the technical basis for the inspection requirements for these components, especially those located in cold heads.

1.2 Current Top Head Inspection Requirements

The NRC regulation 10 CFR 50.55a(g)(6)(ii)(D) requires that all U.S. PWRs augment their inservice inspection programs with ASME Code Case N–729–1 [4]*, subject to several conditions identified in this regulation. This code case defines visual and volumetric/surface inspection intervals for all reactor vessel top head nozzles attached to the head with partial-penetration (i.e., J-groove) welds.

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* Although ASME Code Case N–729–2 [5] has been approved by the Standards Committee, ASME Code Case N-729–1 is the version currently mandated in 10 CFR 50.55a(g)(6)(ii)(D).

For heads with Alloy 600 nozzles, the volumetric/surface inspection intervals (between examinations of all nozzles) are based on the RIY (re-inspection year) parameter, which is a measure of operating time normalized to a head temperature of 600°F using the consensus temperature dependence of the PWSCC crack growth rate. The required interval is every 8 calendar years or before RIY = 2.25, whichever is less. For cold heads, this generally equates to an interval of four or five 18-month fuel cycles, or three or four 24-month fuel cycles. More frequent volumetric/surface examinations may be required if PWSCC has previously been detected in the subject head.

For heads with Alloy 600 nozzles, the visual inspection interval for successive direct examinations of the bare-metal surface is every refueling outage. This interval is extended to every third refueling outage or 5 calendar years, whichever is less, for heads with less than 8 cumulative effective degradation years (EDYs) of operating time and for which PWSCC has not been detected requiring repair.* Like the RIY parameter, the EDY parameter is a measure of operating time normalized to a head temperature of 600°F. However, the EDY parameter is calculated using the best-estimate temperature dependence of the PWSCC crack initiation time instead of the PWSCC crack growth rate. Thus, the EDY parameter is associated with the cumulative operating time to first cracking in a head, while the RIY parameter is associated with the operating time available between inspections for propagation of existing cracks. All 20 cold heads with Alloy 600 nozzles currently operating in the U.S. currently have less than 8 cumulative EDYs, and it is estimated that this will be the case for at least another 20 years. It is further estimated that many cold heads will reach 8 EDYs during the 20-year license extension period beyond the original 40-year license period.

1.3 Technical Basis for Inspection Requirements

The technical basis for the top head inspection requirements defined in ASME Code Case N-729-1 [4] is documented in Section 3 of MRP-117 [6].† The technical basis is supported by the MRP-110 [7] top-level safety assessment report, and the lower-level safety assessments that it references including the MRP-105 [8] probabilistic assessment. As discussed in MRP-110 and

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[*] In addition, an IWA-2212 VT-2 visual examination (per Section XI of the ASME Boiler & Pressure Vessel Code) of the head must be performed under the insulation through multiple access points during refueling outages that the bare metal visual examination is not performed.

[†] The inspection requirements for top head nozzles developed on the basis of the MRP-110 [7] safety assessment were published by EPRI/MRP in MRP-117 [6]. These requirements were intended to supersede the inspection requirements of NRC Order EA-03-009 [9], but instead MRP-110 and MRP-117 formed the technical basis for the inspection requirements of ASME Code Case N-729-1 [4], which has replaced the NRC order as the current mandatory inspection requirements document (subject to certain NRC conditions as listed in 10 CFR 50.55a(g)(6)(ii)(D)).

MRP-117, there are two main safety concerns associated with PWSCC degradation of top head J-groove nozzles: (1) circumferential cracking of the nozzle tube above the weld leading to nozzle ejection, and (2) leakage through a through-wall crack ultimately producing structurally significant volume loss of the low-alloy steel head material due to boric acid corrosion.

1.3.1 Nozzle Ejection Concern

As discussed in Section 3.2 of MRP-117, MRP-105 [8] is the principal nozzle ejection safety assessment report and covers all the domestic operating units on the basis of four representative sample plants. This report includes both deterministic calculations of circumferential crack growth and a full probabilistic Monte Carlo simulation of the process leading to nozzle ejection that reflects the uncertainties in the various process parameters. MRP-104 [10] presents deterministic nozzle ejection calculations specifically for the 48 operating Westinghouse design and 14 operating Combustion Engineering design plants, including an assessment of the effect of normal operating pressure and temperature on the initial interference fit between the nozzle and head. MRP-103 [11] is specific to the seven B&W design plants and includes a deterministic calculation and an event-tree probabilistic safety assessment. As discussed in Section 6 of MRP-110 [7], these assessments are similar in form but are based on different input assumptions for a few parameters.

The probabilistic fracture mechanics (PFM) analyses of MRP-105 using the Monte-Carlo simulation algorithm were performed to determine the probability of failure versus time for a set of input parameters, including head operating temperature, inspection types (visual or volumetric/surface NDE), and inspection intervals. Input into this algorithm included an experience-based time to leakage correlation that uses a Weibull model of plant inspections to date, fracture mechanics analyses of various nozzle configurations containing axial and circumferential cracks, and MRP-developed statistical crack growth rate data for Alloy 600 (MRP-55 [12]). The parameters used in the model were calibrated using the set of reported circumferential cracks located in the nozzle wall above or near the top of the J-groove weld in U.S. plants, and produced results that were in agreement with experience to that time (2004).

These nozzle ejection safety assessment reports ([8], [10], [11]) demonstrate that there is considerable structural margin against nozzle ejection due to circumferential cracking because of the time required for a circumferential crack to grow to the critical size, typically at least 330°. The volumetric/surface examination intervals required by N-729-1, which are defined on the basis of effective time at temperature (re-inspection years—RIYs) accumulated since the time of the previous volumetric/surface examination, support these complementary safety assessments.

In particular, the PFM assessments of MRP-105 demonstrate an acceptably low probability of nozzle ejection given the range of conditional core damage probabilities (CCDPs) that bound the nozzle ejection event (see Section 8 of MRP-110). Given the inspections required by N-729-1, the calculated core damage frequency (nozzle ejection frequency times CCDP) associated with the maximum predicted nozzle ejection frequency (about 7×10^{-4} per plant year [8]) is on the order of 1×10^{-6} per plant year. This result is consistent with the philosophy of NRC Regulatory Guide 1.174, which specifies an acceptable change in core damage frequency of 1×10^{-6} per plant year for permanent changes in plant design parameters, technical specifications, etc. and which also may be applied to evaluation of inspection program changes.

1.3.2 Boric Acid Corrosion Concern

As described in Section 3.4 of MRP-117, the boric acid corrosion concern is principally addressed through the requirement for periodic direct visual examinations. Adequate protection against structurally significant boric acid corrosion through periodic visual examinations at appropriate intervals is supported by plant experience and by deterministic and probabilistic models of the boric acid corrosion process, including those presented in MRP-110 [7]. Since MRP-110 was published in 2004, the MRP sponsored an extensive program of boric acid corrosion testing and additional analysis work ([13], [14], [15], [16], [17]),* including full-scale mockups of leaking CRDM nozzles with careful attention to obtaining thermal-hydraulic conditions representative of a leaking CRDM nozzle in an operating PWR. This test program, which is now complete, confirms the previous conclusions based on plant experience and analytical work [7] that structurally significant volumes of material loss (1) require a reasonably long period of time to develop and (2) are preceded by evidence of leakage and corrosion that is readily visible. Thus, the results of this MRP test program support the adequacy of the current inspection requirements for top heads to address the possibility of boric acid corrosion.

1.3.3 Protection Against Pressure Boundary Leakage

The failure mode and effect analysis (FMEA) and flaw tolerance calculations presented in MRP-110 [7] show that the dominant potential nuclear safety concerns associated with aging degradation of PWR top head penetrations are nozzle ejection and head or cladding rupture due to boric acid corrosion. The very small leak rates typically associated with through-wall cracking in top head nozzles do not represent a direct safety concern. However, through-wall cracking is a necessary precursor for boric acid corrosion of the low-alloy steel material of the

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* ANL [18] has also completed boric acid corrosion testing under sponsorship of NRC with results consistent with those for the MRP program.

head. In addition, experience has shown (supported by stress analyses) that through-wall axial cracking is a likely precursor of circumferential nozzle cracking that could grow to a size that could cause net section collapse and nozzle ejection.

Therefore, the N-729-1 inspection requirements are designed to provide defense in depth by maintaining a low probability of leakage due to aging degradation of Alloy 600 top head nozzles. The MRP-105 [8] evaluation presents probabilistic calculations that show a low probability of leakage if inspections are performed in accordance with N-729-1.

1.4 Purpose of Assessment

The purpose of this document is to evaluate the technical basis for ASME Code Case N-729-1, with particular emphasis on the re-inspection intervals it establishes, to determine whether recent apparent PWSCC indications in two cold heads (plus other top head plant experience to date) are consistent with that technical basis.

1.5 Scope of Assessment

This assessment addresses the technical basis for inspection requirements for reactor vessel top heads with Alloy 600 partial-penetration welded nozzles in U.S. PWRs, including the 20 "cold heads" that operate at the reactor cold-leg temperature (Tcold). As of August 2011, an additional nine heads with Alloy 600 nozzles that operate at temperatures significantly above Tcold (i.e., non-cold heads) are still in service.

1.6 Approach of Assessment

The volumetric/surface inspection intervals for top head Alloy 600 nozzles are based on the RIY parameter because of the central role of these periodic examinations in detecting any PWSCC flaws prior to their propagation to flaws of safety significance. Thus, the set of crack growth rate inputs to the various top head safety assessments is a key part of the technical basis for the re-inspection interval for volumetric/surface inspections. However, the inputs describing the time to crack initiation also may have a significant effect on the probability of nozzle ejection as initiation is a necessary precursor for there to be any possibility of nozzle ejection. Thus, the model parameters describing the probability of crack initiation are also an important part of the technical basis for the inspection intervals. Hence, the implications of top head inspection experience for crack initiation time and crack growth rates are assessed in this document.

The inspection experience for top heads is directly relevant to the basis in the MRP-105 probabilistic model for predicting the time until cracking occurs. The crack initiation module in the MRP-105 model is based directly on plant experience per a Weibull statistical approach. Thus, in Section 3.1 below, an assessment is made of the effect of the recent indications of PWSCC detected in two cold heads on the Weibull crack initiation parameters applied in MRP-105. The specific concern addressed is whether the probability of crack initiation implied by the recent cold head experience is greater than that assumed in the MRP-105 evaluation in 2004. In Section 3.2 the effect of the updated industry Weibull parameters on the results and conclusions of the MRP-105 study are assessed. In particular, the effect on the probability of nozzle ejection for cold heads is assessed.

In addition to the implications for the probability of crack initiation, the recent plant experience has relevance to the crack growth rate inputs of the MRP-105 probabilistic model. These crack growth rate inputs were developed on the basis of the laboratory PWSCC crack growth rate data obtained using controlled fracture mechanics specimens of Alloy 600 material available worldwide as of 2002, as evaluated in the MRP-55 study [12]. In the case of crack growth rates, laboratory data are the most reliable basis for establishing model inputs. However, PWSCC plant experience is a potential additional source of crack growth rate data that may be assessed for consistency with standard crack growth rate inputs to PWSCC analyses. In Section 4.1 and 4.2 the top head inspection experience to date is assessed for cases in which estimates of relative crack growth rates may be made. In Section 4.3 the implications of these implied relative crack growth rates are assessed.

Prior to this more detailed approach to assessment of the implications of recent inspection experience, Section 2 below assesses the effectiveness of the current set of inspection requirements and head replacements previously performed in detecting any PWSCC degradation in a timely fashion.

2 *Effectiveness of Current Inspection Requirements*

As part of the top head safety assessment published in 2004 [7], a detailed assessment was made of top head plant inspection experience to that point in time, including tabulation of the numbers of nozzles affected by part-depth PWSCC and through-wall PWSCC (i.e., leakage). This plant experience assessment has been periodically updated by the MRP, and the latest such assessment is presented in Attachment 2.

Over the period from 2002 to early 2008, a baseline volumetric/surface examination of all original heads with Alloy 600 nozzles was performed (with the exception of a small number of heads that were replaced prior to a baseline examination being required per the NRC Order [9]). The baseline examinations for cold heads were performed over the period from 2005 to early 2008. All Alloy 600 heads still in service are now in a program of periodic repeat volumetric/surface examinations, with the first repeat examinations in cold heads generally starting in 2011.

The findings of the top head examinations performed to date support the adequacy of the current inspection requirements including the intervals for periodic volumetric/surface examinations:

- Since the top head safety assessment [7] was published in 2004, no circumferential PWSCC indications located near or above the top of the weld have been detected. These are the types of flaws that could produce a nozzle ejection were they to grow to a very large size.
- Since the top head safety assessment [7] was published in 2004, there have been no reports of top head nozzle leakage (i.e., through-wall cracking) occurring after the time that the first in-service volumetric/surface examination was performed. (In fact, there have been no cases in which leakage was detected after a first in-service volumetric/surface examination was performed of all CRDM or CEDM nozzles.*) The only incidence of nozzle leakage ([19], [20]) since 2004 was detected in 2010 during the first in-service inspection (after about 6 calendar years of operation) performed of a replacement Alloy 600 head from a cancelled plant. Thus, this initial examination experience is not directly relevant to the adequacy of the re-inspection interval requirement. No discernible corrosion was detected of the low-alloy steel head material during the bare-metal visual examinations of this replacement Alloy 600 head. It is noted that in late 2011 this first replacement head was replaced with a head having PWSCC-resistant nozzles.
- The volumetric/surface examinations performed on cold heads and the repeat volumetric/surface examinations performed on non-cold heads have been effective in detecting the PWSCC degradation reported in its relatively early stages, with modest numbers of nozzles affected by part-depth cracking, often located below the weld, where the nozzle tube is inside (not directly a part of) the pressure boundary.
- Only two of the 20 operating cold heads with Alloy 600 nozzles have shown indications of PWSCC. Baseline volumetric/surface examinations have been performed of all these heads. This cracking was part-depth, and for one of these two heads was associated with a weld fabrication defect. Hence, plant experience continues to show a very low probability of nozzle leakage for the cold heads given the examinations being performed.

It is emphasized that the relatively low incidence of PWSCC in the cold heads is consistent with the relatively large sensitivity of the probability of PWSCC crack initiation to operating temperature ([7], [8]). Moreover, there is widespread acceptance among PWSCC researchers ([12], [21]) that changes in temperature at the crack location have a consistent and well

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[*] This statement does not apply to some of the NDE examinations performed of top head nozzles in the 1990s. These examinations generally excluded the OD surface of the nozzle tube below the weld, and generally excluded ultrasonic (i.e., volumetric) techniques.

characterized effect on the PWSCC crack growth rate, with a consensus value for the thermal activation energy describing this temperature dependence of 31 kcal/mole (130 kJ/mole). Thus, there is a relatively large benefit of operating near the cold leg temperature in reducing the PWSCC crack growth rate in comparison to heads operating at higher temperatures. The expected reduction factor for the PWSCC crack growth rate is between 4.0 and 2.8 for the range of cold leg temperatures at U.S. PWRs of about 547°F to 561°F versus a temperature of 600°F. These reduction factors result in substantially longer times for through-wall cracking to be produced, for circumferential flaws located above the weld to grow to a significant size, and for leaking cracks to grow larger and produce the leak rate magnitudes necessary for relatively large volumes of material loss to be produced via boric acid corrosion.

3 *Assessment of Implications for Crack Initiation Time*

In Section 3.1, an assessment is made of the effect of the recent indications of PWSCC detected in two cold heads on the Weibull crack initiation parameters applied in MRP-105. In Section 3.2, the effect of the updated industry Weibull parameters on the results and conclusions of the MRP-105 study are assessed, in particular the effect on the probability of nozzle ejection for cold heads.

3.1 Updated Weibull Statistical Assessment

In support of this assessment, as documented in Attachment 2, the MRP Weibull statistical assessment of U.S. top head inspection experience was revised to reflect experience through spring 2011, including the two cases of apparent PWSCC detected at one cold head plant in 2007 [1] and at a second in 2011 [3].

Several different Weibull fits to the U.S. plant experience for Alloy 600 top heads were developed in Attachment 2:

- Table 1 summarizes the fit parameters for the various cases investigated.
- Figure 1 shows the Weibull fit applied in the MRP-105 study based on plant experience prior to its publishing in 2004. Also shown are the Weibull lines for the bounding values of characteristic time assumed in MRP-105. For each Monte Carlo trial in the MRP-105 probabilistic assessment, a Weibull distribution is applied lying between the bounding lines shown in this figure. In particular these inputs are applied in MRP-105 for the four case studies defined in its Table 8-9, including Case IV for an example cold head. The Weibull slope parameter, which describes the degree of scatter in the time to cracking, applied in these case studies of MRP-105 is 3. At the time MRP-105 was completed in 2004, it was judged that there were insufficient data to determine a best-fit slope value using the top

head plant experience available at that time. Instead the typical slope value of 3 for Alloy 600 steam generator tube PWSCC was selected.

- The Weibull fit to top head experience from the 2011 update (Attachment 2) is shown in Figure 2. Like Figure 1, this plot reflects the operating time until detectable PWSCC is produced in at least one of the nozzles in a head. Both part-depth cracks and through-wall (i.e., leaking) cracks are included in the basis for this Weibull fit. However, a best-fit slope is fitted to the top head data to model the scatter among different heads. It was judged that with the additional data since 2004, especially the PWSCC experience for two cold heads, it was appropriate to use a fitted slope rather than a standard value of 3. The fitted slope of 1.60 results in a somewhat higher probability of cracking for relatively small cumulative EDY values as discussed below. The slope of 1.60 represents a greater relative degree in scatter in time to crack initiation than the previously assumed slope of 3, and is a consequence of the range of nozzle material processing practices and head fabrication practices applied across the U.S. fleet.
- For the 2011 Weibull assessment (Attachment 2), Weibull distributions were also fit to Alloy 600 top head nozzle leakage experience. Only nozzles that were reported to have through-wall cracking per volumetric/surface and/or direct visual examinations were tabulated in the statistical basis for these Weibull fits. Figure 3 shows the 2011 Weibull fit based on a best-fit slope to the leakage-only data, while Figure 4 shows the result assuming a slope of 1.60 per the best-fit slope to the cracking case (Figure 2).

Figure 5 and Figure 6 show how the Weibull fits developed per the 2011 analysis compare to the Weibull fit developed in 2004 for application to the MRP-105 case studies. Specifically, Figure 5 compares the MRP-105 Weibull fit to the 2011 Weibull fit to cracking data, and Figure 6 makes the comparison versus the 2011 Weibull fit to leakage data.

