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February 13, 2017
L-17-021

10 CFR 50.55a

ATTN: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT:
Beaver Valley Power Station, Unit No. 1
Docket No. 50-334, License No. DPR-66
Proposed Alternative to American Society of Mechanical Engineers Boiler and Pressure Vessel Code Reactor Pressure Vessel Head Penetration Examination Frequency Requirements (Request 1-TYP-4-RV-05)

In accordance with the provisions of 10 CFR 50.55a(z)(1), FirstEnergy Nuclear Operating Company (FENOC) hereby requests Nuclear Regulatory Commission (NRC) approval of a proposed alternative to American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section XI, reactor pressure vessel head examination frequency requirements for Beaver Valley Power Station, Unit No. 1. The proposed alternative is enclosed and provides an acceptable level of quality and safety.

FENOC requests approval of the proposed alternative by February 22, 2018 to support the spring 2018 refueling outage.

There are no regulatory commitments contained in this submittal. If there are any questions or if additional information is required, please contact Mr. Thomas A. Lentz, Manager – Fleet Licensing, at (330) 315-6810.

Sincerely,

Marty L. Richey

Enclosures:

A. Beaver Valley Power Station, Unit No. 1, 10 CFR 50.55a Request 1-TYP-4-RV-05, Revision 0

B. Dominion Engineering Technical Note TN-5696-00-02, Revision 0, "Assessment of Laboratory PWSCC Crack Growth Rate Data Compiled for Alloys 690, 52, and 152 with regard to Factors of Improvement (FOI) versus Alloys 600 and 182"

cc: NRC Region I Administrator
NRC Resident Inspector
NRC Project Manager
Director BRP/DEP
Site BRP/DEP Representative

Enclosure A
L-17-021

Beaver Valley Power Station, Unit No. 1
10 CFR 50.55a Request 1-TYP-4-RV-05, Revision 0

(11 Pages Follow)

Proposed Alternative
In Accordance with 10 CFR 50.55a(z)(1)

--Alternative Provides Acceptable Level of Quality and Safety—

1. ASME Code Component(s) Affected:

The affected components are American Society of Mechanical Engineers (ASME) Class 1 pressurized water reactor (PWR) reactor vessel upper head (reactor pressure vessel head, or RPV head) penetration nozzles and partial-penetration welds fabricated with primary water stress corrosion cracking (PWSCC)-resistant materials.

Component Numbers: RPV Head Penetration Nozzles 1 through 62 of 62.

2. Applicable Code Edition and Addenda:

ASME Boiler and Pressure Vessel Code (ASME Code), Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," 2001 Edition through 2003 Addenda is the code of record for the fourth ten-year inservice inspection interval.

3. Applicable Code Requirement:

The Code of Federal Regulations 10 CFR 50.55a(g)(6)(ii)(D)(1), requires (in part) that:

> All licensees of pressurized water reactors must augment their inservice inspection program with ASME Code Case N-729-1, subject to the conditions specified in paragraphs (g)(6)(ii)(D)(2) through (6) of this section. Licensees of existing operating reactors as of September 10, 2008, must implement their augmented inservice inspection program by December 31, 2008.

ASME Code Case N-729-1, "Alternative Examination Requirements for PWR Reactor Vessel Upper Heads With Nozzles Having Pressure-Retaining Partial-Penetration Welds Section XI, Division 1," approved March 28, 2006 (hereafter referred to as ASME Code Case N-729-1), Table 1, "Examination Categories, Class 1 PWR Reactor Vessel Upper Head," specifies the frequency of examination for item number B4.40, "Nozzles and partial-penetration welds of PWSCC-resistant materials in head," as all nozzles, not to exceed one inspection interval (nominally 10 calendar years).

4. Reason for Request:

The Code of Federal Regulations 10 CFR 50.55a(g)(6)(ii)(D)(1), requires that inservice inspection programs must be augmented with ASME Code Case N-729-1, subject to conditions specified in paragraphs (g)(6)(ii)(D)(2) through (6). ASME Code Case N-729-1, Table 1, specifies that the frequency of examination of PWSCC-resistant materials in RPV head penetration nozzles and partial-penetration welds is not to exceed one inspection interval (nominally 10 calendar years).

The 10-year examination schedule specified by ASME Code Case N-729-1 was intended to be conservative and subject to reassessment once additional plant experience and laboratory data on the performance of RPV head penetration nozzle and weld materials became available. Using plant and laboratory data that has since become available, Electric Power Research Institute (EPRI) Materials Reliability Program (MRP), MRP-375, "Technical Basis for Reexamination Interval Extension for Alloy 690 PWR Reactor Vessel Top Head Penetration Nozzles," Report No. 3002002441, dated February 2014 (publically available at www.epri.com), was developed to support a technically-based volumetric and surface re-examination interval using appropriate analytical tools.

The EPRI MRP-375 technical basis along with other information presented in Section 5 of this request supports extending the re-examination interval while maintaining an acceptable level of quality and safety. Therefore, FirstEnergy Nuclear Operating Company (FENOC) is requesting approval of this alternative to allow the use of an inservice inspection interval extension for BVPS-1 RPV head penetration nozzles.

5. Proposed Alternative and Basis for Use:

Proposed Alternative

In lieu of performing the required volumetric and surface examinations for the identified ASME Code components at the frequency specified in Table 1, Item B4.40 of ASME Code Case N-729-1, FENOC proposes to extend the frequency approximately 5 years beyond the inspection interval (nominally 10 calendar years from installation of the BVPS-1 replacement RPV head) to the 27th refueling outage that is scheduled to commence in April of 2021.

No alternatives to the examination processes required by ASME Code Case N-729-1, or conditions specified in 10 CFR 50.55a(g)(6)(ii)(D) are proposed.

Basis for Use

The original BVPS-1 RPV head was replaced with a new RPV head during the refueling outage that ended in April 2006. In accordance with Table 1, Item B4.40 of ASME Code Case N-729-1, and 10 CFR 50.55a(g)(6)(ii)(D)(3), the first volumetric and/or surface examination of essentially 100 percent of the BVPS-1 RPV head would have been required by the beginning of 2016. The Nuclear Regulatory Commission (NRC) staff authorized request 1 TYP-4-RV-04 (Accession No. ML14363A409) to extend the first in-service volumetric/surface examination frequency to a 12-year period. Based on that authorized request, the first volumetric/surface examination is currently scheduled to be performed on the BVPS-1 replacement RPV head by the 25th refueling outage that will commence in the spring of 2018.

RPV Head Materials and Design Features

The original BVPS-1 RPV head was manufactured with Alloy UNS N06600, UNS N06082 and UNS W86182 (Alloy 600/82/182) materials. The BVPS-1 replacement RPV head penetration nozzles were fabricated from Inconel SB-167 Alloy UNS N06690TT (Alloy 690). The penetration nozzle J-groove welds utilized

ERNiCrFe-7 Alloy UNS N06052 (Alloy 52) and ENiCrFe-7 Alloy UNS W86152 (Alloy 152) weld material. These three materials are also referred to hereafter as Alloy 690/52/152.

The BVPS-1 replacement RPV head penetration nozzles were designed to reduce the residual stresses in the J-groove welds and thereby reduce the susceptibility of the welds to PWSCC. The J-groove welds were installed using a narrow-gap design that used less filler metal and resulted in less residual stress. Also, the J-groove welds were installed with automatic welding equipment to reduce variability and thereby reduce the potential for localized residual stresses. These methods substantially reduce the PWSCC susceptibility of the BVPS-1 replacement RPV head beyond that assumed in the generic EPRI MRP-375 study, resulting in additional assurance that the BVPS-1 replacement RPV head can be operated for 15 years prior to the next volumetric and/or surface examination with an acceptable level of quality and safety.