In Figure 5, it is seen that for cumulative EDY values greater than 9 the new fit predicts a reduced mean probability of cracking, but for cumulative EDY values less than 9 the opposite is the case. It is instructive to consider Figure 5 in terms of the current cumulative EDY values for each of the 29 Alloy 600 heads in service in the U.S.:

- It is estimated that the 20 operating cold heads currently (August 2011) have a range of cumulative EDY values between 2.3 and 4.1, with a median of 3.4. For this range of EDY values, the 2011 Weibull fit results in a probability of crack initiation that is between 3 and 7 times higher than the corresponding probability for the 2004 Weibull fit, with a median ratio of 4. As additional EDYs accumulate in the future, the ratio between the two Weibull lines will decrease. The estimated range of EDY values at the end of a 60-year operating period for each of the cold heads is between 5 and 11.
- Not including the first replacement Alloy 600 head that was replaced with a PWSCC-resistant head in late 2011, all nine of the Alloy 600 non-cold heads still operating are estimated to currently have significantly more than EDY = 9.

3.2 Effect on Technical Basis

The effect of these somewhat higher probabilities of crack initiation on the N-729-1 technical basis for cold heads can be assessed through examination of Table 8-14 of MRP-105 [8]. This table indicates the peak probability of nozzle ejection calculated for each of four case study examples representing a range of head temperatures and plant designs, and three different inspection schedules. Case Study IV is of particular interest because it is for an example cold head operating at a temperature of 567°F (see Table 8-9 of MRP-105). The highest peak probability (or frequency) of nozzle ejection for Case IV is 9.6×10^{-5} per year for the "MRP Plan B" inspection plan. The interval between volumetric/surface inspections assumed for this inspection plan for Case IV was five 18-month cycles (7.5 calendar years).

It is concluded that the increased probability of crack initiation for cold heads has an acceptably small effect on the results of the MRP-105 probabilistic assessment based on the following points:

- A factor of 5 increase in the probability of ejection can be accommodated in the result in MRP-105 for Case IV and "MRP Plan B" before the result for Case I and "MRP Plan B" is reached. This factor is about 7 if comparison is made to the result for Case I and "MRP Plan C," and the factor is about 10 if the acceptance criterion cited in MRP-105 of 1×10^{-3} is considered. These factors compare to the increase in probability of crack initiation between a factor of 3 and 7, with median of 4, for the 2011 Weibull assessment with the best-fit slope of 1.60.
- For the relatively low probabilities of crack initiation for cold heads, the probability of nozzle ejection per the MRP-105 model is expected to be roughly proportional to the probability of initiation. This is the case because if a cracking event is predicted in the MRP-105 simulation, it is likely that only one of the CRDM nozzles will be affected. Then as an approximation the probability of nozzle ejection is equal to the probability of crack initiation times the conditional probability of ejection given the occurrence of an initiated flaw and the periodic inspections assumed. So, in approximate terms, as the probability of initiation is adjusted, the probability of ejection changes in a manner proportional to the change in initiation probability. Thus, there is margin in the probability of nozzle ejection for Case IV in MRP-105 that can accommodate the increase in probability of initiation per the 2011 Weibull assessment.
- "MRP Plan B" represented a tentative approach to scheduling periodic volumetric/surface examinations on the basis of an interval of no more than ΔEDY = 2 or 8 calendar years, whichever is shorter. The interval in MRP-117 [6], which was subsequently adopted in N-729-1, is based instead on the RIY parameter but also with the limit of 8 calendar years. The RIY approach takes reduced credit as head temperature is reduced, and the re-inspection intervals of MRP-117 and N-729-1 are bounded by the case studies of MRP-105 [32]. In the specific case of Case IV (head temperature of 567°F), N-729-1 would require, for typical capacity factors, that volumetric/surface examinations be performed once every three 18-month fuel cycles, versus every five 18-month fuel cycles for "MRP Plan B."

- The first in-service volumetric/surface examination for Case IV is at EDY = 6.2. This is considerably greater than the estimated current range of 2.3 to 4.1 for the 20 operating cold heads. At EDY = 6.2, the difference between the 2004 and 2011 Weibull fits is considerably reduced (ratio of 1.7).
- The MRP-105 probabilistic model applies the Weibull inputs as the basis for the time that leakage, and not just cracking, is produced. In addition, the MRP-105 approach assumes that a 30° through-wall circumferential crack located above the J-groove weld exists at the time leakage occurs based on the Weibull inputs. These are rather significant sources of conservatism in the calculated probability of nozzle ejection when applying Weibull parameters based on the time to cracking rather than leakage. As shown in Figure 6, the Weibull line for the 2011 leakage case with a best-fit slope of 3.05 is significantly below the Weibull line assumed in MRP-105. If instead the slope fitted from the 2011 cracking case is applied to the 2011 leakage case, then the probability of leakage per the updated Weibull assessment is modestly greater than the probability per the MRP-105 line for EDY less than about 4.5. For EDY values of interest, the ratio of probabilities is no more than a factor of 2. This ratio compares to the factor of 10 margin between the result in MRP-105 for Case IV and "MRP Plan B" and the 1×10^{-3} acceptance criterion.
- The leakage probability shown in Table 8-14 of MRP-105 for Case IV and "MRP Plan B" is 0.48% per year. This is about 9 times lower than the 4.4% value shown for Case II and "MRP Plan B." This ratio is greater than the ratio of 3 to 7 for the change in crack initiation Weibull probability cited above. As mentioned above, N-729-1 would require that volumetric/surface examinations be performed more frequently for Case IV than per "MRP Plan B." This effect would tend to counteract the effect of the increased probability of crack initiation.

Hence, it is concluded that the technical basis for the N-729-1 volumetric/surface inspection intervals remains valid in consideration of the revised best-estimate probability of crack initiation for cold heads.

3.3 Assessment of Hypothetical PWSCC Detected in Additional Cold Heads

In this subsection, hypothetical cases of PWSCC detected in additional cold heads are presented in order to assess the potential implications of such experience on the adequacy of the current inspection requirements. The Weibull methodology described in Attachment 2 was applied for each sensitivity case to determine how the Weibull distribution for the probability of cracking (i.e., time to first cracking) would be affected if the additional hypothetical cracking were added to the actual plant experience. For these sensitivity cases a Weibull slope was fit to the data using the same method applied to produce the fit shown in Figure 2, which was used above to assess the implications of the plant experience since the time that the MRP-105 [8] probabilistic assessment was published.

The degree to which additional assumed PWSCC experience in cold heads affects the Weibull distribution for the probability of cracking depends on the extent of cracking assumed and the normalized cumulative operating time (i.e., the EDY value) at which the cracking is assumed to be detected. As more extensive cracking is assumed in terms of the number of heads and nozzles affected, the effect on the probability of cracking distribution becomes greater. Likewise, if the cracking is assumed to be detected earlier in terms of EDY value, then the effect on the probability of cracking distribution also becomes greater.

The following four specific sensitivity cases were selected to cover a wide range of possibilities:

- Sensitivity Case #1 (Figure 7) – One additional cold head with detected PWSCC in four CRDM nozzles. It is assumed that the PWSCC is detected at EDY = 3.4, which is the current estimated median EDY value for the Alloy 600 cold heads that are in service.
- Sensitivity Case #2 (Figure 8) – Two additional cold heads with detected PWSCC in four CRDM nozzles each. It is assumed that the PWSCC is detected at EDY = 3.4 in the first head and EDY = 3.5 in the second head.
- Sensitivity Case #3 (Figure 9) – Three additional cold heads with detected PWSCC in one CRDM nozzle each. It is assumed that the PWSCC is detected at EDY = 3.4 in the first head, EDY = 3.5 in the second head, and EDY = 3.6 in the third head.
- Sensitivity Case #4 (Figure 10) – Two additional cold heads with detected PWSCC. It is assumed that PWSCC is detected in the first head in one CRDM nozzle at EDY = 2.4. It is assumed that PWSCC is detected in the second head in two CRDM nozzles also at EDY = 2.4. EDY = 2.4 is the estimated minimum EDY value projected to spring 2012 for the group of 20 Alloy 600 cold heads that are currently in service. Thus, this sensitivity case is bounding with regard to the effect of assumed EDY value at the time PWSCC is detected.

The results of the Weibull fitting procedure for these four sensitivity cases are shown in Figure 7 through Figure 10. In each figure, the hypothetical plant data points used in the procedure per Attachment 2 are identified as "Plant α," "Plant β," and "Plant γ," as applicable. Also in each figure, the resulting sensitivity case Weibull distribution is compared to the 2011 update Weibull distribution from Figure 2 (i.e., the base case). Over the estimated range of current cold head EDY values (2.3 to 4.1), Sensitivity Case #1 shows a probability between 20% and 30% higher than the base case, Sensitivity Case #2 shows a probability between 40% and 60% higher than the base case, Sensitivity Case #3 shows a probability between 35% and 45% higher than the base case, and Sensitivity Case #4 shows a probability between 35% and 50% higher than the base case. As additional EDYs are accumulated for each cold head over time, these percentage differences will decrease as the sensitivity case and base case Weibull lines approach each other.

The effect of these percentage increases in the probability of cracking of up to 60% versus the base case may be assessed in the same manner as the base case was evaluated above in Section 3.2. Considering the margin in the probability of nozzle ejection calculated in MRP-105 for its cold head case (Case IV) versus the acceptance criterion of 1×10^{-3} and the other sources of conservatism discussed in Section 3.2, it is concluded that each of these four sensitivity cases has an acceptably small effect on the nozzle ejection frequency. Similarly, it is concluded that each of them also has an acceptably small effect on the probability of nozzle leakage calculated in MRP-105. In other words, there is sufficient margin in the MRP-105 results to accommodate a further 60% increase in the probability of first cracking in a cold head above the increase from the MRP-105 probability of cracking input to that calculated per plant experience to date.

Hence, it is concluded that the technical basis for the N-729-1 volumetric/surface inspection intervals would continue to remain valid if additional PWSCC were to be detected in other cold heads similar to the sensitivity cases assumed, in terms of the numbers of affected heads and nozzles and EDY values at time of detection. If cold head cracking more extensive than that assumed in these sensitivity cases is detected, then an appropriate response should be determined possibly including steps such as updating of the Weibull assessment of cracking experience, other types of analyses, or changes to the inspection requirements of Code Case N-729-1.

4 Assessment of Implications for Crack Growth Rates

Laboratory testing is the principal technique applied to determine relative crack growth rates for Alloy 600 wrought material and Alloy 82/182 weld metal material. The relative crack growth rate corresponds to the resistance of the material to PWSCC crack extension, and is calculated as the observed crack growth rate normalized for the effects of temperature and crack-tip stress intensity factor. Laboratory testing has the advantage of using simplified specimen geometries and loading that facilitate accurate calculation of crack-tip loading conditions, i.e., stress intensity factor. Using an extensive set of worldwide laboratory test data, the MRP-55 [12] crack growth rate study developed a log-normal distribution that describes the variability in crack growth rate due to the variability in material PWSCC resistance for Alloy 600 wrought material.

However, plant experience is a source of data that can in some cases be used to make estimates of the relative crack growth rate for comparison with statistical assessments of the laboratory crack growth rate data. As discussed below, the plant PWSCC experience for reactor vessel top head nozzles was assessed for cases in which meaningful crack growth rate information could be developed. In some cases, ranges of relative crack growth rates could be inferred from the inspection results for comparison with the MRP-55 crack growth rate inputs to the MRP-105 probabilistic assessment.

4.1 Cold Head Experience

There have been two cases of apparent PWSCC detected in cold top heads in the U.S.:

- *2007 Cold Head Experience.* The first case of apparent PWSCC detected at a cold head was for the first in-service volumetric/surface examination at this plant in 2007 ([1], [2]) and was associated with a weld fabrication flaw. As such, this case was not a good candidate for assessment per the techniques described in the next bullet.
- *2011 Cold Head Experience.* The second cold head case was for the second in-service volumetric/surface examination at another plant in 2011 ([3], [35]). After an inspection interval of four cycles or approximately 6 calendar years, indications of PWSCC were detected in four CRDM nozzles, which were subsequently repaired during the same outage. Given the head temperature of 557°F [22] applicable to the period between the two examinations performed, the RIY value for this interval is estimated to be 1.86.

  Crack growth calculations were performed specific to each of the five indications in the four nozzles that were reported as service-related in 2011. All five indications were reported to be connected to the nozzle tube OD, with four being primarily axial in orientation and one primarily circumferential. In each crack growth calculation, the flaw was modeled as growing with a constant length-to-depth aspect ratio based on the flaw length and depth reported for the 2011 examination. Based on a comparison of the ultrasonic examination data collected in 2005 and 2011, flaw growth increments in the depth direction in the range from 0.083 to 0.097 inch were reported for each of the five indications [35]. In the crack growth calculation, a uniform hoop stress of variable magnitude is assumed to drive the crack growth, with the stress intensity factor solution by Marie et al. [23] applied for the case of an axial or circumferential semi-elliptical flaw on the outside surface of a pipe, as applicable.

  Multiple cases were considered in the crack growth calculations to determine combinations of the driving stress value and relative crack growth rate (i.e., percentile of the MRP-55 uncertainty distribution) that result in the reported extension in crack depth for each reported flaw. Driving stresses in the range from 18 to 42 ksi were found to result in the observed extensions in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed. This stress range is consistent with the hoop stress results published for the nozzle tube wall below the weld by two organizations ([24], [25]) using FEA weld residual stress analysis techniques applied to example CRDM nozzle cases. Furthermore, this range of crack growth rate percentiles is consistent with the assumptions of the MRP-105 probabilistic model. The MRP-105 model samples crack growth rate values according to a log-triangular distribution that reaches about the 99th percentile of the MRP-55 log-normal distribution. In addition, the MRP-105 model applies a "local crack growth rate variability" term that can result in crack growth rates up to about 5 times higher than the value sampled from the log-triangular distribution describing the relative crack growth rate (i.e., the power-law constant in MRP-105). Moreover the case studies of MRP-105 assume that the relative crack growth rate (i.e., power-law constant) is perfectly negatively correlated with the sampled time to crack initiation. Thus, there is a large bias in which the flaws that are simulated to initiate at relatively small EDY values are assumed to have high relative crack growth rates.

  Hence, it is concluded that the extensions in crack depth reported for this cold head experience are consistent with the probabilistic crack growth rate inputs developed on the basis of the MRP-55 [12] assessment of laboratory crack growth rate data and used in the MRP-105 [8] probabilistic assessment.

4.2 Non-Cold Head Experience

Through a detailed review of the non-cold head experience to date, five cases were identified as candidates for providing meaningful information on relative crack growth rates. Generally, meaningful crack growth rate information cannot be derived from cases in which the flaw was detected during the first NDE of the affected nozzle because of the lack of constraint on the crack initiation time. The five cases are discussed in the following:

- *1994-96 Non-Cold Head Experience.* In 1994, indications of PWSCC were detected on the inside surface of CRDM Nozzle #75 at this plant. These indications were re-examined in 1996, when the nozzle was weld repaired. The results of a crack growth rate assessment were presented in MRP-55 [12]. As shown in Figure 5-2 of MRP-55, the crack growth rates implied by the extension in length and depth of the deepest crack in this nozzle are significantly below that predicted by the MRP-55 equation, which corresponds to the 75th percentile of the crack growth rate uncertainty distribution per MRP-55.
- *2002-03 Non-Cold Head Experience.* In 2002, PWSCC was detected in three CRDM nozzles at a second non-cold head plant [34]. During the subsequent refueling outage in 2003, PWSCC was detected in an additional 11 nozzles [33]. Detailed data were not collected for this case, which reflects examinations performed prior to improvements made in CRDM nozzle inspection technology. Thus this effort to deduce relative crack growth rates from plant data concentrated on more recent cases.
- *2005 Non-Cold Head Experience.* In 2005, three CRDM nozzles were identified with possible indications of PWSCC at a third non-cold head plant [26]. These nozzles were previously examined in 2003 without PWSCC being reported. However, the flaws detected in 2005 were relatively shallow, with the maximum depth being 0.143 inch, or 22% through-wall per the nozzle tube wall thickness [27]. This maximum flaw depth is slightly greater than the typical flaw depth detectability limit of 10-15% through-wall expected for CRDM nozzle tubes examined by ultrasonic testing. Thus this experience is consistent with the crack growth rate assumptions of the MRP-105 probabilistic model.
- *2010 Non-Cold Head Experience.* As described in Attachment 2, in 2010 after about 6 calendar years of operation, PWSCC including indications of pressure boundary leakage was detected in a first replacement head having Alloy 600 CRDM nozzles [20]. As part of its response, the utility sponsored detailed crack growth calculations including FEA stress calculations specific to the replacement head. The results of this work are discussed in the NRC Special Inspection report [19]. Considering that less than the 6 calendar years of operation were available for crack growth, the detailed calculations indicated that the flaw growth was consistent with relative growth rates in the range between the 75th and 95th percentiles of the MRP-55 uncertainty distribution.

  It is also noted that under sponsorship of NRC, ANL has performed laboratory PWSCC crack growth rate testing of Alloy 600 CRDM nozzle tube material removed from the original head at this plant at the time the head was retired ([30], [31]). The ANL study concluded that the crack growth rates approximately corresponded to the 95th percentile of the MRP-55 uncertainty distribution. The nozzle material for the original and first replacement heads at this plant, as well as for the 2011 cold head experience cited above, was produced by the same material supplier. Material produced by this supplier also tended to show relatively high crack growth rates in the data compiled in the MRP-55 [12] study in comparison to other suppliers for heads installed in U.S. plants. As discussed above, the MRP-105 probabilistic assessment includes a significant bias in which the nozzles that are predicted to crack at relatively small EDY values are assumed to have high relative crack growth rates.

- *2009 Non-Cold Head Experience.* In fall 2009, a total of two indications reported to be service-related were detected in two CRDM nozzles at another non-cold head plant ([28], [36]). Each of the two indications detected in 2009 was circumferential in orientation and located on the nozzle tube OD below the weld. The RIY increment for each fuel cycle for this head is estimated to be 1.42 based on the head temperature of 601.3°F [29].

  In the same manner as for the 2011 cold head experience, a simplified crack growth calculation was performed for each of these two flaws. In this case the stress intensity factor solution per Marie et al. [23] was applied for the case of a circumferential semi-elliptical flaw on the outside surface of a pipe. In each crack growth calculation, the flaw was modeled as growing with a constant length-to-depth aspect ratio based on the flaw length and depth reported for the 2009 examination. Based on a comparison of the ultrasonic examination data collected in 2009 and during the previous two refueling outages, flaw growth increments in the depth direction of 0.053 and 0.093 inch were reported for the two indications [36]. The 0.093-inch increment corresponded to one cycle of growth, and the 0.053-inch increment corresponded to two cycles of growth.