Alloy 690/52/152 Operating Experience

Because of its approximate 30 percent chromium content, Alloy 690 is highly resistant to PWSCC. Operating experience for replacement and repaired components using Alloy 690/52/152 has shown a proven record of resistance to PWSCC during numerous examinations in the 20-plus years of its application. The accumulated service experience for Alloy 690/52/152 includes operation at both pressurizer temperature and hot leg temperature. It also includes thick wall and thin wall components, and components made of both wrought material (Alloy 690) and weld material (Alloy 52/152). Thousands of Alloy 690 steam generator tubes have been in-service since 1989 with no PWSCC detected. Steam generator tube plugs have been manufactured from Alloy 690 since the late 1980s. Even though the tube plugs are subject to high tensile stresses and cold work, there have been no reports of PWSCC detected in them. In contrast, PWSCC was discovered in some Alloy 600 steam generator tube plugs within two years of service. In addition to the service history of steam generator Alloy 690 components, there have been many other applications of Alloy 690/52/152 in reactor coolant system instrument nozzles, pressurizer heater sleeves, and pressurizer nozzles. As of 2004 when EPRI MRP-110, "Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants," Report No. 1009807, April 2004 (Accession No. ML041680506), was published, approximately 400 Alloy 690/52/152 components had been placed in service, with no evidence of PWSCC being detected in any of them. Over 100 RPV heads that have been fabricated using Alloy 690/52/152 material have been placed into service around the world. The first Alloy 690/52/152 RPV head was installed around 1992. As of December 2016, ASME Code Case N-729-1 volumetric/surface examinations had been performed on 16 of the 40 Alloy 690/52/152 replacement RPV heads in the United States (US). None of these Alloy 690/52/152 reactor head examinations revealed any PWSCC cracking. When comparing the service history of Alloy 600/82/182 with the service history of Alloy 690/52/152 in similar applications, the service experience data alone supports a factor of improvement of at least 5 to 20 in the time frame for detectable PWSCC to occur.

Several of the US plants that have performed volumetric/surface examinations on Alloy 690/52/152 RPV heads operate in the upper end of the head temperature range, with

one plant operating as high as 613 degrees Fahrenheit (°F). In contrast, the BVPS-1 RPV head temperature is approximately 601.2°F during normal operation. Because PWSCC is accelerated by higher temperatures, it is expected that the lower operating temperature of the BVPS-1 replacement RPV head makes it less susceptible to PWSCC than some of the plants that have already performed volumetric/surface examinations.

Operating experience at French plants indicates that Alloy 690/52/152 is resistant to PWSCC. The 58 French units have repaired or replaced RPV heads with Alloy 690 nozzles and Alloy 52/152 attachment welds. Out of the 58 RPV heads, three are included in an inspection program that requires a volumetric examination every 10 years. The three RPV heads currently in the French inspection program are among the earliest RPV heads that were replaced. At one specific plant (Bugey 3), the first 10-year volumetric examination of the RPV head did not reveal any PWSCC indications. The second 10-year volumetric examination was performed at this plant in 2013, with no indications of PWSCC in the Alloy 690/52/152 material after 20 years of operation. This is significant because it provides operating experience for an Alloy 690 RPV head that exceeds the total operating experience time accumulated on any of the replacement RPV heads in the United States.

Inservice Inspections

A pre-service volumetric examination of the BVPS-1 replacement RPV head J-groove welded control rod drive mechanism (CRDM) penetration nozzles, the instrumentation penetration nozzle, and the level indication penetration nozzle was performed prior to installation. The volumetric examinations scanned the nozzles to the fullest extent possible. The examination extended to 3 inches above the J-groove weld to ensure the 2-inch coverage requirement was achieved. All of the accessible tube below the lowest part of the J-groove weld was examined. There was no detectible degradation observed in any of the penetration welds or tube outer diameter locations during the volumetric examinations. Additionally, a pre-service eddy current examination of the CRDM tubing, the instrumentation tubing, and the level indication tubing was performed. There was no detectible degradation observed in any of the penetration welds or tube outer diameter locations during the eddy current examinations.

Three bare metal visual (BMV) examinations have been performed on the BVPS-1 replacement RPV head. The baseline BMV examination was performed in 2005, the first in-service BMV examination was performed in 2010, and the second in-service BMV examination was performed in 2015. All of the BMV examinations met the requirements of ASME Code Case N-729-1, Table 1, Item B4.30, and all of the BMV examinations were performed by qualified VT-2 examiners. The BMV examinations covered 360 degrees around each of the 60 CRDM penetration nozzles and the two RPV head vent penetration nozzles. The interface between the penetration nozzles and the replacement RPV head base material was examined for any signs of leakage. Additionally, each BMV examination covered the surface of the carbon steel base material of the reactor head. The BMV examinations did not reveal any surface or nozzle penetration boric acid that would be indicative of nozzle leakage. The BMV examination required by ASME Code Case N-729-1 will continue to be performed every

third refueling outage or five calendar years, whichever is less. This examination is scheduled to be performed again at BVPS-1 in the refueling outage that will commence in the fall of 2019.