  Again, multiple cases were considered in the crack growth calculations to determine combinations of the driving stress value and relative crack growth rate (i.e., percentile of the MRP-55 uncertainty distribution) that result in the reported extension in crack depth for each reported flaw. For the flaw that showed an increment of 0.093 inch, a driving stress in the range from 32 to 52 ksi was found to result in the observed extension in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed. For the flaw that showed an increment of 0.053 inch, a driving stress in the range from 16 to 20 ksi was found to result in the observed extension in crack depth if a crack growth rate percentile in the range from the 75th to 95th percentile is assumed.

  These stress ranges are consistent with the hoop stress results published for the nozzle tube wall below the weld by two organizations ([24], [25]) using FEA weld residual stress analysis techniques applied to example CRDM nozzle cases. Furthermore, the assumed range of crack growth rate percentiles is consistent with the assumptions of the MRP-105 probabilistic model. Hence, it is concluded that the extensions in crack depth reported for this head are consistent with the probabilistic crack growth rate inputs developed on the basis of the MRP-55 [12] assessment of laboratory crack growth rate data and used in the MRP-105 [8] probabilistic assessment.

4.3 Effect on Technical Basis

Plant inspection experience for both cold heads and heads operating at temperatures significantly above Tcold (i.e., non-cold heads) was assessed with regard to implied relative crack growth rates. The first case of apparent PWSCC detected at a cold head was for the first in-service volumetric/surface examination and was associated with a weld fabrication flaw. As such this case was not a good candidate for assessment. The second cold head case was for a second in-service volumetric/surface examination at a different plant in 2011. The crack growth rates implied by the ultrasonic examination data for this cold head are consistent with the probabilistic crack growth rate inputs developed on the basis of the MRP-55 [12] assessment of laboratory crack growth rate data and used in the MRP-105 [8] probabilistic assessment. Furthermore, the cases in which relative crack growth rates could reasonably be inferred for non-cold heads were also consistent with the crack growth rate inputs of the MRP-105 probabilistic assessment. Hence, the crack growth rate assumptions of the technical basis for the N-729-1 inspection requirements remain valid in light of the CRDM nozzle inspection experience.

5 Conclusions

The conclusions of this assessment are as follows:

- Demonstrated effectiveness of current inspection requirements. The current inspection requirements have been effective in detecting the PWSCC degradation reported in a timely fashion, before the degradation produces flaws of safety significance. No nozzle leaks have been detected after a first in-service volumetric/surface examination was performed of all CRDM or CEDM nozzles.
- Effect of cold head cracking experience on probability of crack initiation assessed to be acceptable. Plant experience to date indicates a somewhat higher probability of crack initiation for cold heads than that calculated per the set of MRP-105 [8] Weibull crack initiation inputs. However, this is concluded to have an acceptably small effect on the probability of nozzle ejection calculations in MRP-105 for cold heads (and specifically Case IV[*]). The required volumetric/surface inspection intervals for cold heads are concluded still to be appropriate and conservative.
- Consistency of crack growth rates implied by top head inspection data with the crack growth rate inputs applied in the probabilistic safety assessment. Top head experience was assessed for cases in which meaningful crack growth rate information could be developed, typically subsequent to a first in-service examination. Through this detailed review, six heads were identified as candidate sources for crack growth rate data. In five of these six cases, the crack growth rates implied by the inspection data were well within the MRP-55 [12] crack growth rate uncertainty distribution applied in the MRP-105 [8] probabilistic model. Detailed data were not collected for the sixth case, which reflects examinations performed in 2002 and 2003 prior to improvements made in inspection technology.
- Adequacy of current visual examinations to protect against structurally significant boric acid corrosion. Plant experience continues to support the adequacy of the current requirements for top heads to perform periodic visual inspections for evidence of leakage in order to protect against structurally significant boric acid corrosion. The visual

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[*] See Tables 8-9 and 8-14 of MRP-105 [8].

examination requirements for cold heads (i.e., heads with EDY < 8) remain appropriate given the very low demonstrated probability of leakage for cold heads per plant experience, the relatively large benefits of reduced head temperature for crack initiation time and crack growth rates, and the results of the recently completed MRP boric acid corrosion test program.

In summary, the inspection requirements for PWR reactor vessel top heads with Alloy 600 nozzles per ASME Code Case N-729-1 [4] are still concluded to be conservative and adequate to ensure nuclear safety with respect to the PWSCC degradation concern. There is no need to revise the technical safety assessments or inspection requirements for the reactor vessel top head nozzles.

6 References

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Table 1. Summary of Weibull Distribution Fit Parameters

Weibull Fit Case		No. Heads in Weibull Fit (with volumetric or bare metal visual exam)	No. Heads with Cracks or Leaks	Weibull Slope β		Weibull Characteristic Time Θ
Analysis Date	Failure Considered to be Crack or Leak			Description	Value	
MRP-105 (Spring 2003)	Cracks (incl. leaks)	30	14	Assumed	3	15.2 (Figs. 1, 5, 6)
2011	Cracks (incl. leaks)	63	20	Fit	1.60	23.2 (Figs. 2, 5)
2011	Leaks Only	69	11	Fit	3.05	25.7 (Figs. 3, 6)
2011	Leaks Only	69	11	Assumed	1.60	43.8 (Figs. 4, 6)

Notes:

(1) It is assumed for these cases that the head temperature for each head is as reported in MRP-48, with the exception that for the 2011 cases the head temperature for each B&W plant head is 8°F higher than the hot leg temperature.

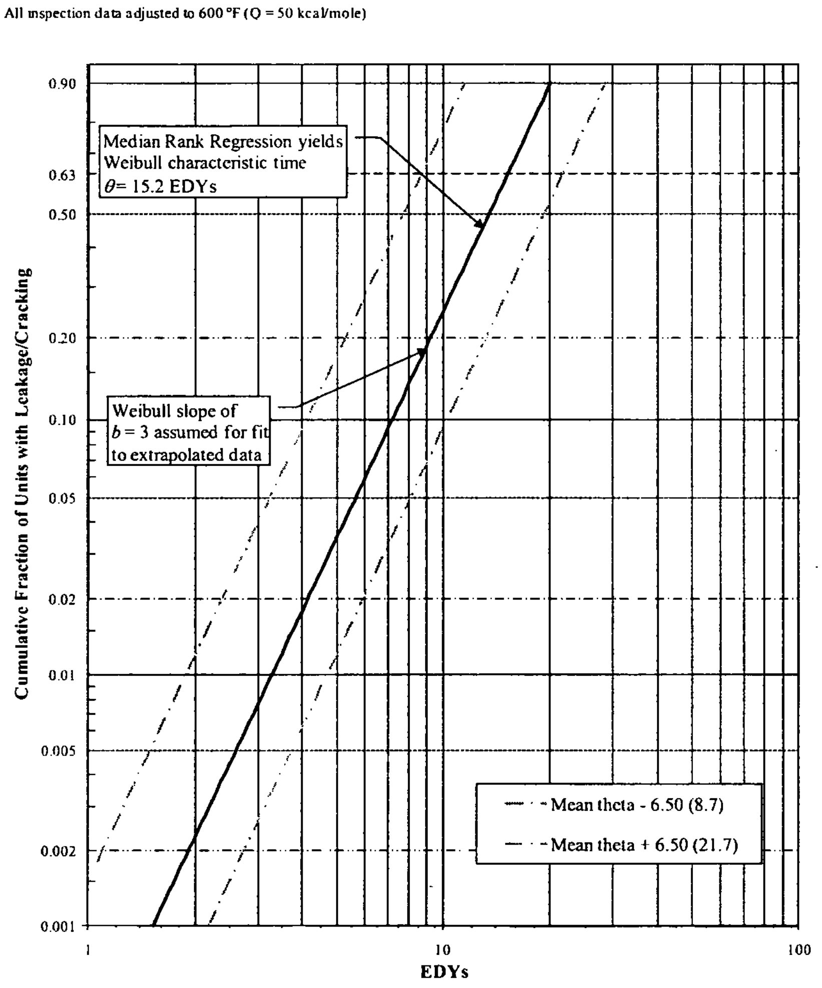


Figure 1. **MRP-105 Case Study IV Assumed Fit with Uncertainty Bounds**

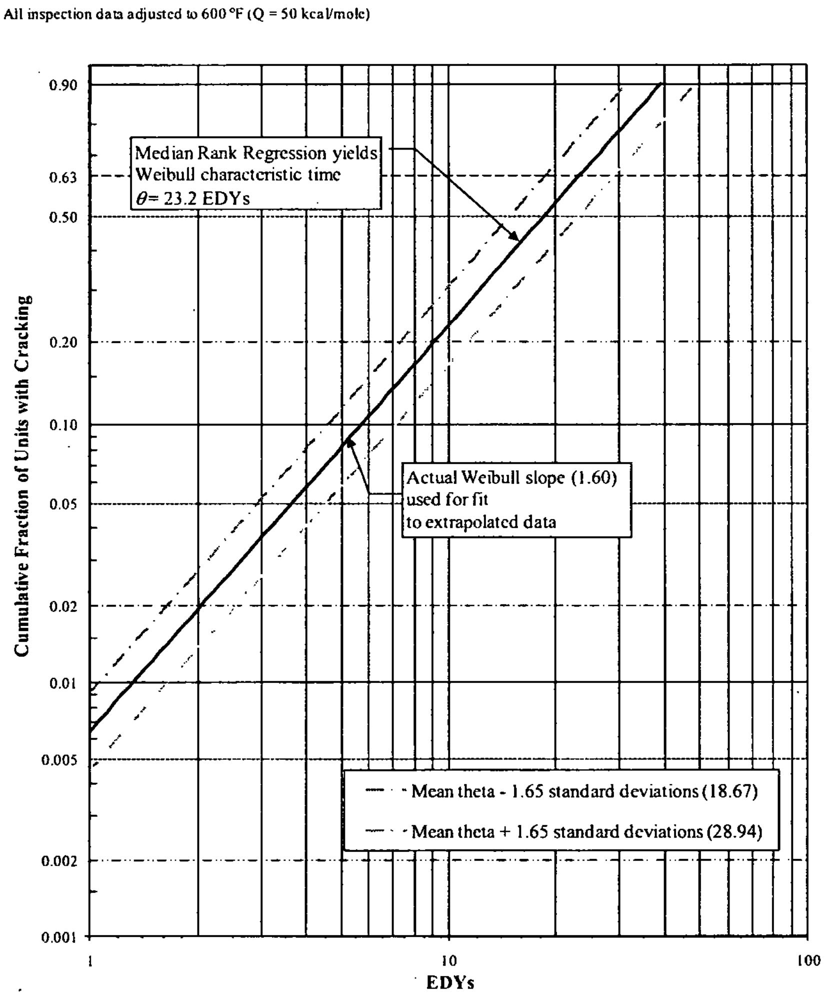
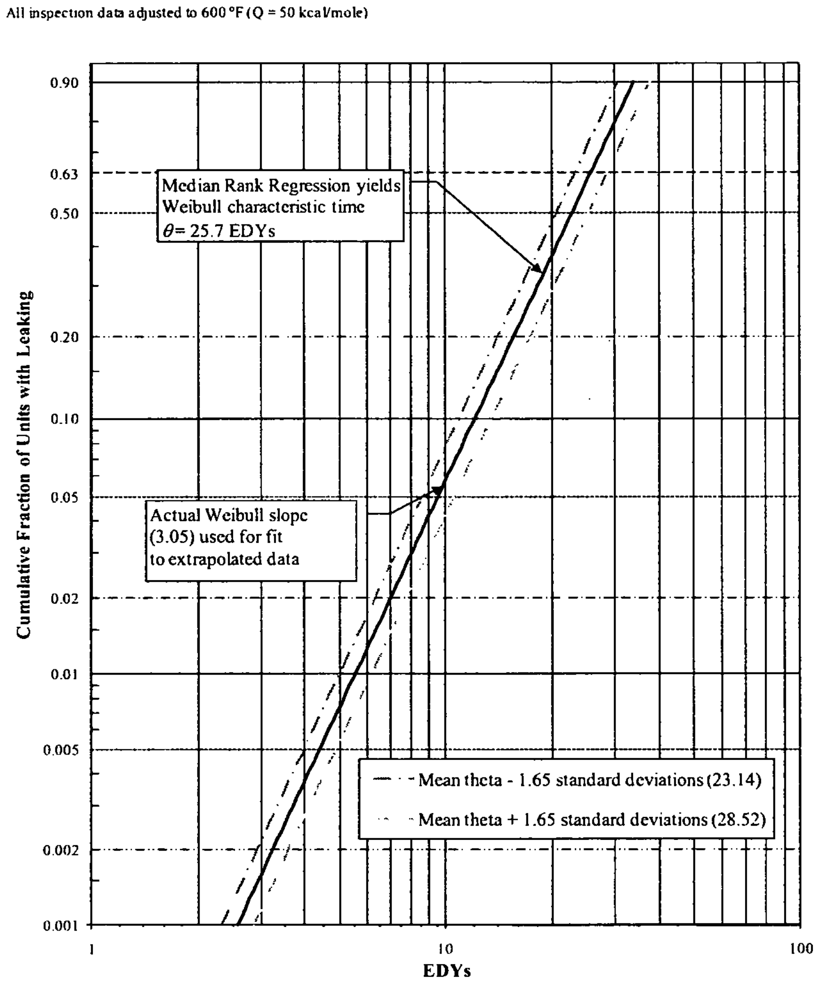


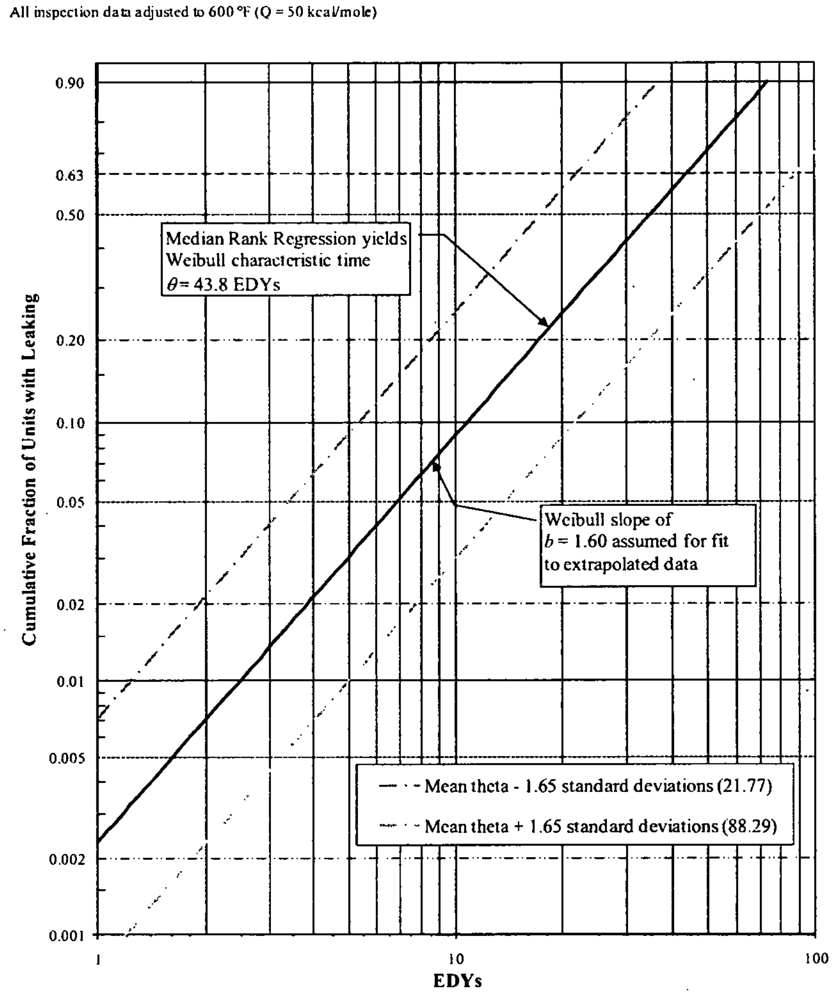
Figure 2. **2011 Update NDE Best-Estimate Fit with Uncertainty Bounds – New Temperatures (+8°F for all B&W Heads)**


All inspection data adjusted to 600 °F (Q = 50 kcal/mole)

Median Rank Regression yields Weibull characteristic time θ= 25.7 EDYs

Actual Weibull slope (3.05) used for fit to extrapolated data

Figure 3. 2011 Update BMV Best-Estimate Fit with Uncertainty Bounds – New Temperatures (+8°F for all B&W Heads)


All inspection data adjusted to 600 °F (Q = 50 kcal/mole)

Median Rank Regression yields Weibull characteristic time θ= 43.8 EDYs

Weibull slope of b = 1.60 assumed for fit to extrapolated data

Figure 4. 2011 Update BMV Assumed Fit with Uncertainty Bounds – New Temperatures (+8°F for all B&W Heads)

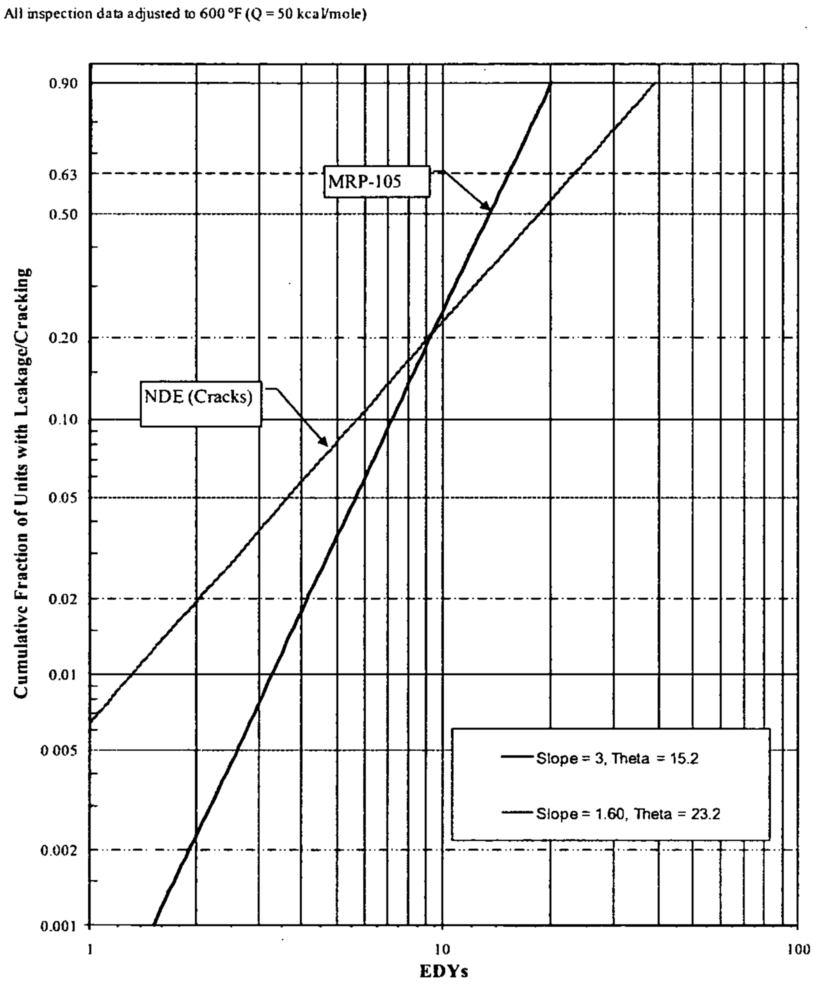


Figure 5. Comparison of MRP-105 Case Study IV Fit with 2011 Update NDE Fit

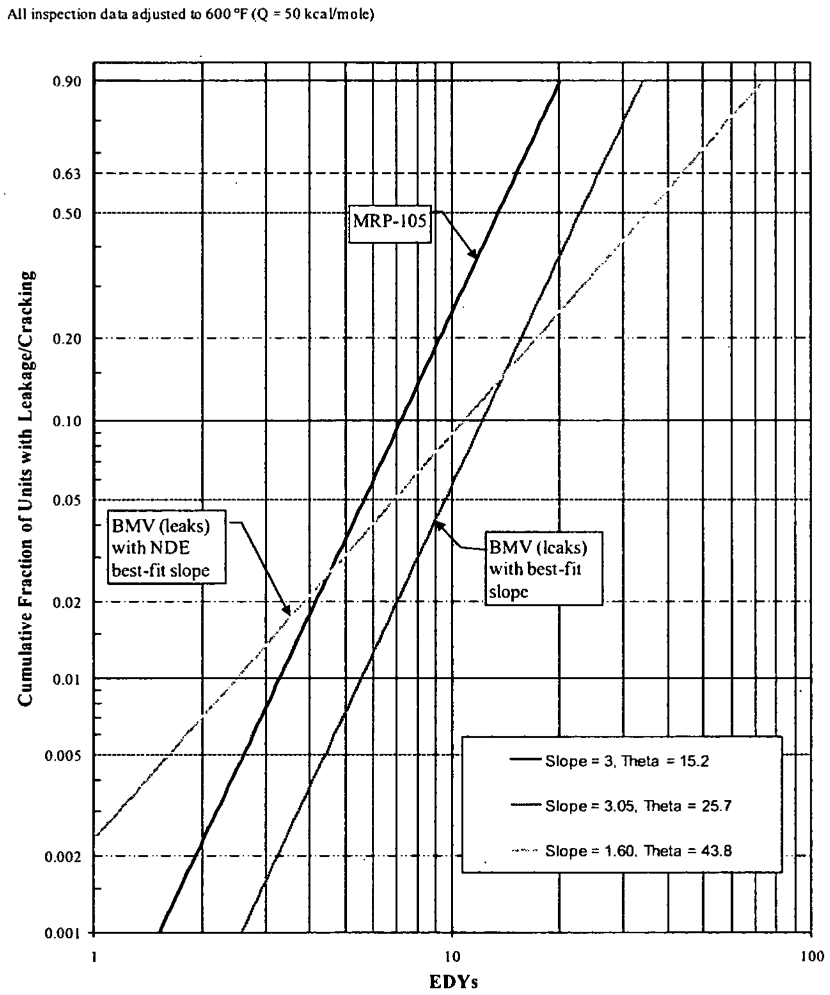


Figure 6. Comparison of MRP-105 Case Study IV Fit with 2011 Update BMV Fits

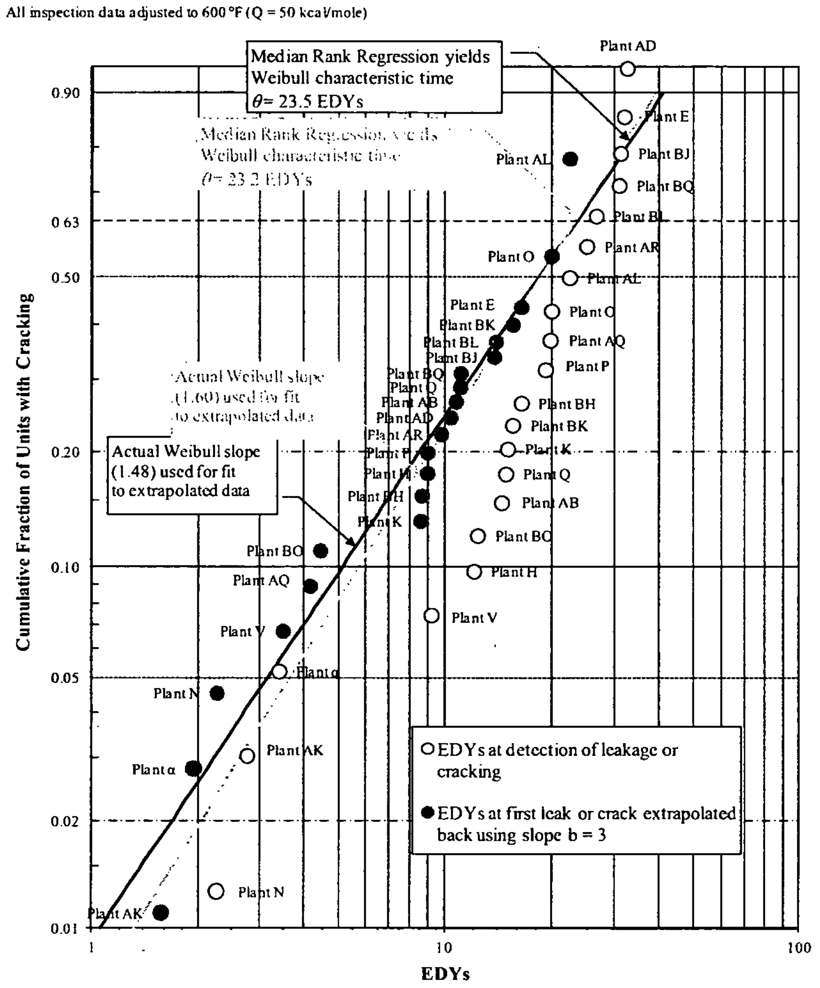


Figure 7. Comparison of 2011 Update NDE Fit with Sensitivity Case #1 (One Cold Head Plant Finds PWSCC in 4 CRDM Nozzles at EDY = 3.4)

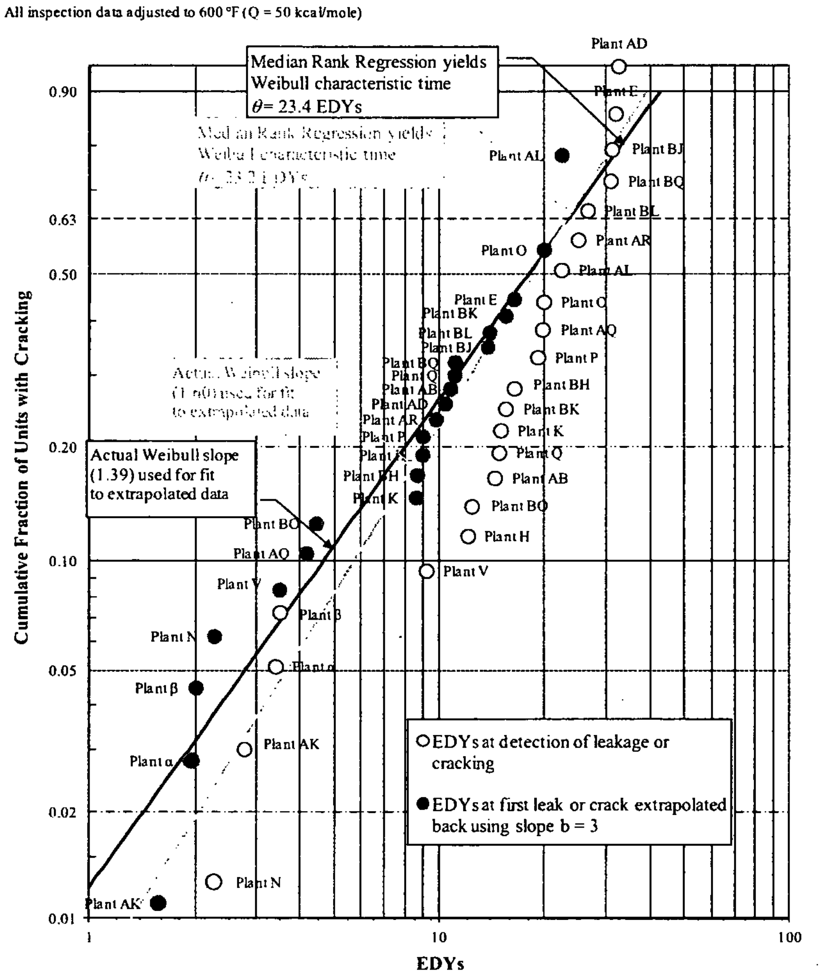


Figure 8. Comparison of 2011 Update NDE Fit with Sensitivity Case #2 (Two Cold Head Plants Find PWSCC in 4 CRDM Nozzles Each at EDY = 3.4 and EDY = 3.5)

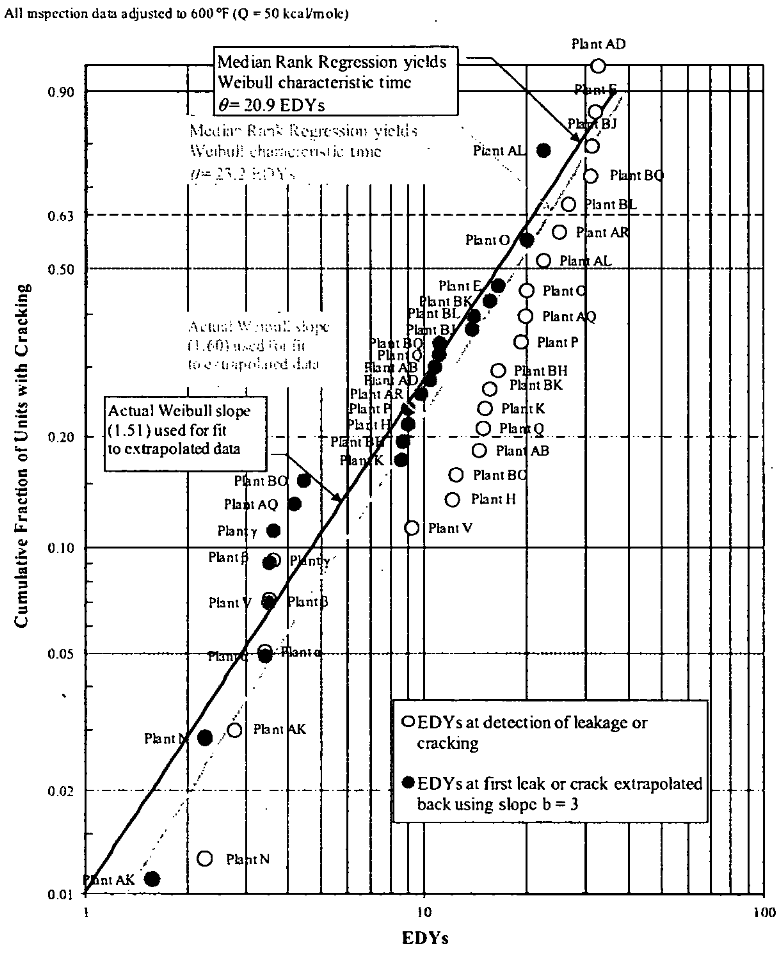


Figure 9. Comparison of 2011 Update NDE Fit with Sensitivity Case #3 (Three Cold Head Plants Find PWSCC in 1 CRDM Nozzle Each at EDY = 3.4, EDY = 3.5, and EDY = 3.6)

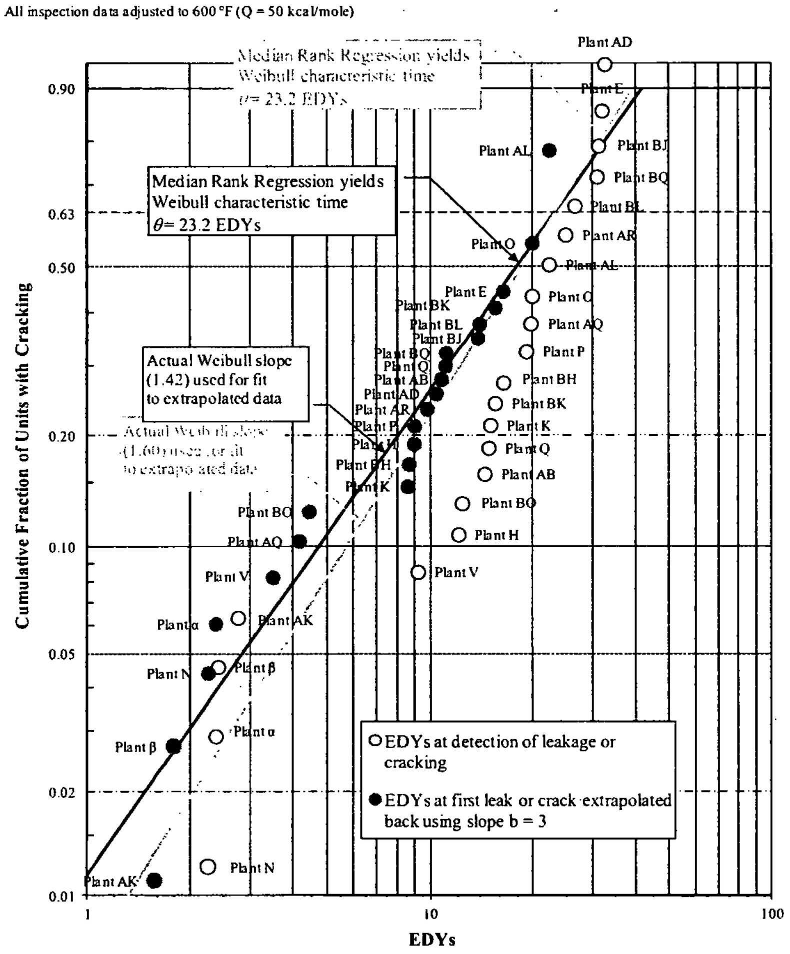


Figure 10. Comparison of 2011 Update NDE Fit with Sensitivity Case #4 (Two Cold Head Plants Find PWSCC in 1 and 2 CRDM Nozzles, Respectively, at EDY = 2.4)

ATTACHMENT 2
2011 UPDATE OF WEIBULL STATISTICAL ASSESSMENT OF U.S. ALLOY 600 CRDM/CEDM NOZZLE INSPECTION EXPERIENCE

1 Purpose

The objective of this document is to describe the results of a 2011 update to the Weibull statistical analysis originally performed as part of MRP-105, *Materials Reliability Program Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking* [1]. The purpose of MRP-105 was to determine appropriate volumetric re-examination intervals to address the concern for primary water stress corrosion cracking (PWSCC) of Alloy 600 CRDM, CEDM, and other top head nozzles, including through-wall crack penetration (i.e., leakage) and the potential for nozzle ejection due to circumferential cracking. This update follows recent key CRDM nozzle experience, specifically the findings of Alloy 600 CRDM nozzle cracking in spring 2010 in the first replacement reactor vessel top head at one plant, and in spring 2011 in a top head at another plant that in this case operates at the reactor cold leg temperature. Reactor vessel top heads that operate at the reactor cold leg temperature are commonly referred to as "cold heads."

2 Background

2.1 MRP-105 Weibull Analysis

Section 4 of MRP-105 [1] described the analysis of field experience in the U.S. with reactor vessel head CRDM/CEDM nozzle cracking through early 2003. U.S. plants were prioritized for baseline volumetric examination using an approximate susceptibility ranking for top head nozzle cracking based on a parameter known as effective degradation years (EDYs). This parameter adjusts operating time for the key effect of differences in operating head temperature. As described in MRP-105, a Weibull statistical analysis was used to develop a distribution describing the variability in the EDYs from initial operation to the time of detectable cracking (i.e., first crack). The heads that were inspected and found not to have reportable indications were treated as "suspended items" in the analysis, in accordance with the standard approach described by Abernethy [2]. Suspended item analysis takes appropriate statistical credit for inspections in which failures were not observed.

The population of heads used for this analysis included only plants that had performed non-visual non-destructive examination (NDE) (i.e., surface and/or volumetric examinations). Plants that had only performed bare metal visual (BMV) examination without reported leakage are not included because of the possibility of significant part-depth cracking.

2.2 2005 Weibull Analysis Update

In 2005, the MRP-105 Weibull statistical assessment was updated to consider an additional two years of head experience. Specifically, Table 4-2 (which displays the results of the Weibull analysis) and Figure 4-2 (which plots the cumulative fraction of units with cracking—including leaking cracks—versus EDYs) of MRP-105 were revised. Figure 1 and Figure 2 are the 2003 and 2005 versions of Figure 4-2, respectively.

3 2011 Weibull Analysis Update

3.1 Tabulation of Head Experience

In mid-2011, the set of U.S. top head experience was updated to reflect inspections performed through fall 2010* and the addition of a first replacement reactor vessel head having Alloy 600 CRDM nozzles to the fleet. The tabulated experience is shown in Table 1, which is similar to Table 4-1 of MRP-105. However, for the 2011 assessment, the experience with through-wall cracking and leakage has been separated into a separate assessment from the more general case of cracking experience. Thus, Table 1 separates NDE inspection results from BMV inspection results.

The sources for NDE and visual inspection results are the plant submittals and outage reports to the NRC in response to the following NRC orders and bulletins:

- NRC Order EA-03-009, Rev. 1, February 2004 (Rev. 0 was issued February 2003), "Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors"
- NRC Bulletin 2001-01, "Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles"

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* Data from the spring 2011 inspections at the cold head plant for which four CRDM nozzles were reported to have PWSCC indications [3] (Plant AK in Table 1) are included as part of this assessment. No additional PWSCC is believed to have been reported for U.S. PWR reactor vessel top heads in spring 2011, although a comprehensive review was not performed.

- NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity"
- NRC Bulletin 2002-02, "Reactor Pressure Vessel Head Penetration Nozzle Inspection Programs"

An additional source of inspection experience was the MRP-219 [4] series of PWR inspection data survey reports. It is noted that shallow surface indications (e.g., surface craze cracking) were not counted as cracks in Table 1 since such indications are not considered to be PWSCC degradation. It is also noted that the design data (number of J-groove nozzles by type, head fabricator, etc.) and operating head temperatures in Table 1 (with the exception of the original and first replacement heads discussed in Section 3.5 below) were taken from MRP-48 [5], and that the head replacement dates in Table 1 for past replacements are per MRP-219 [4].