The BVPS-1 replacement RPV head is similar to other Alloy 690/52/152 replacement RPV heads. The Comanche Peak Unit 1 replacement RPV head was also manufactured by Equipos Nucleares, S.A. (ENSA). A BMV examination was performed on the Comanche Peak Unit 1 replacement RPV head in 2014, with no observed surface or nozzle penetration boric acid that would have been indicative of nozzle leakage.

No in-service volumetric inspections have been performed on replacement RPV heads that have been manufactured by ENSA. However, in-service volumetric inspections have been performed on the Turkey Point Units 3 and 4 replacement RPV heads, which were manufactured to material specifications that are similar to the material specifications of the BVPS-1 replacement RPV head. Both the BVPS-1 and Turkey Point replacement RPV heads were procured to ASME Section III, 1989 Edition, no addenda. The BVPS-1 and Turkey Point CRDM nozzle tubes were fabricated by Valinox Nucleaire in accordance with SB-167 material specifications. Also, the CRDM nozzle tube material for both BVPS-1 and Turkey Point was thermally treated. The J-groove attachment welds at both BVPS-1 and Turkey Point utilized ERNiCrFe-7 (UNS N06052) and/or ENiCrFe-7 (UNS W86152) weld materials. Volumetric inspections were performed on the Turkey Point Units 3 and 4 replacement RPV heads in 2014, with no indications of PWSCC or service induced cracking identified.

Volumetric inspections have also been performed at some of the plants that most closely resemble the operating conditions that are experienced by the BVPS-1 replacement RPV head. North Anna 1 and 2, Surry 1 and 2, and Turkey Point 3 and 4 are all Westinghouse three-loop plants with Alloy 690/52/152 replacement RPV heads that operate at hot leg temperatures. Among the plants that most closely resemble the operating conditions of BVPS-1, no PWSCC degradation has been discovered during the in-service volumetric/surface examinations of the replacement RPV heads.

Factor of Improvement Evaluation

The basis of the inspection frequency specified for Table 1, item B4.40, of ASME Code Case N-729-1 comes, in part, from the analysis performed in EPRI MRP-111, "Resistance to Primary Water Stress Corrosion Cracking of Alloys 690, 52, and 152 in Pressurized Water Reactors," Report No. 1009801, dated March 2004 (Accession No. ML041680546), that was summarized in the safety assessment for RPV heads in EPRI MRP-110. At the time EPRI MRP-110 was written, it identified that the material improvement factor for PWSCC of Alloy 690/52/152 materials over that of mill annealed Alloy 600/82/182 was shown to be on the order of 26 or greater.

The inspection frequency specified in ASME Code Case N-729-1 was also based in part on PWSCC crack growth rates (CGRs) and data contained in EPRI MRP-55, "Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials," Report No. 1006695, Revision 1, dated November

2002, and EPRI-MRP-115, "Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds," Report No. 1006696, dated November 2004 (both documents are available at www.epri.com).

The ASME Code Case N-729, "Technical Basis Document," dated September 14, 2004, acknowledged that the original 10-year volumetric/surface examination frequency for Alloy 690 RPV heads was conservative. It also acknowledged that operating time is a key parameter for determining the likelihood of cracking, and that once more laboratory data and plant experience was obtained it would be appropriate to adjust the 10-year volumetric/surface examination frequency. The current inspection regime was established in 2004 as a conservative approach and was intended to be subject to reassessment upon the availability of additional laboratory data and plant experience on the performance of Alloy 690/52/152 material.

Since the development of ASME Code Case N-729-1, additional evaluations have been performed to investigate the PWSCC resistance of Alloy 690/52/152. Additional laboratory data and plant operating experience are now available that indicate that Alloy 690/52/152 is much more resistant to PWSCC than Alloy 600/82/182. Crack growth rates are much smaller and crack initiation times are much greater for Alloy 690/52/152 materials than they are for Alloy 600/82/182 materials. A recent EPRI MRP initiative performed evaluations to demonstrate the resistance of Alloy 690/52/152 to PWSCC. The results of this initiative are presented in EPRI MRP-375. EPRI MRP-375 summarized the most recent set of world-wide laboratory test data and operating experience for Alloy 690/52/152, and presented both deterministic and probabilistic evaluations that assessed the improved PWSCC resistance of Alloy 690/52/152 material.

The evaluations performed in EPRI MRP-375 were prepared to bound all PWR replacement RPV head designs that are manufactured using Alloy 690 base material and Alloy 52/152 weld materials. The evaluations assume a bounding continuously operating RPV head temperature of 613 degrees Fahrenheit (°F) and a relatively large number of RPV head penetrations (89). The BVPS-1 replacement RPV head contains 62 nozzle penetrations of which 56 are used for CRDMs, four are used for instrumentation, and two small diameter penetrations near the center of the RPV head are used for venting and level indication. The 62 BVPS-1 penetrations are bounded by the 89 penetrations evaluated in the EPRI MRP-375 analysis. The operating hot leg temperature for BVPS-1 is approximately 611 °F. Core bypass flow is expected to reduce the upper RPV head temperature resulting in an average RPV head temperature of approximately 601.2°F. Based on this, the BVPS-1 RPV head average operating temperature (which is the measure of temperature relevant to potential PWSCC degradation) is bounded by the EPRI MRP-375 evaluation temperature of 613°F.

The evaluation performed in EPRI MRP-375 considers a FOI approach applied in a conservative manner to model the increased resistance of Alloy 690 compared to Alloy 600 at equivalent temperature and stress conditions. Even though base metal and welding variability of test data exist (heat affected zones, weld dilution zones, and so on), conservative FOIs were estimated for the improved Alloy 690/52/152 materials using an extensive database of test data. Results for both crack initiation and crack

growth conclude a higher resistance to PWSCC for Alloy 690 base material and Alloy 52/152 weld materials. EPRI MRP-375, Figures 3-2, 3-4, and 3-6 provide crack growth data for Alloy 690/52/152 materials and Alloy 690 heat affected zones with represented curves plotting FOIs of 1, 5, 10, and 20.

Per EPRI MRP-115 it was noted that the Alloy 82 CGR is 2.6 times slower than Alloy 182. There is no strong evidence for a difference in Alloy 52 and 152 CGRs. Therefore data used to develop factors of improvement for Alloy 52/152 were referenced against the base case Alloy 182, as Alloy 182 is more susceptible to initiation and growth when compared to Alloy 82.

Regarding crack initiation, the laboratory and plant data discussed in EPRI MRP-375 demonstrate a FOI in excess of 20 in terms of the time to PWSCC initiation. FOIs reported for crack initiation, although significant, are conservative because, in many cases, crack initiation of Alloy 690/52/152 was not observed during testing; instead, the initiation time was assumed to be equivalent to the test duration. Conservatively, credit was not taken for the improved resistance of Alloy 690/52/152 to PWSCC initiation in the EPRI MRP-375 analyses.

Regarding crack growth rates, EPRI MRP-375 assessed laboratory PWSCC CGR data for the purpose of assessing FOI values for growth. Data analyzed to develop a conservative FOI include laboratory specimens with substantial levels of cold work. Much of the data used to support Alloy 690 CGRs was produced using materials with significant levels of cold work, which tends to increase the CGRs. Figure 3-2 of EPRI MRP-375 compares data from Alloy 690 specimens with less than 10 percent cold work and the statistical distribution from EPRI MRP-55 describing the material variability in CGRs for Alloy 600. Most of the laboratory CGR data comparisons were bounded by a FOI of 20, and all were bounded by a FOI of 10. Most data supported a FOI of much larger than 20. This is similar for testing of the Alloy 690 heat affected zone (HAZ) as shown in Figure 3-4 of EPRI MRP-375 (relative to the distribution from EPRI MRP-55) and for the Alloy 52/152 weld metal (relative to the distribution from EPRI MRP-115) as shown in Figure 3-6 of EPRI MRP-375. Based on the data, it is conservative to assume a FOI of between 10 and 20 for CGRs.