3.2 Number of Cracked CRDM Nozzles for First Replacement Alloy 600 Head

A spring 2010 NDE of a first replacement head having Alloy 600 CRDM nozzles [6, 7] (Plant V in Table 1) resulted in 12 of its 69 CRDM nozzles reported to have PWSCC indications in the Alloy 600 base metal material. These nozzles were subsequently repaired prior to the head being returned to service. In addition, another 12 CRDM nozzles were repaired based on flaw indications detected through dye penetrant (PT) and eddy current (ET) examinations of the wetted surface of the J-groove attachment welds. However, the reported sizes for these weld indications (0.375 inch or smaller) were below that generally resulting in reports of PWSCC for previous industry experience for CRDM nozzle J-groove welds. Thus, to maintain consistency with the set of previous industry experience, the number of cracked CRDM nozzles for this first replacement head (Plant V) was taken to be 12 for the purpose of this Weibull assessment.

It is noted that the number of leaking CRDM nozzles for this first replacement head (Plant V) was taken as two, which is the number of confirmed leaking nozzles reported by the plant [6, 7], for the purpose of the Weibull assessment of the time to first leakage.

3.3 Number of Cracked CRDM Nozzles for 2011 Cold Head Experience

The spring 2011 volumetric/surface examination of one cold head [3] (Plant AK in Table 1) resulted in 4 of its 78 CRDM nozzles reported to have PWSCC indications (some of which were considered to be in the reactor coolant system pressure boundary region). No indications of leakage were detected. The nozzles were subsequently repaired prior to the head being returned to service.

3.4 Calculation of Effective Degradation Years (EDYs)

PWSCC is a thermally activated process [1, 5]. Thus, data for the plants included in the Weibull analysis are sorted by EDYs at the time of the most recent inspection, calculated in accordance with the standard Arrhenius relationship that describes thermally activated processes:

$$\dot{r} = \dot{r}_0 \exp\left(-\frac{Q}{RT}\right) \qquad [1]$$

where $\dot{r}$ is the cracking rate, $\dot{r}_0$ is a constant, Q is an activation energy, R is the universal gas constant, and T is the absolute temperature. Using the EDY model, it may be shown that a plant operating at a 560°F head temperature requires more than 50 years to accumulate the same effective degradation as a plant with a 600°F head temperature would accumulate in 10 years. This example illustrates the temperature dependence inherent in the EDY model.

In this 2011 update of the Weibull assessment of top head inspection experience, as was also done in the Weibull analysis performed as part of MRP-105 [1], the effective full power years of operating time are normalized to a reference temperature of 600°F and are determined from plant effective full power years (EFPYs) at various head temperatures using a standard thermal activation energy. The activation energy of 50 kcal/mole is an accepted industry best-estimate activation energy for SCC initiation in primary water environments (e.g., see [8]).

Specifically, the EDY parameter is defined as follows [1, 5]:

$$EDY = \sum_{j=1}^{n} \left\{ \Delta EFPY_j \exp\left[-\frac{Q_i}{R}\left(\frac{1}{T_{head,j}} - \frac{1}{T_{ref}} \right) \right] \right\} \qquad [2]$$

where:

EDY = total effective degradation years, normalized to a reference temperature of 600°F
$\Delta EFPY_j$ = effective full power years accumulated during time period j
Q_i = activation energy for crack initiation (50 kcal/mole)
R = universal gas constant (1.103×10^{-3} kcal/mol-°R)
$T_{head,j}$ = 100% power head temp. during time period j (°R = °F + 459.67)
T_{ref} = reference temperature (600°F = 1059.67°R)

In order to estimate the EDYs at the time of the inspection outages listed in Table 1, the EDYs tabulated in MRP-48 [5] per Equation [2] were extrapolated forward in time from the March 1, 2001, reference date of MRP-48 assuming an overall reactor thermal power capacity factor of 92%. However, for 18 of the 70 total heads in Table 1, the EDY extrapolation was instead based on the EDY figure reported to the NRC in an outage report per NRC Order EA-03-009. Finally, the EDYs for the original (Plant BL) and first replacement (Plant V) heads at the plant where PWSCC was observed in the first replacement head in spring 2010 were based on EFPY data (15.8 EFPYs for the original head at time of replacement in 2002-03; 5.46 EFPYs for the first replacement head at time of spring 2010 refueling outage) and revised head temperature figures (613°F in both cases) provided by the licensee.

3.5 Temperature for First Replacement Alloy 600 Head

The 613°F head temperature for the original (Plant BL) and first replacement (Plant V) heads at the plant where PWSCC was observed in the first replacement head in spring 2010 represents an increase of 8°F above the hot leg operating temperature previously assumed to apply for these heads. This difference was reported to MRP by the licensee following its root cause assessment of the CRDM nozzle PWSCC detected in spring 2010, and reflects channeling of water directly from fuel assemblies toward the top head. The licensee reported the 613°F operating head temperature as an appropriate nominal value for the head considering both time (within fuel cycle and cycle-to-cycle) and spatial (nozzle location) variations in temperature. Using the 613°F head temperature value, the EDY value for the first replacement head was determined to be 9.17 at the time of the spring 2010 refueling outage, as shown in Table 1.

3.6 Weibull Fit Cases

Following the same type of methodology as applied in MRP-105 [1], a Weibull statistical fit was applied to the tabulated head experience. For example, the heads that were inspected and found not to have reportable indications were treated as "suspended items" in the analysis, in accordance with the standard approach described by Abernethy [2]. However, an extended set of cases were considered to investigate the effect of key assumptions:

- *Weibull Failure Criterion.* As reflected in the detailed Weibull analysis table (Table 2, which is similar to Table 4-2 of MRP-105 [1]), separate assessments were performed for the case of indications of cracking per surface/volumetric NDE and the case of indications of leakage (through-wall cracking) per BMV examination (and in some cases per surface/volumetric NDE). The cracking Weibull assessment reflects the variability in operating time in EDYs until cracking detectable via NDE first develops in a head, while the leakage Weibull assessment reflects the variability in operating time in EDYs until through-wall cracking and leakage first develops. In the former case, the population of heads is limited to those plants that have performed volumetric and/or surface NDE. This totals 63 of the 70 Alloy 600 heads in the complete database. In the latter case, a single head that was replaced prior to performance of a BMV or surface/volumetric examination was eliminated from consideration, resulting in a population of 69 heads.

- *B&W Plant Head Temperature Assumption.* The recent information regarding the temperature for the replacement head for which PWSCC was detected in 2010 indicates that the Alloy 600 heads in the other six B&W plants (now all replaced with PWSCC-resistant Alloy 690 heads) may also have had nominal head operating temperatures significantly greater than the hot leg temperatures previously assumed. Thus, additional Weibull analysis cases were performed under the assumption that each of these other six B&W plant heads also operated at a temperature 8°F higher than its respective hot leg temperature. The cases assuming that these six B&W plant heads operated at hot leg temperature are designated as "original temperatures" cases, while the cases assuming they operated at a temperature 8°F higher than hot leg temperature are designated as "B&W + 8°F" cases.
- *Assumed vs. Computed Weibull Slope.* The Weibull slope parameter β reflects the degree of scatter inherent in the EDYs to first cracking or first leakage. In the same manner as for the MRP-105 [1] Weibull assessment, a WeiBayes approach was taken in which the Weibull slope for the distribution describing the time to first cracking/leakage was assumed to have a value of 3. The value of 3 is a typical value for other PWSCC experience in Alloy 600, including laboratory data and steam generator tube cracking in PWRs. Assuming the slope of 3, a Weibull distribution was fit to the EDY data shown in Table 2 using the standard least-squares fit to the linearized Weibull equation. As a set of sensitivity cases, the least-squares fit procedure was applied to fit both the Weibull slope and Weibull characteristic time together ("computed" slope cases). Finally, as described below, in every case, the EDY data for each failure point in the Weibull fit was adjusted backward in time to the point at which cracking or leakage was estimated to first have occurred.

3.7 Extrapolation Back to Time of First Cracking or First Leakage

In all cases including in the original MRP-105 [1] analysis, the time of first cracking/leakage was estimated for each head with reported cracking/leakage through a back extrapolation process. In all cases it was assumed that the "back extrapolation" Weibull slope has the typically expected value of 3. The back extrapolation process was implemented as follows:

- The data are inserted into the two-parameter Weibull equation [2]:

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}} \qquad [3]$$

where F is the cumulative failure fraction, and t is the time of operation. The Weibull slope parameter (designated by beta or β) is related to the rate at which degradation spreads through the nozzle population after it first becomes detectable. High values of β correspond to degradation that spreads rapidly through the nozzle population. The other Weibull parameter, the characteristic time (designated as theta or θ), is a measure of the time scale for the degradation; it defines the time at which 63.2% of the population is predicted to be degraded.

- Assuming a slope of 3, a "time factor" is computed for each of the plants in which leakage or cracking was observed. For example, for Plant BO in Table 1 [9, 10], in which 14 cumulative cracked nozzles (out of 69) were observed during an inspection performed at 12.4 EDYs (see Table 1), the fraction of nozzles cracked, in accordance with the median ranking equation, is $F = (14-0.3)/(69+0.4) = 0.1974$ (see Table 2). If just one nozzle were cracked, the fraction would be $F = (1-0.3)/(69+0.4) = 0.0101$. Applying the Weibull equation with a slope of 3, the time to reach $F = 0.0101$ is predicted to take only 0.3586 of the time necessary to reach $F = 0.1974$ (time factor = 0.3586). Thus, since 14 nozzles were found cracked at 12.4 EDYs, it is predicted that the first cracked nozzle in the Plant BO head occurred at 4.43 EDYs (12.4 x 0.3586 = 4.43), as shown in Table 2. This approach was used for each of the plants that had multiple cracked nozzles to determine the predicted times to first cracking. The greater the number of cracked or leaking nozzles found, the smaller the time factor, and thus the greater the difference between inspection EDYs and predicted EDYs to first cracking (or first leakage).

3.8 Weibull Fit Results

Table 3 summarizes the fit parameters of the various Weibull analysis cases. Figures 3 through 8 show the Weibull plots of the time to first cracking or first leakage as fit to the plant experience for the WeiBayes approach:

- Figure 3 shows the Weibull fit for the case of original temperatures (except for the Plant BL/V original and first replacement heads) and time to first cracking.
- Figure 4 shows the fit corresponding to Figure 3 for the time to first leakage.
- Figure 5 (time to first cracking) and Figure 6 (time to first leakage) show the Weibull fits corresponding to Figure 3 and Figure 4, under the assumption that all seven B&W plants have a representative operating head temperature 8°F higher than the hot leg temperature.
- Figure 7 and Figure 8 show the same data as Figure 5 (time to first cracking through fall 2010), but also include bounding Weibull fits. Assuming normally distributed data scatter, the 5% and 95% confidence bounds were calculated on the basis of θ values 1.65 standard deviations from the mean θ for the fit to the linearized Weibull equation. Figure 7 shows the original 5%/95% bounds (relative to a mean θ of 15.2) used in the base studies of the MRP-105 analysis, as well as the bounding values of θ used in Case Study I to IV of MRP-105 (15.2±6.5). Figure 8 shows the updated 5%/95% confidence bounds per the current 2011 analysis.
- Figure 9 and Figure 10 show the updated 2011 Weibull distributions, but based on a best-fit slope to the adjusted data.* Figure 9 corresponds to the failure data in Figure 5 (time to first cracking), and Figure 10 corresponds to the failure data in Figure 6 (time to first leakage). It was judged that with the additional data since 2004, especially the PWSCC experience for two cold heads, it was appropriate to consider a fitted slope rather than a standard value of 3. The fitted slope of 1.60 for the cracking case results in a somewhat

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* For the best-fit slope cases, a slope of 3 still was applied for the adjustment of multiple nozzles with detected PWSCC back to the time of first cracking/leakage. This is appropriate in that the scatter in initiation time across multiple material suppliers and head fabricators is generally expected to be greater than for the nozzles in a single head.

higher probability of cracking for relatively small cumulative EDY values (see Attachment 1). The slope of 1.60 represents a greater relative degree in scatter in time to crack initiation than the previously assumed slope of 3, and is a consequence of the range of nozzle material processing practices and head fabrication practices applied across the U.S. fleet.

- Figure 11 shows the 2011 Weibull fit to the leakage-only data assuming a slope of 1.60 per the best-fit slope to the cracking case. This is an alternative fit that reflects the degree of observed scatter in the time to cracking, for which there is a larger and broader set of experience.

4 Conclusions

Following are key conclusions of this 2011 Weibull assessment of CRDM/CEDM nozzle PWSCC:

- Inclusion of top head experience through fall 2010 resulted in a modest shift in the Weibull distribution from the MRP-105 [1] analysis if a Weibull slope of 3 is assumed (Figure 3 versus Figure 1). If instead a slope is fitted to the failure data in consideration of the new cold head PWSCC experience, then a somewhat higher probability of cracking for relatively small cumulative EDY values results (Figure 9 versus Figure 1).
- As expected, the time to first leakage is predicted to be substantially greater than the time to first cracking. Specifically, the characteristic time for the leakage cases is about 75-80% greater than for the cracking cases (Figure 4 versus Figure 3, and Figure 6 versus Figure 5). This represents a large source of conservatism in the MRP-105 [1] assessment of the probability of nozzle ejection since MRP-105 assumed that a through-wall circumferential flaw extending over 30° of the circumference (and thus leakage) occurs according to the MRP-105 Weibull fit for the time to first cracking (Figure 1).
- Consideration of the potential for each B&W plant to have an operating head temperature higher than hot leg temperature resulted in an increase in Weibull characteristic time (relative extension in time to cracking or leakage) of about 10% (Figure 5 versus Figure 3, and Figure 6 versus Figure 4).
- Considering the Weibull cases assuming a slope of 3 across the industry, the data point representing the Plant V first replacement head fell within the bounding values used in Case Study I to IV of MRP-105 [1] (Figure 7) and within the 5% and 95% confidence bounds using the bounding fit values calculated per the data for the current analysis (Figure 8). In addition, the Plant V first replacement head experience falls well within the bounds around the Weibull fits applying a best-fit slope approach (Figure 9). In summary, the Plant V first replacement head is not an outlier with respect to the Weibull analysis for time to first cracking used in the MRP-105 analyses (nor for time to first leakage as assessed in this 2011 Weibull update—see Figure 6, Figure 10, and Figure 11).

5 References

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3. Letter from T. J. Tulon (Exelon) to U. S. Nuclear Regulatory Commission, "Licensee Event Report 2011-002-00, Unit 1 Reactor Pressure Vessel Head Penetration Nozzle Weld Flaws Attributed to Primary Water Stress Corrosion Cracking," dated May 18, 2011.

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5. *PWR Materials Reliability Program Response to NRC Bulletin 2001-01 (MRP-48)*, EPRI, Palo Alto, CA: 2001. 1006284.

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7. Letter from B. S. Allen (FirstEnergy Nuclear Operating Company) to U. S. Nuclear Regulatory Commission, "Davis-Besse Nuclear Power Station; Docket Number 50-346, License Number NPF-3; Licensee Event Report 2010-002 Revision 01," L-10-258, dated September 30, 2010.

8. J. A. Gorman, R. A. Ogren, and J. P. N. Paine, "Correlation of Temperature with Steam Generator Tube Corrosion Experience," *Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors*, E. Simonen and D. Cubicciotti, eds., American Nuclear Society, LaGrange Park, Illinois, 1992.

9. Letter from J. A. Price (Dominion Nuclear Connecticut, Inc.) to U.S. Nuclear Regulatory Commission, "Millstone Nuclear Power Station, Unit Nos. 2 and 3, Response to NRC Bulletin 2002-01, Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," dated April 2, 2002.

10. Letter from L. N. Hartz (Dominion Nuclear Connecticut, Inc.) to U.S. Nuclear Regulatory Commission, "Dominion Nuclear Connecticut, Inc., Millstone Power Station, Unit 2, Sixty-Day Report, NRC Order EA-03-009," Serial No. 04-044, Rev. 0, dated January 23, 2004.

Table 1. Alloy 600 CRDM/CEDM Nozzle Inspection Data through Fall 2010 (Original Temperatures)