As identified above, the reduced susceptibility to PWSCC initiation and growth of Alloy 690/52/152 compared to Alloy 600/82/182 supports elimination of all volumetric exams throughout the plant service period. However, since work is still on going to determine the performance of Alloy 690/52/152 metals, the determination of the proposed inspection interval is based on a conservatively smaller FOI.

ASME Code Case N-729-1 is based upon conclusions reached that a RPV head with Alloy 600 nozzles and operating at a temperature of 600°F is acceptable to operate up to 2.25 years between volumetric or surface examinations. The same period for Alloy 690 RPV heads in ASME Code Case N-729-1 is 10 years, which represents a FOI of approximately 4 over the Alloy 600 RPV heads. A simple extension of that improvement factor to 15 years would be a FOI of approximately 6.7 for the proposed period between volumetric/surface examinations for BVPS-1.

The RPV head operating temperature assumed in the technical basis for heads with Alloy 600 nozzles for ASME Code Case N-729-1 was 600°F, compared to an assumed operating temperature of 601.2°F for BVPS-1. ASME Code Case N-729-1 addresses the effect of differences in operating temperature on the required volumetric/surface reexamination interval for RPV heads with Alloy 600 nozzles on the basis of the re-inspection years (RIY) parameter. The RIY parameter adjusts the effective full power years of operation between inspections, for the effect of RPV head operating temperature, using the thermal activation energy appropriate to PWSCC crack growth. For RPV heads with Alloy 600 nozzles, ASME Code Case N-729-1 limits the interval between subsequent volumetric and surface inspections to RIY equals 2.25. The RIY parameter, which is referenced to a RPV head temperature of 600°F, limits the time available for potential crack growth between inspections.

The representative BVPS-1 RPV head operating temperatures of 601.2°F would result in an RIY temperature adjustment factor of 1.03 (versus the reference temperature of 600°F) using the activation energy of 31 kilocalorie per mole for crack growth of ASME Code Case N-729-1. Laboratory PWSCC crack growth rate testing for Alloy 690 wrought material by multiple investigators has shown thermal activation energy values comparable to the standard activation energy applied to model growth of Alloy 600/82/182 (31 kilocalorie per mole or 130 kilojoules per mole). Thus, it is appropriate to apply this standard activation energy for modeling crack growth of Alloy 690/52/152 plant components. Conservatively assuming that the effective full power years of operation accumulated at BVPS-1 since RPV head replacement is equal to the calendar years since replacement, the RIY for the requested extended period at BVPS-1 would be (1.03) x (15 years) which equals 15.46 RIY. The FOI implied by this RIY value for BVPS-1 is (15.46)/(2.25) which equals 6.87 FOI. The FOI of 6.87 implied by the requested extension period represents a level of reduction in PWSCC CGR verses that for Alloy 600/82/182 that is completely bounded by the laboratory data compiled in EPRI MRP-375 when material variability is accounted for. Given the lack of PWSCC detected to date in any PWR plant applications of Alloy 690/52/152, the simple FOI assessment clearly supports the requested period of extension.

Enclosure B presents Dominion Engineering Technical Note TN-5696-00-02, Revision 0, "Assessment of Laboratory PWSCC Crack Growth Rate Data Compiled for Alloys 690, 52, and 152 with regard to Factors of Improvement (FOI) versus Alloys 600 and 182," and provides further support for the requested alternative inspection interval based on the available laboratory PWSCC CGR data and the FOI approach. The requests for additional information that the NRC has transmitted to other licensees in the context of similar relief requests are addressed in Enclosure B. Enclosure B describes the materials tested for data points within a factor of 12 below the EPRI MRP-55 and EPRI MRP-115 crack growth rate curves for the 75th percentile of material variability. Enclosure B also compares the Alloy 690/52/152 test specimens to the operating conditions that are most likely to be experienced by material that is currently used in operating US reactors. The factor of improvement of 12 that is evaluated in Enclosure B conservatively bounds the factor of improvement of 6.87 that is implied by the extension period proposed in this relief request for BVPS-1.