Head #	Code	NSSS	Cold Head?	No. J-Groove Nozzles							Head Temp (°F) (MRP-48)	Fabricator	Replace Date		NDE Date, Scope, and Results					BMV Date, Scope, and Results				
				CRDM/CEDM	ICI	Vent	TC	J-AHA	DGL	Total					Outage	Year	EDY	NDE CRDM/ CEDM	Cum. Cracked	Outage	Year	EDY	BMV CRDM/ CEDM	Cum. Leaked
1	Plant A	W	Cold	78	0	1	0	0	0	79	559.9	CE			Fall	2006	2.56	78	0	Fall	2009	3.07	78	0
2	Plant B	W	Cold	78	0	1	0	0	0	79	552.0	B&W			Spring	2005	1.90	78	0	Fall	2006	2.08	78	0
3	Plant C	CE	NonCold	65	8	1	0	0	0	74	593.7	CE	Spring	2007	Spring	2005	16 67	65	0	Spring	2005	16.67	65	0
4	Plant D	W	Cold	78	0	1	0	0	0	79	557.0	Rotterdam			Fall	2006	2.96	78	0	Fall	2009	3.41	78	0
5	Plant E	B&W	NonCold	69	0	0	8	0	0	77	602.0	B&W	Fall	2003	Spring	2002	23.16	23	5	Fall	2003	24.65	69	4
6	Plant F	W	Cold	78	0	1	0	0	0	79	560.0	CE			Fall	2006	3.27	78	0	Fall	2009	3.79	78	0
7	Plant G	W	NonCold	78	0	1	0	0	0	79	594.1	CE	Spring	2005	NONE			0	0	Fall	2003	10.17	78	0
8	Plant H	CE	NonCold	45	8	1	0	0	0	54	586.4	CE			Spring	2009	12.05	45	2	Fall	2010	12.86	45	0
9	Plant I	W	Cold	78	0	1	0	0	0	79	556.8	CE	Fall	2014	Spring	2007	3.21	78	0	Spring	2007	3.21	78	0
10	Plant J	W	NonCold	78	0	0	0	0	0	78	593.5	CE			Spring	2009	16.28	78	0	Spring	2009	16.28	78	0
11	Plant K	W	NonCold	65	0	1	0	0	0	66	595.0	B&W/CE	Spring	2006	Fall	2004	15.01	65	4	Fall	2004	15.01	65	0
12	Plant L	W	Cold	78	0	1	0	0	0	79	560.0	CE			Spring	2007	3.06	78	0	Spring	2010	3.58	78	0
13	Plant M	W	NonCold	65	0	1	0	0	0	66	594.4	B&W	Fall	2004	Spring	2003	18.17	65	0	Spring	2003	18.17	65	0
14	Plant N	W	Cold	78	0	1	0	0	0	79	550.4	B&W			Fall	2008	2.25	78	1	Fall	2008	2.25	78	0
15	Plant O	W	NonCold	65	0	1	0	0	0	66	600.1	Rotterdam	Spring	2003	Fall	2001	19.89	30	1	Fall	2001	19.89	65	1
16	Plant P	W	NonCold	65	0	1	0	0	0	66	597.8	B&W/Rotterdam	Spring	2003	Fall	2001	19.12	16	6	Fall	2001	19.12	65	4
17	Plant Q	W	NonCold	65	0	1	0	0	0	66	595.0	CE			Fall	2009	14.84	65	2	Spring	2011	15.89	65	0
18	Plant R	CE	NonCold	97	0	1	0	0	0	98	591.7	CE	Fall	2009	Spring	2008	14.65	97	0	Spring	2008	14.65	97	0
19	Plant S	CE	NonCold	81	8	1	0	0	0	90	594.8	CE			Fall	2009	16.84	81	0	Fall	2009	16.84	81	0
20	Plant T	CE	NonCold	97	0	1	0	0	0	98	592.2	CE	Fall	2010	Spring	2009	15.19	97	0	Spring	2009	15.19	97	0
21	Plant U	CE	NonCold	91	10	1	0	0	0	102	590.6	CE	Fall	2012	Fall	2008	18.74	91	0	Fall	2008	18.74	91	0
22	Plant V	B&W	NonCold	69	0	0	0	0	0	69	613.0	B&W	Fall	2011	Spring	2010	9.17	69	12	Spring	2010	9.17	69	2
23	Plant W	W	Cold	78	0	1	0	0	0	79	558.4	CE			Spring	2007	2.58	78	0	Spring	2010	3.06	78	0
24	Plant X	W	Cold	65	0	1	0	0	0	66	558.0	CBI			Spring	2006	2.80	65	0	Spring	2009	3.28	65	0
25	Plant Y	W	Cold	78	0	1	0	0	0	79	557.3	Rotterdam			Spring	2008	1.76	78	0	Fall	2009	2.01	78	0
26	Plant Z	W	NonCold	74	0	1	0	0	1	76	561.0	CE	Fall	2009	Fall	2006	11.70	74	0	Spring	2008	11.97	74	0
27	Plant AA	W	NonCold	65	0	1	0	0	0	66	594.4	B&W	Spring	2005	Fall	2003	18.50	65	0	Fall	2003	18.50	65	0
28	Plant AB	W	NonCold	78	0	1	0	0	0	79	600.7	CBI	Fall	2007	Spring	2006	14.43	78	2	Spring	2006	14.43	78	0
29	Plant AC	W	NonCold	40	0	1	0	0	0	41	583.1	B&W/CE	Fall	2004	NONE			0	0	Spring	2003	11.76	40	0
30	Plant AD	B&W	NonCold	69	0	0	0	0	0	69	602.0	B&W	Spring	2004	Fall	2002	23.61	69	19	Fall	2002	23.61	69	14
31	Plant AE	W	NonCold	79	0	1	0	0	0	80	594.7	CE	Fall	2005	Spring	2004	12.90	79	0	Spring	2004	12.90	79	0
32	Plant AF	W	NonCold	40	0	1	0	0	0	41	580.2	CL	Spring	2005	NONE			0	0	Fall	2003	10.92	40	0
33	Plant AG	W	Cold	78	0	1	0	0	0	79	557.0	Rotterdam			Fall	2006	3.04	78	0	Fall	2006	3.04	78	0
34	Plant AH	W	NonCold	79	0	1	0	0	0	80	590.0	CE	Fall	2010	Spring	2009	13.24	79	0	Spring	2009	13.24	79	0
35	Plant AI	W	Cold	78	0	1	0	0	0	79	556.0	B&W			Spring	2006	2.24	78	0	Fall	2007	2.45	78	0

Table 1. Alloy 600 CRDM/CEDM Nozzle Inspection Data through Fall 2010 (Original Temperatures) (cont'd)

Head #	Code	NSSS	Cold Head?	No. J-Groove Nozzles							Head Temp (°F) (MRP-48)	Fabricator	Replace Date		NDE Date, Scope, and Results					BMV Date, Scope, and Results				
				CRDM/CEDM	ICI	Vent	TC	J-AHA	DGL	Total					Outage	Year	EDY	NDE CRDM/CEDM	Cum. Cracked	Outage	Year	EDY	BMV CRDM/CEDM	Cum. Leaked
36	Plant AJ	W	NonCold	65	0	1	0	0	0	66	597.8	B&W/Rotterdam	Fall	2003	NONE			0	0	Spring	2002	19.50	65	0
37	Plant AK	W	Cold	78	0	1	0	0	0	79	551.0	B&W			Spring	2011	2.76	78	4	Spring	2011	2 76	78	0
38	Plant AL	B&W	NonCold	69	0	0	0	0	0	69	601.0	B&W	Fall	2003	Fall	2001	16.20	9	1	Fall	2001	16.20	69	1
39	Plant AM	W	Cold	78	0	1	0	4	0	83	547.0	Rotterdam			Fall	2007	1.94	78	0	Spring	2009	2.08	78	0
40	Plant AN	W	NonCold	69	0	1	0	0	0	70	596.5	B&W/CE	Fall	2004	Spring	2003	17.46	69	0	Spring	2003	17.46	69	0
41	Plant AO	W	NonCold	49	0	1	0	0	0	50	591.6	B&W/CE	Spring	2005	Fall	2003	16.60	49	0	Fall	2003	16.60	49	0
42	Plant AP	W	NonCold	40	0	1	0	0	0	41	580.2	CL	Spring	2006	NONE			0	0	Fall	2004	11.33	40	0
43	Plant AQ	W	NonCold	65	0	1	0	0	0	66	600.1	Rotterdam	Spring	2003	Fall	2002	19.71	65	45	Fall	2002	19.71	65	8
44	Plant AR	B&W	NonCold	69	0	0	8	0	0	77	601.0	B&W	Fall	2003	Fall	2001	18.08	12	8	Fall	2001	18.08	69	5
45	Plant AS	W	Cold	78	0	1	0	0	0	79	561.0	CE			Spring	2005	2.03	77	0	Fall	2009	2.84	78	0
46	Plant AT	W	Cold	78	0	1	0	0	0	79	561.0	CE	Spring	2007	NONE			0	0	Spring	2004	2.25	78	0
47	Plant AU	W	Cold	78	0	1	0	0	0	79	557.0	CE			Fall	2007	2.89	78	0	Fall	2007	2.89	78	0
48	Plant AV	W	NonCold	69	0	0	0	0	0	69	599.7	CE	Fall	2005	Spring	2004	21.69	69	0	Spring	2004	21.69	69	0
49	Plant AW	W	Cold	78	0	1	0	0	0	79	558.0	CE			Fall	2006	3.08	78	0	Fall	2006	3.08	78	0
50	Plant AX	W	NonCold	79	0	1	0	0	0	80	578.0	CE	Fall	2006	Spring	2005	8.70	79	0	Spring	2005	8.70	79	0
51	Plant AY	CE	NonCold	69	8	1	0	0	0	78	590.6	CE	Spring	2006	Spring	2004	16.70	69	0	Spring	2004	16.70	69	0
52	Plant AZ	W	Cold	78	0	1	0	4	0	83	547.0	Rotterdam			Fall	2006	1.86	78	0	Fall	2009	2.14	78	0
53	Plant BA	CE	NonCold	91	10	1	0	0	0	102	590.5	CE	Fall	2011	Fall	2009	19 78	91	0	Fall	2009	19.78	91	0
54	Plant BB	W	NonCold	37	0	1	0	0	0	38	580.2	B&W	Fall	2003	NONE			0	0	NONE			0	0
55	Plant BC	CE	NonCold	97	0	1	0	0	0	98	592.0	CE	Spring	2010	Fall	2008	15.29	97	0	Fall	2008	15.29	97	0
56	Plant BD	W	Cold	78	0	1	0	0	0	79	557.0	CE			Spring	2007	3.11	78	0	Spring	2010	3.56	78	0
57	Plant BE	W	NonCold	69	0	1	0	0	0	70	596.9	B&W/CE	Fall	2005	Spring	2004	16.80	69	0	Spring	2004	16.80	69	0
58	Plant BF	W	NonCold	97	0	0	0	0	0	97	585.5	CE			Spring	2010	11.69	97	0	Spring	2010	11.69	97	0
59	Plant BG	W	NonCold	78	0	1	0	0	0	79	593.0	CE	Fall	2009	Spring	2008	14.37	78	0	Spring	2008	14.37	78	0
60	Plant BH	CE	NonCold	91	10	1	0	0	0	102	595.6	CE	Fall	2007	Spring	2006	16.40	91	5	Spring	2006	16.40	91	0
61	Plant BI	CE	NonCold	65	8	1	0	0	0	74	593.7	CE	Spring	2006	Spring	2004	16.42	65	0	Spring	2004	16.42	65	0
62	Plant BJ	B&W	NonCold	69	0	0	0	0	0	69	602.0	B&W	Fall	2005	Spring	2004	22.62	69	8	Spring	2004	22.62	69	1
63	Plant BK	W	NonCold	49	0	1	0	0	0	50	591.6	B&W	Fall	2005	Spring	2004	15.50	49	1	Spring	2004	15.50	49	0
64	Plant BL	B&W	NonCold	69	0	0	0	0	0	69	613.0	B&W	Fall	2003	Spring	2002	26.50	69	5	Spring	2002	26.50	69	3
65	Plant BM	W	NonCold	74	0	1	0	0	1	76	561.0	CE	Spring	2010	Spring	2007	12.19	74	0	Fall	2008	12.46	74	0
66	Plant BN	CE	NonCold	91	10	1	0	0	0	102	599.7	CE			Fall	2009	21.96	91	0	Fall	2009	21.96	91	0
67	Plant BO	CE	NonCold	69	8	1	0	0	0	78	593.9	CE	Spring	2005	Fall	2003	12.36	69	14	Fall	2003	12.36	69	0
68	Plant BP	CE	NonCold	41	6	1	0	0	0	48	588.0	CE	Fall	2006	Spring	2005	13.09	41	0	Spring	2005	13.09	41	0
69	Plant BQ	B&W	NonCold	69	0	0	0	0	0	69	602.0	B&W	Spring	2003	Fall	2001	22.39	69	14	Fall	2001	22.39	69	14
70	Plant BR	W	Cold	65	0	1	0	0	0	66	557.3	CBI			Fall	2006	3.16	65	0	Fall	2009	3.62	65	0

Note that the temperatures listed for both the Plant BL/V original and first replacement heads have been revised from MRP-48 to reflect plant input.

Table 2. Inspection Data Through Fall 2010 Extrapolated Back to Predicted Time to First Crack/Leak (Based on Weibull Slope $\beta = 3$)

				NDE Data, Scope, and Results												BMV Data, Scope, and Results											
												at Detection of Cracking		at 1st Crack Extrapolated Back using b=3										at Detection of Leak		at 1st Leak Extrapolated Back using b=3	
Head #	Code	No. CRDM/ CEDM Nozzles	CDF (1st Leak or Crack)	Outage	Year	EDY	NDE CRDM/ CEDM	Cum. Cracked	CDF (# Cracked)	Time Factor (# Cracked)	EDYs at 1st Crack or Inspection	CDF of Units with Cracks (Orig. Temps.)	CDF of Units with Cracks (+8°F for all B&W Heads)	CDF of Units with Cracks (Orig. Temps.)	CDF of Units with Cracks (+8°F for all B&W Heads)	Outage	Year	EDY	BMV CRDM/ CEDM	Cum. Leaked	CDF (# Leaking)	Time Factor (# Leaking)	EDYs at 1st Leak or Inspection	CDF of Units with Leaks (Orig. Temps.)	CDF of Units with Leaks (+8°F for all B&W Heads)	CDF of Units with Leaks (Orig. Temps.)	CDF of Units with Leaks (+8°F for all B&W Heads)
1	Plant A	78	0.0089	Fall	2006	2.56	78	0			2.5559					Fall	2009	3 07	78	0			3.0695				
2	Plant B	78	0.0089	Spring	2005	1.90	78	0			1.8994					Fall	2006	2.08	78	0			2.0805				
3	Plant C	65	0.0107	Spring	2005	16.67	65	0			16.6688					Spring	2005	16.67	65	0			16.6688				
4	Plant D	78	0.0089	Fall	2006	2.96	78	0			2.9590					Fall	2009	3 41	78	0			3.4094				
5	Plant E	69	0.0101	Spring	2002	23.16	23	5	0.0677	0.5248	12 1537	0.75	0.86	0.34	0.43	Fall	2003	24 65	69	4	0.0533	0.5698	14.0459	0.78	0.91	0.15	0.28
6	Plant F	78	0.0089	Fall	2006	3.27	78	0			3.2703					Fall	2009	3.79	78	0			3.7875				
7	Plant G	78	0.0089	NONE			0	0								Fall	2003	10.17	78	0			10.1726				
8	Plant H	45	0.0154	Spring	2009	12 05	45	2	0.0374	0.7412	8.9293	0 08	0.08	0.23	0.16	Fall	2010	12 86	45	0			12.8569				
9	Plant I	78	0.0089	Spring	2007	3.21	78	0			3.2092					Spring	2007	3.21	78	0			3.2092				
10	Plant J	78	0.0089	Spring	2009	16 28	78	0			16.2754					Spring	2009	16.28	78	0			16.2754				
11	Plant K	65	0.0107	Fall	2004	15 01	65	4	0.0566	0 5696	8.5493	0.19	0.19	0.18	0.12	Fall	2004	15.01	65	0			15.0100				
12	Plant L	78	0.0089	Spring	2007	3.06	78	0			3.0599					Spring	2010	3 58	78	0			3 5776				
13	Plant M	65	0.0107	Spring	2003	18.17	65	0			18.1659					Spring	2003	18.17	65	0			18.1659				
14	Plant N	78	0.0089	Fall	2008	2.25	78	1	0.0089	1.0000	2.2547	0.01	0.01	0.03	0.03	Fall	2008	2.25	78	0			2.2547				
15	Plant O	65	0.0107	Fall	2001	19.89	30	1	0.0107	1.0000	19.8859	0.50	0.41	0.58	0.54	Fall	2001	19 89	65	1	0.0107	1.0000	19 8859	0.34	0.23	0.40	0.40
16	Plant P	65	0.0107	Fall	2001	19.12	16	6	0.0872	0.4905	9.3800	0.38	0.30	0.25	0.18	Fall	2001	19.12	65	4	0 0566	0.5696	10.8922	0.18	0.08	0.12	0.06
17	Plant Q	65	0.0107	Fall	2009	14.84	65	2	0.0260	0.7420	11.0115	0.16	0 16	0.32	0.28	Spring	2011	15.89	65	0			15.8912				
18	Plant R	97	0.0072	Spring	2008	14 65	97	0			14.6502					Spring	2008	14 65	97	0			14 6502				
19	Plant S	81	0.0086	Fall	2009	16.84	81	0			16.8399					Fall	2009	16 84	81	0			16.8399				
20	Plant T	97	0.0072	Spring	2009	15.19	97	0			15.1860					Spring	2009	15.19	97	0			15.1860				
21	Plant U	91	0.0077	Fall	2008	18.74	91	0			18.7386					Fall	2008	18 74	91	0			18.7386				
22	Plant V	69	0.0101	Spring	2010	9 17	69	12	0.1686	0.3801	3.4853	0 05	0.05	0.05	0.05	Spring	2010	9 17	69	2	0.0245	0.7421	6.8055	0.02	0.02	0 02	0 02
23	Plant W	78	0.0089	Spring	2007	2.58	78	0			2.5752					Spring	2010	3 06	78	0			3 0602				
24	Plant X	65	0.0107	Spring	2006	2.80	65	0			2 8039					Spring	2009	3.28	65	0			3.2809				
25	Plant Y	78	0.0089	Spring	2008	1.76	78	0			1.7611					Fall	2009	2.01	78	0			2.0070				
26	Plant Z	74	0.0094	Fall	2006	11.70	74	0			11.7029					Spring	2008	11 97	74	0			11.9713				
27	Plant AA	65	0.0107	Fall	2003	18 50	65	0			18.4957					Fall	2003	18 50	65	0			18.4957				
28	Plant AB	78	0.0089	Spring	2006	14.43	78	2	0.0217	0.7424	10.7104	0.13	0.13	0.30	0.25	Spring	2006	14 43	78	0			14.4275				
29	Plant AC	40	0.0173	NONE			0	0								Spring	2003	11.76	40	0			11.7589				
30	Plant AD	69	0.0101	Fall	2002	23.61	69	19	0.2695	0.3184	7.5189	0.84	0 93	0.14	0.23	Fall	2002	23 61	69	14	0.1974	0.3586	8.4664	0 67	0.81	0 06	0 10
31	Plant AE	79	0.0088	Spring	2004	12.90	79	0			12.8951					Spring	2004	12 90	79	0			12.8951				
32	Plant AF	40	0.0173	NONE			0	0								Fall	2003	10 92	40	0			10.9202				
33	Plant AG	78	0.0089	Fall	2006	3.04	78	0			3.0359					Fall	2006	3 04	78	0			3.0359				
34	Plant AH	79	0.0088	Spring	2009	13.24	79	0			13.2412					Spring	2009	13.24	79	0			13.2412				
35	Plant AI	78	0.0089	Spring	2006	2.24	78	0			2.2399					Fall	2007	2 45	78	0			2.4501				

Table 2. Inspection Data Through Fall 2010 Extrapolated Back to Predicted Time to First Crack/Leak (Based on Weibull Slope $\beta = 3$) (cont'd)