Enclosure B considers the Alloy 690 CRDM material supplied by Valinox Nucleaire, that was included in the EPRI MRP-375 data compilation. Valinox Nucleaire supplied the material for the BVPS-1 replacement RPV head CRDM penetrations, so the CGR data and the FOI assessment documented in Enclosure B are applicable as a basis for the BVPS-1 requested frequency extension. It is concluded from Enclosure B that the available CGR data does not indicate any susceptibility concerns specific to the nozzle or weld materials of the BVPS-1 replacement RPV head.

In the safety evaluation for a similar relief request (Accession No. ML16292A761), the NRC did not validate all of the data presented in EPRI MRP-375. Instead, the NRC relied solely on the Alloy 690/52/152 laboratory test data that had been demonstrated by two NRC contractors: Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (ANL). In the identified safety evaluation, the NRC concluded that "...an FOI value of 7.35 is justified and bounded by the relevant available data included in the PNNL and ANL data summary report." Therefore, it can be concluded that the FOI of 6.87 that is implied by the extension period proposed in this relief request for BVPS-1 is bounded even when only considering the data available from PNNL and ANL.

EPRI MRP-375 Deterministic Evaluation

A deterministic crack growth evaluation is commonly applied to assess PWSCC risks for specific components and operating conditions. The deterministic evaluation is intended to demonstrate the time from an assumed initial flaw to some adverse condition.

Deterministic crack modeling results were presented in EPRI MRP-375 for previous references in which both growth of part-depth surface flaws and through-wall circumferential flaws were evaluated and normalized to an adjusted growth of 613°F to bound the PWR fleet. The time for through-wall crack growth in Alloy 600 nozzle tube material, when adjusted to a bounding temperature of 613°F, ranged between 1.9 and 3.8 EFPY. Assuming a growth FOI of 10 to 20 as previously established for Alloy 690/52/152 materials, the median time for through-wall growth was 37.3 EFPY. In a similar manner, crack growth results for through-wall circumferential flaws were tabulated and adjusted to a temperature of 613°F. Applying a growth FOI of 20 resulted in a median time of 176 EFPYs for growth of a through-wall circumferential flaw to 300 degrees of circumferential extent. The results of the generic evaluation are summarized in Table 4-1 of EPRI MRP-375. All cases were bounding and support an inspection interval greater than that being proposed. It is important to note that the operating temperature of the BVPS-1 RPV head is 601.2°F and is well within the bounds of the assumptions.

Deterministic calculations performed in EPRI MRP-375 demonstrate that the alternative volumetric re-examination interval is sufficient to detect any PWSCC before it could develop into a safety significant circumferential flaw that approaches the large size (that is, more than 300 degrees) necessary to produce a nozzle ejection. The deterministic calculations also demonstrate that any base metal PWSCC would likely be detected prior to a through-wall flaw occurring.

Probabilistic calculations are based on a Monte Carlo simulation model of the PWSCC process, including PWSCC initiation, PWSCC crack growth, and flaw detection via ultrasonic testing and visual examinations for leakage. The basic structure of the probabilistic model is similar to that used in the EPRI MRP-105, "Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking," Report No. 1007834, April 2004 (Accession No. ML041680489), technical basis report for the inspection requirements for RPV heads with Alloy 600 nozzles, but the current approach includes more detailed modeling of flaw initiation and growth (including multiple flaw initiation for each nozzle on base metal and weld surfaces), and the initiation module has been calibrated to consider the latest set of experience for U. S. RPV heads. The outputs of the probabilistic model are leakage frequency (that is, frequency of through-wall cracking) and nozzle ejection frequency. Even assuming conservatively small factors of improvement for the CGR for the replacement nickel-base alloys (with no credit for improved resistance to initiation), the probabilistic results with the alternative inspection regime show:

1. An effect on nuclear safety substantially within the acceptance criterion applied in the EPRI MRP-117, "Inspection Plan for Reactor Vessel Closure Head Penetrations in U.S. PWR Plants," Report No. 1007830, December 2004 (Accession No. ML043570129), technical basis for Alloy 600 RPV heads, and
2. A substantial improvement in nuclear safety compared to that for an RPV head with Alloy 600 nozzles examined per current requirements.

Furthermore, the results confirm a low probability of leakage if modest credit is taken for the improved resistance to PWSCC initiation compared to that for Alloys 600 and 182.