				NDE Data, Scope, and Results												BMV Data, Scope, and Results													
												at Detection of Cracking		at 1st Crack Extrapolated Back using b=3										at Detection of Leak		at 1st Leak Extrapolated Back using b=3	
Head #	Code	No. CRDM/ CEDM Nozzles	CDF (1st Leak or Crack)	Outage	Year	EDY	NDE CRDM/ CEDM	Cum. Cracked	CDF (# Cracked)	Time Factor (# Cracked)	EDYs at 1st Crack or Inspection	CDF of Units with Cracks (Orig. Temps.)	CDF of Units with Cracks (+8°F for all B&W Heads)	CDF of Units with Cracks (Orig. Temps.)	CDF of Units with Cracks (+8°F for all B&W Heads)	Outage	Year	EDY	BMV CRDM/ CEDM	Cum. Leaked	CDF (# Leaking)	Time Factor (# Leaking)	EDYs at 1st Leak or Inspection	CDF of Units with Leaks (Orig. Temps.)	CDF of Units with Leaks (+8°F for all B&W Heads)	CDF of Units with Leaks (Orig. Temps.)	CDF of Units with Leaks (+8°F for all B&W Heads)
36	Plant AJ	65	0.0107	NONE			0	0								Spring	2002	19.50	65	0			19.4970				
37	Plant AK	78	0.0089	Spring	2011	2.76	78	4	0.0472	0.5703	1.5747	0.03	0.03	0.01	0.01	Spring	2011	2.76	78	0			2.7610				
38	Plant AL	69	0.0101	Fall	2001	16.20	9	1	0.0101	1.0000	16.1983	0.25	0.49	0.44	0.77	Fall	2001	16.20	69	1	0.0101	1.0000	16.1983	0.05	0.33	0.19	0.60
39	Plant AM	78	0.0089	Fall	2007	1.94	78	0			1.9383					Spring	2009	2.08	78	0			2.0820				
40	Plant AN	69	0.0101	Spring	2003	17.46	69	0			17.4581					Spring	2003	17.46	69	0			17.4581				
41	Plant AO	49	0.0142	Fall	2003	16.60	49	0			16.5959					Fall	2003	16.60	49	0			16.5959				
42	Plant AP	40	0.0173	NONE			0	0								Fall	2004	11.33	40	0			11.3288				
43	Plant AQ	65	0.0107	Fall	2002	19.71	65	45	0.6835	0.2107	4.1523	0.44	0.36	0.07	0.07	Fall	2002	19.71	65	8	0.1177	0.4412	8.6956	0.25	0.15	0.08	0.04
44	Plant AR	69	0.0101	Fall	2001	18.08	12	8	0.1110	0.4417	7.9879	0.32	0.56	0.12	0.21	Fall	2001	18.08	69	5	0.0677	0.5248	9.4903	0.11	0.42	0.10	0.13
45	Plant AS	78	0.0089	Spring	2005	2.03	77	0			2.0305					Fall	2009	2.84	78	0			2.8446				
46	Plant AT	78	0.0089	NONE			0	0								Spring	2004	2.25	78	0			2.2516				
47	Plant AU	78	0.0089	Fall	2007	2.89	78	0			2.8882					Fall	2007	2.89	78	0			2.8882				
48	Plant AV	69	0.0101	Spring	2004	21.69	69	0			21.6900					Spring	2004	21.69	69	0			21.6900				
49	Plant AW	78	0.0089	Fall	2006	3.08	78	0			3.0824					Fall	2006	3.08	78	0			3.0824				
50	Plant AX	79	0.0088	Spring	2005	8.70	79	0			8.7004					Spring	2005	8.70	79	0			8.7004				
51	Plant AY	69	0.0101	Spring	2004	16.70	69	0			16.7000					Spring	2004	16.70	69	0			16.7000				
52	Plant AZ	78	0.0089	Fall	2006	1.86	78	0			1.8551					Fall	2009	2.14	78	0			2.1376				
53	Plant BA	91	0.0077	Fall	2009	19.78	91	0			19.7833					Fall	2009	19.78	91	0			19.7833				
54	Plant BB	37	0.0187	NONE			0	0								NONE			0	0							
55	Plant BC	97	0.0072	Fall	2008	15.29	97	0			15.2946					Fall	2008	15.29	97	0			15.2946				
56	Plant BD	78	0.0089	Spring	2007	3.11	78	0			3.1081					Spring	2010	3.56	78	0			3.5618				
57	Plant BE	69	0.0101	Spring	2004	16.80	69	0			16.8000					Spring	2004	16.80	69	0			16.8000				
58	Plant BF	97	0.0072	Spring	2010	11.69	97	0			11.6892					Spring	2010	11.69	97	0			11.6892				
59	Plant BG	78	0.0089	Spring	2008	14.37	78	0			14.3701					Spring	2008	14.37	78	0			14.3701				
60	Plant BH	91	0.0077	Spring	2006	16.40	91	5	0.0514	0.5261	8.6281	0.28	0.25	0.21	0.14	Spring	2006	16.40	91	0			16.3996				
61	Plant BI	65	0.0107	Spring	2004	16.42	65	0			16.4150					Spring	2004	16.42	65	0			16.4150				
62	Plant BJ	69	0.0101	Spring	2004	22.62	69	8	0.1110	0.4417	9.9911	0.67	0.78	0.27	0.33	Spring	2004	22.62	69	1	0.0101	1.0000	22.6173	0.56	0.71	0.70	0.80
63	Plant BK	49	0.0142	Spring	2004	15.50	49	1	0.0142	1.0000	15.5000	0.22	0.22	0.41	0.39	Spring	2004	15.50	49	0			15.5000				
64	Plant BL	69	0.0101	Spring	2002	26.50	69	5	0.0677	0.5248	13.9070	0.92	0.64	0.37	0.36	Spring	2002	26.50	69	3	0.0389	0.6345	16.8137	0.89	0.52	0.25	0.19
65	Plant BM	74	0.0094	Spring	2007	12.19	74	0			12.1918					Fall	2008	12.46	74	0			12.4637				
66	Plant BN	91	0.0077	Fall	2009	21.96	91	0			21.9591					Fall	2009	21.96	91	0			21.9591				
67	Plant BO	69	0.0101	Fall	2003	12.36	69	14	0.1974	0.3586	4.4309	0.10	0.10	0.10	0.10	Fall	2003	12.36	69	0			12.3574				
68	Plant BP	41	0.0169	Spring	2005	13.09	41	0			13.0947					Spring	2005	13.09	41	0			13.0947				
69	Plant BQ	69	0.0101	Fall	2001	22.39	69	14	0.1974	0.3586	8.0297	0.58	0.71	0.16	0.30	Fall	2001	22.39	69	14	0.1974	0.3586	8.0297	0.45	0.62	0.04	0.08
70	Plant BR	65	0.0107	Fall	2006	3.16	65	0			3.1591					Fall	2009	3.62	65	0			3.6179				

Table 3. Summary of Weibull Distribution Fit Parameters

Weibull Fit Case		No. Heads in Weibull Fit (with volumetric or bare metal visual exam)	No. Heads with Cracks or Leaks	Weibull Slope β			Weibull Characteristic Time Θ	
Analysis Date	Failure Considered to be Crack or Leak			Description	Original Temps. (Note 1)	B&W + 8°F (Note 2)	Original Temps. (Note 1)	B&W + 8°F (Note 2)
Spring 2003	Cracks (incl. leaks)	30	14	Assumed	3.00	--	15.21 (Fig. 1)	--
Spring 2005	Cracks (incl. leaks)	41	18	Assumed	3.00	--	15.18 (Fig. 2)	--
2011	Cracks (incl. leaks)	63	20	Assumed	3.00	3.00	13.4 (Fig. 3)	14.5 (Figs. 5, 7, 8)
2011	Leaks Only	69	11	Assumed	3.00	3.00	23.4 (Fig. 4)	26.0 (Fig. 6)
2011	Cracks (incl. leaks)	63	20	Fit	1.64	1.60	21.4	23.2 (Fig. 9)
2011	Leaks Only	69	11	Fit	2.85	3.05	24.2	25.7 (Fig. 10)
2011	Leaks Only	69	11	Assumed	--	1.60	--	43.8 (Fig. 11)

Notes:

(1) It is assumed for these cases that the head temperature for each head is as reported in MRP-48, with the exception that for the 2011 cases the temperature for both the both the Plant BL/V original and first replacement heads were revised to reflect plant input.

(2) It is assumed for these cases that the head temperature for each B&W plant head is 8°F higher than the hot leg temperature.

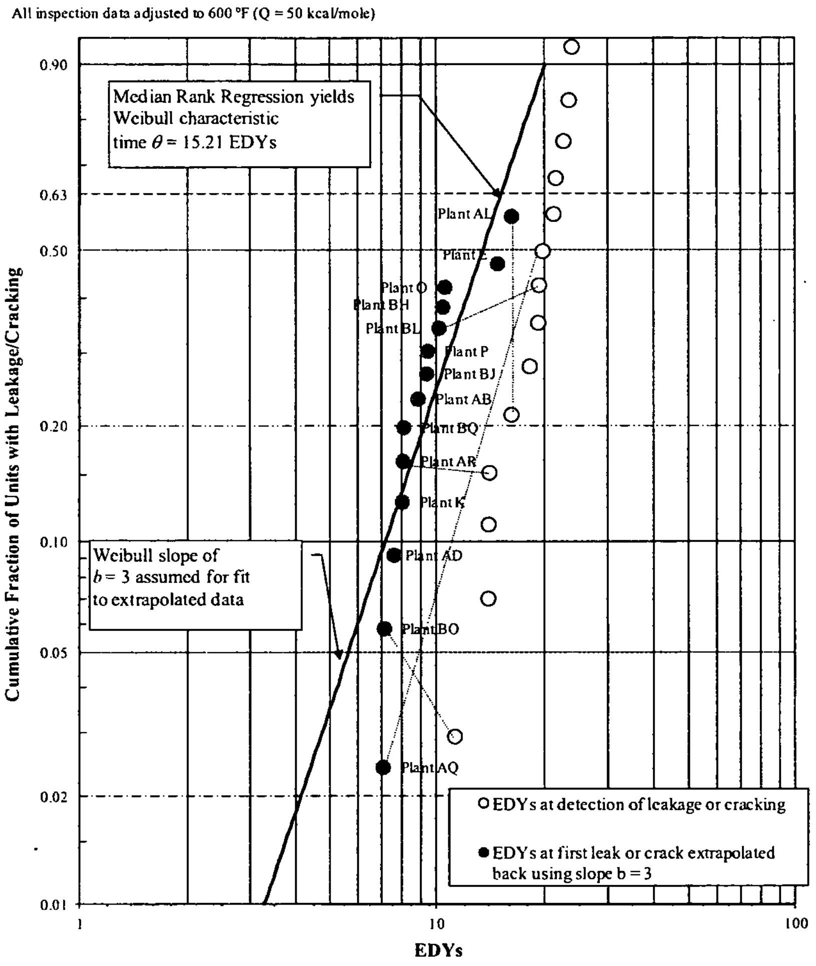

Figure 1. **Original (Spring 2003), NDE+BMV: 30 Heads; 14 w/cracks or leaks**

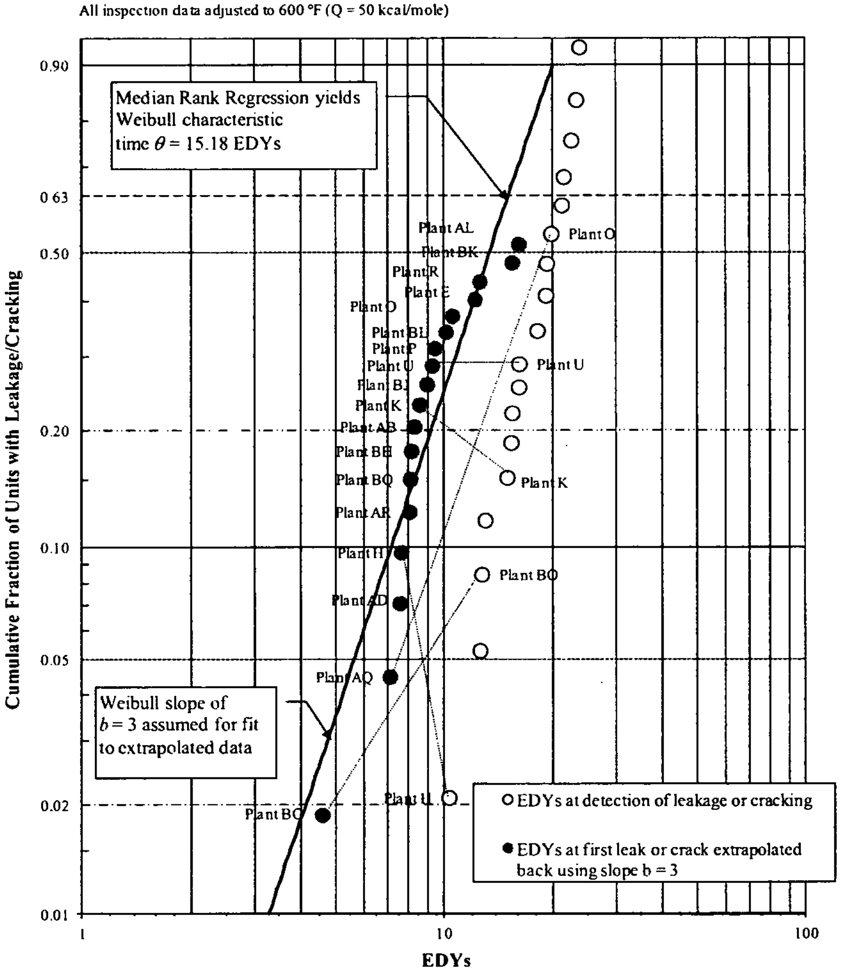

Figure 2. **Prior Update (Spring 2005), NDE+BMV: 41 Heads; 18 w/cracks or leaks**

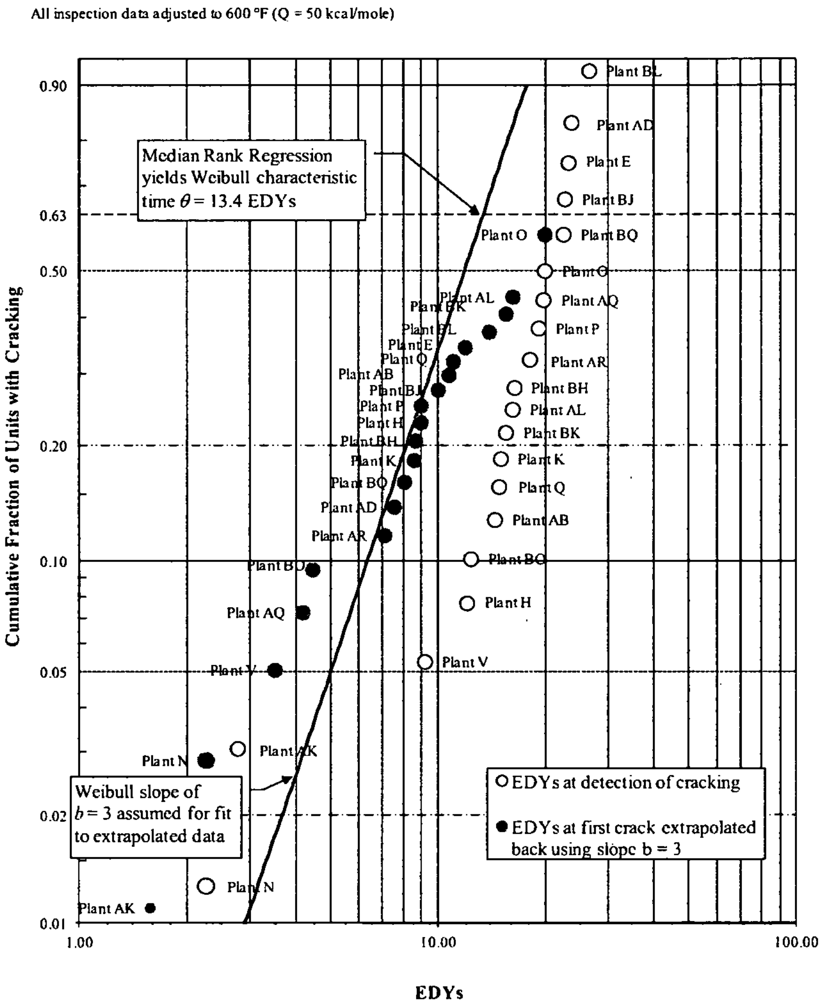

Figure 3. **2011 Update – Assumed Slope, Original Temperatures, NDE: 63 Heads; 20 w/cracks (Plant BL/V original and first replacement head temperatures revised to 613°F per plant input)**

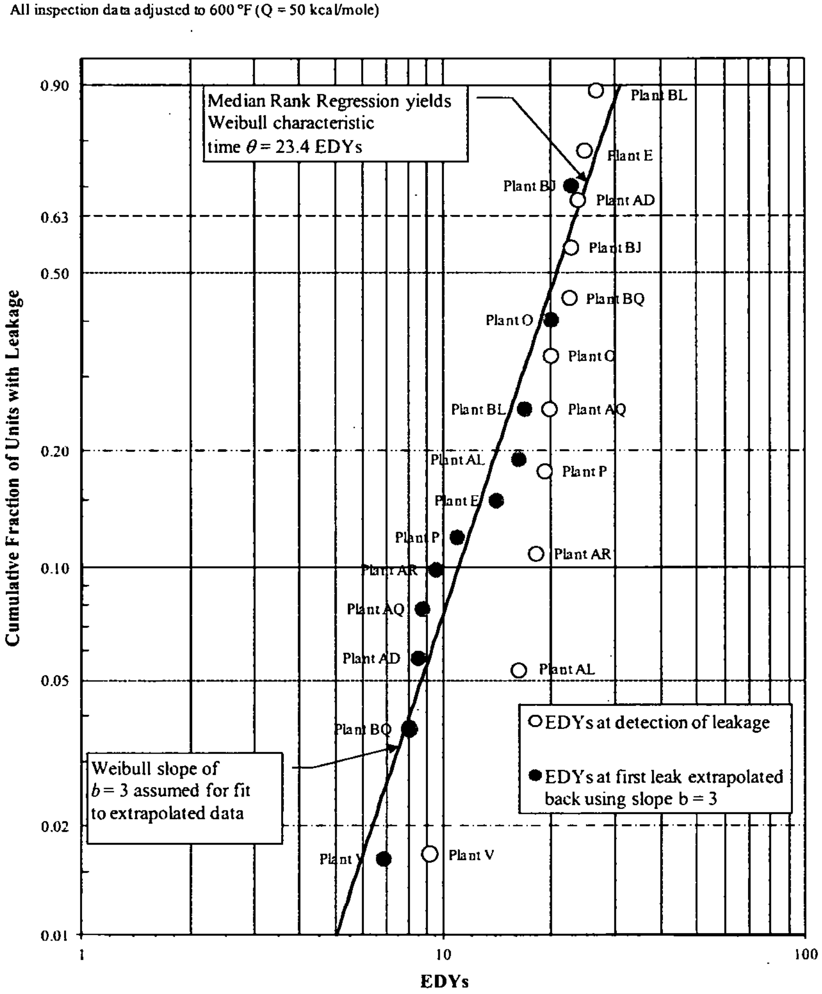

Figure 4. **2011 Update – Assumed Slope Original Temperatures, BMV: 69 Heads; 11 w/leaks (Plant BL/V original and first replacement heads temperature revised to 613°F per plant input)**

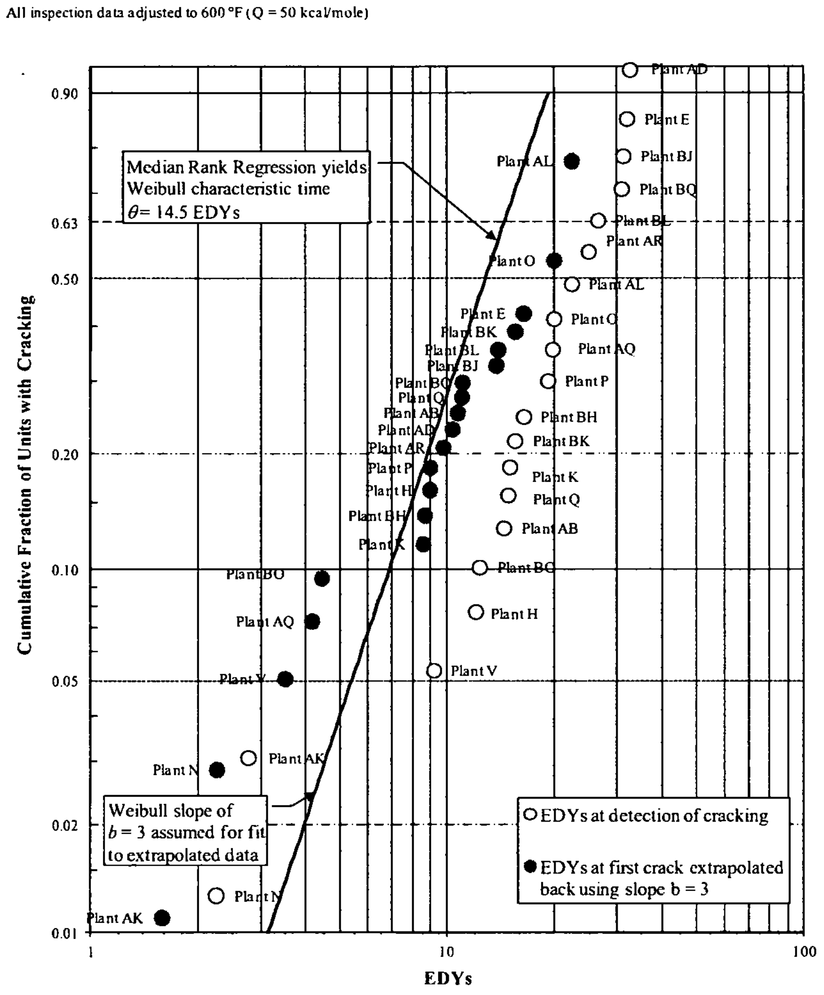

Figure 5. 2011 Update – Assumed Slope, New Temperatures (+8°F for all B&W Heads), NDE: 63 Heads; 20 w/cracks

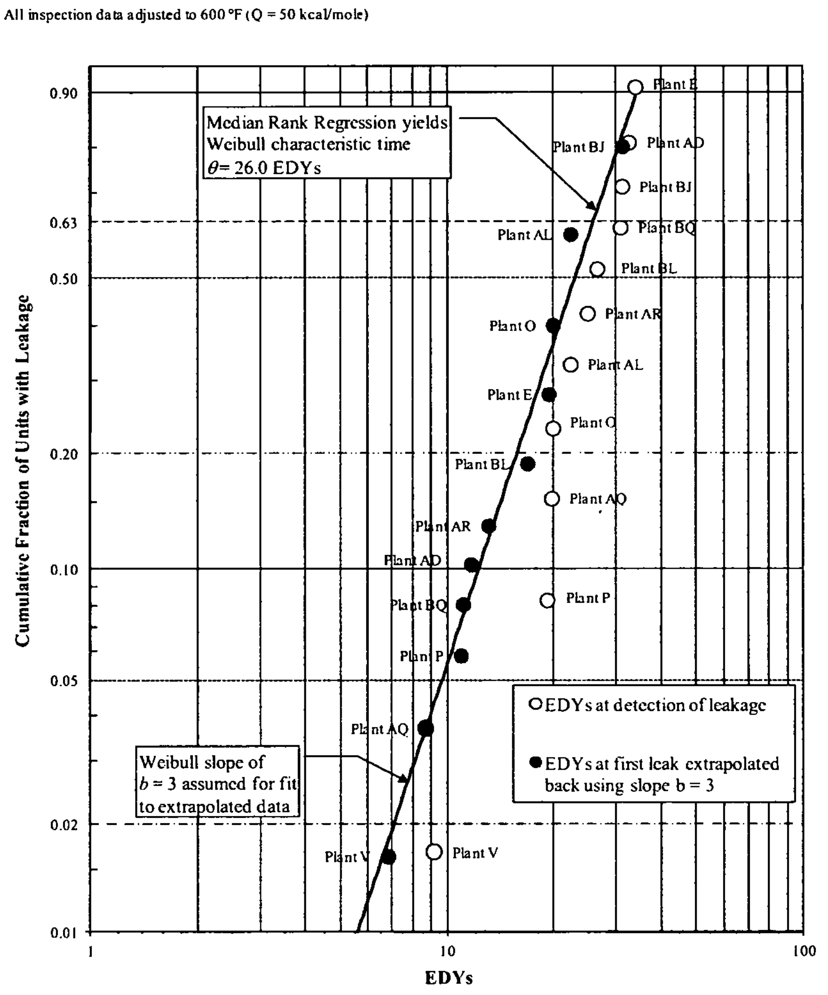

Figure 6. 2011 Update – Assumed Slope, New Temperatures (+8°F for all B&W Heads), BMV: 69 Heads; 11 w/leaks

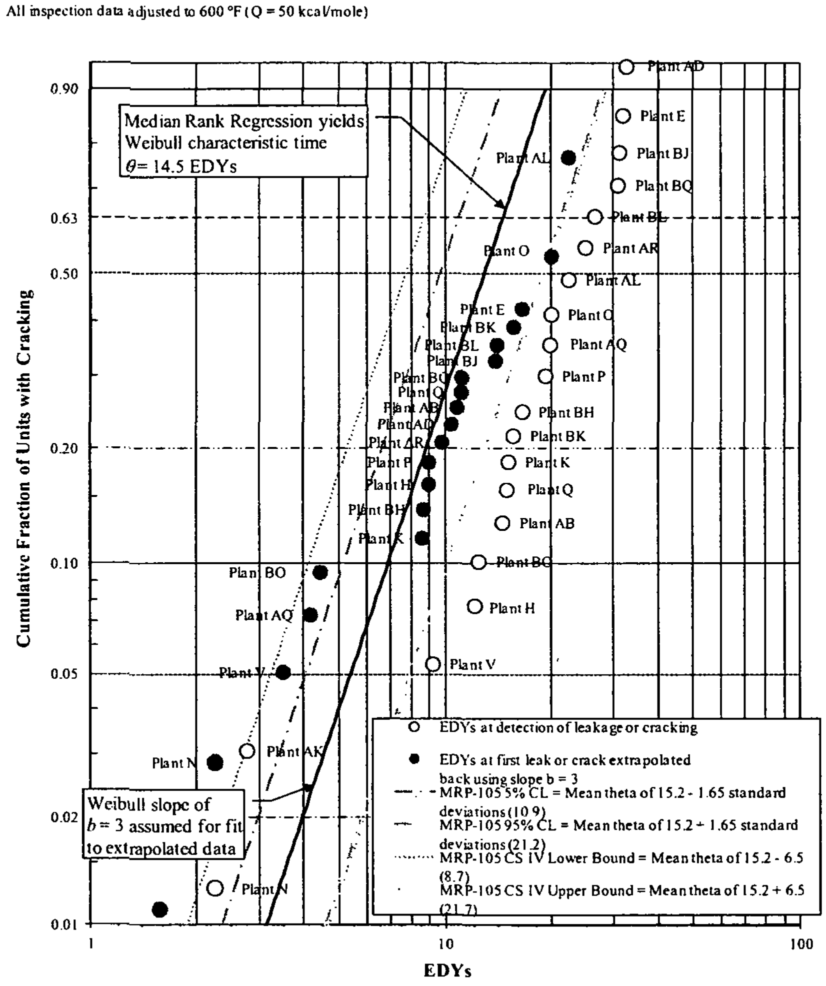

Figure 7. **MRP-105 Uncertainty Bounds Applied to 2011 Update NDE Inspection Data (+8°F for all B&W Heads)**

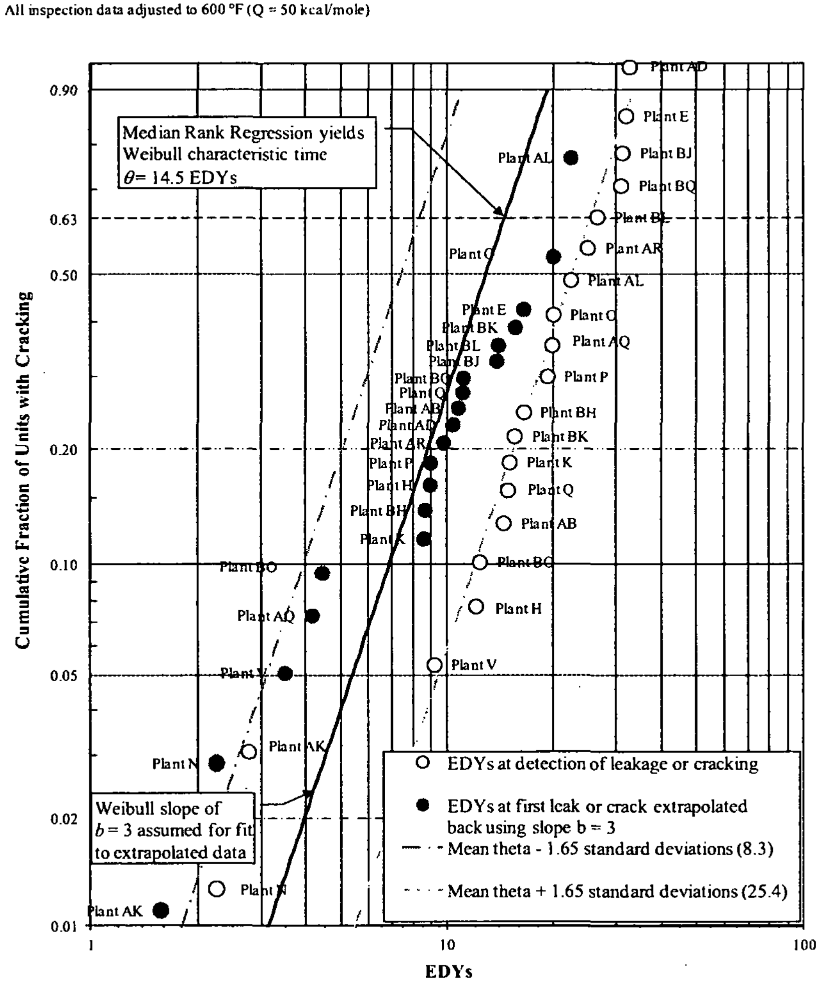

Figure 8. **Newly Calculated Uncertainty Bounds Applied to 2011 Update NDE Inspection Data (+8°F for all B&W Heads)**

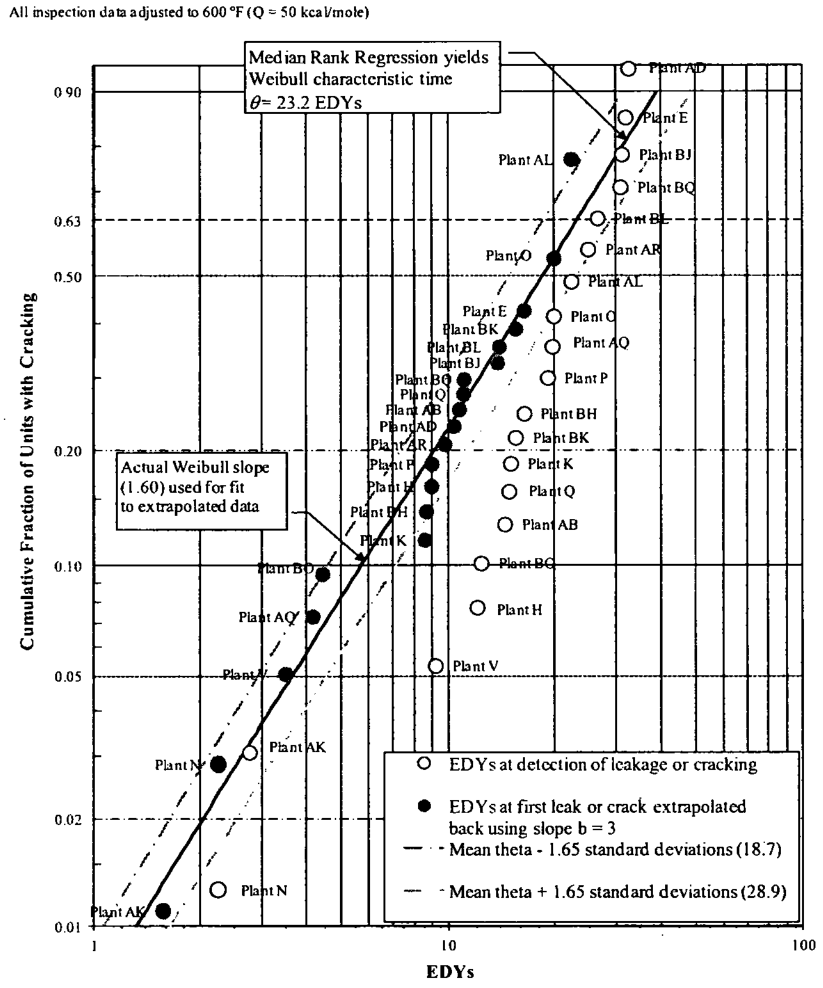

Figure 9. 2011 Update – Fitted Slope, New Temperatures (+8°F for all B&W Heads), NDE: 63 Heads; 20 w/cracks

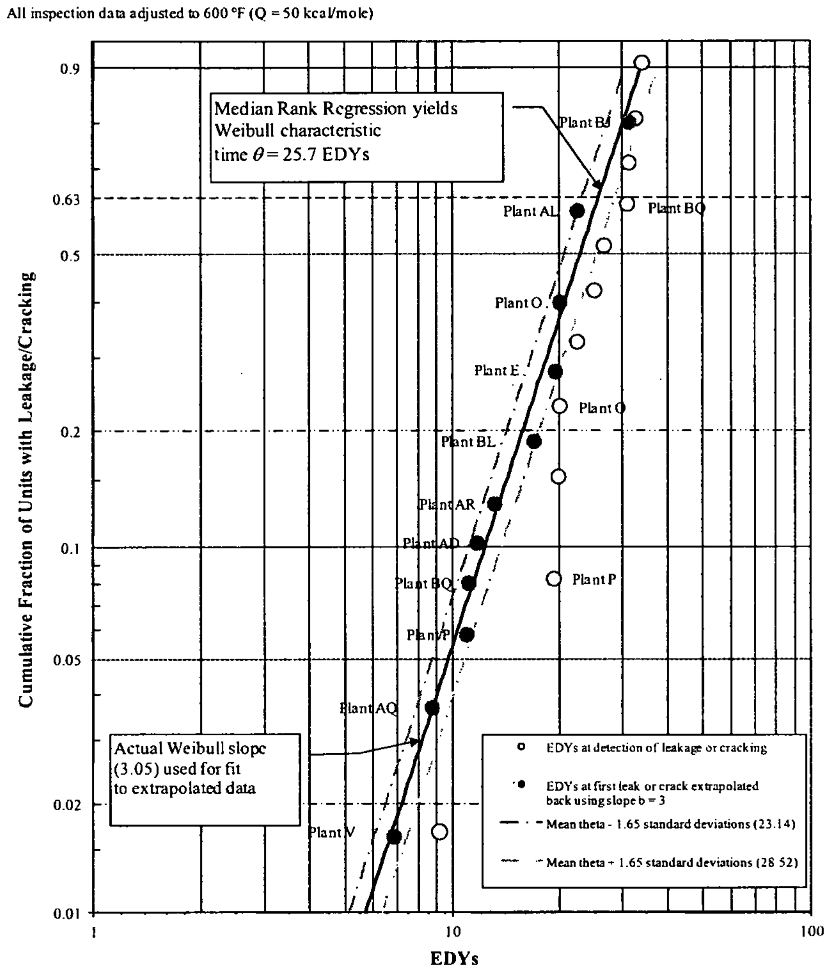

Figure 10. 2011 Update – Fitted Slope, New Temperatures (+8°F for all B&W Heads), BMV: 69 Heads; 11 w/leaks

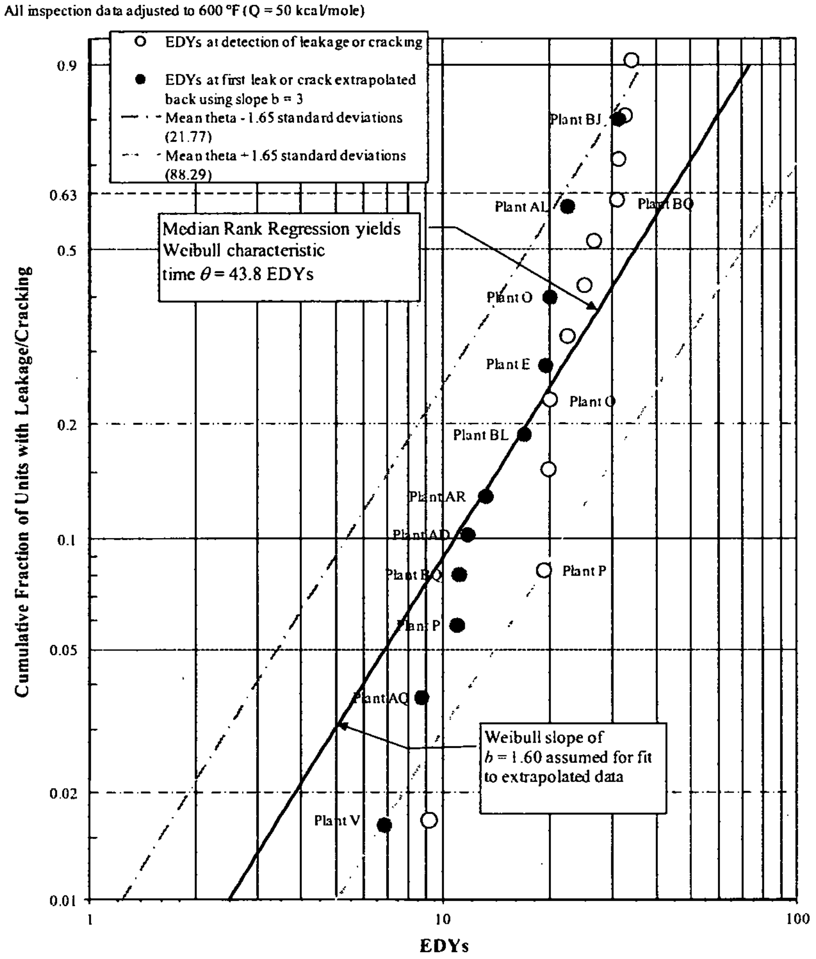

Figure 11. 2011 Update – Assumed Slope, New Temperatures (+8°F for all B&W Heads), BMV: 69 Heads; 11 w/leaks