FENOC is not requesting NRC review and approval of EPRI MRP-375 to approve this request for an alternative to the ASME Code Case N-729-1 requirements. However, the insights gained in this technical report help substantiate the extension duration being requested for BVPS-1 of approximately 5 years beyond the 10-year examination frequency established in ASME Code Case N-729-1. In particular, the tabulation of CGR data for Alloy 690/52/152 (Section 3 of EPRI MRP-375) and review of inspection experience for Alloy 690/52/152 plant components (Section 2 of EPRI MRP-375) are sufficient to demonstrate the acceptability of the extension duration being requested. This request is not dependent on the more detailed probabilistic calculations presented in Section 4 of EPRI MRP-375.

Conclusion

The basis for extending the intervals from once each interval (nominally 10 calendar years) to nominally once every 15 calendar years is based on plant service experience, FOI studies using laboratory initiation and growth data, deterministic modeling, and probabilistic study results. The results of the analysis show that the alternative proposed frequency results in a substantial improvement in nuclear safety when compared to a RPV head with Alloy 600 nozzles that is examined per the current requirements. The minimum FOI implied by the requested extension period represents a level of reduction in PWSCC crack growth rate versus that for Alloy 600/82/182 that is

completely bounded by the laboratory data compiled in EPRI MRP-375 when accounting for heat-to-heat variability of Alloy 600 and weld-to-weld variability of Alloy 82/182. The proposed revised interval will continue to provide reasonable assurance of structural integrity.

Additional assurance of structural integrity is provided by the design features of the BVPS-1 replacement RPV head such as the narrow gap J-groove weld design and automatic welding processes that reduce residual stresses in the weld. Furthermore, the BMV examinations and acceptance criteria as required by Item B4.30 of Table 1 of ASME Code Case N-729-1 are not affected by this request and will continue to be performed on a frequency of every third refueling outage or 5 calendar years, whichever is less. As discussed in Section 5.2.3 of EPRI MRP-375, the BMV examination requirement of the outer surface of the RPV head for evidence of leakage supplements the volumetric and/or surface examination requirement and conservatively addresses the potential concern for boric acid corrosion of the low-alloy steel RPV head due to PWSCC leakage.

For the reasons noted above, it is requested that the NRC authorize this proposed alternative in accordance with 10 CFR 50.55a(z)(1) as the alternative provides an acceptable level of quality and safety.

6. Duration of Proposed Alternative:

The proposed alternative is requested for the remainder of the fourth and fifth inservice inspection intervals because utilizing the proposed examination frequency will require the examination to be performed in the fifth interval during the 27th BVPS-1 refueling outage that is scheduled to commence in the spring of 2021. The BVPS-1 fourth inservice inspection interval is currently scheduled to end March 31, 2018. The Beaver Valley, Unit 1, fifth inservice inspection interval is currently scheduled to end March 31, 2028.

7. Precedent

The NRC staff authorized the use of a similar request by Florida Power & Light to defer volumetric and surface examinations required by item B4.40 of ASME Code Case N-729-1 to a frequency of 15.5 years at St. Lucie, Unit No. 2. Penetration nozzles and vent pipe at St. Lucie Unit No. 2 are fabricated from Alloy 690 with Alloy 52/152 attachment welds. The NRC staff letter authorizing the alternative is referenced below.

NRC staff letter to Florida Power & Light Co. regarding inservice inspection plan fourth 10-year interval Relief Request No. 11 (RR-11) for St Lucie, Unit No. 2, Docket No. 50-389, dated November 1, 2016 (Accession No. ML16292A761).

Enclosure B
L-17-021

Dominion Engineering Technical Note TN-5696-00-02, Revision 0,
"Assessment of Laboratory PWSCC Crack Growth Rate Data
Compiled for Alloys 690, 52, and 152 with regard to Factors of Improvement (FOI)
versus Alloys 600 and 182"

(32 Pages Follow)

Dominion Engineering, Inc.

TECHNICAL NOTE

Assessment of Laboratory PWSCC Crack Growth Rate Data Compiled for Alloys 690, 52, and 152 with Regard to Factors of Improvement (FOI) versus Alloys 600 and 182

TN-5696-00-02
Revision 0

March 2015

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RECORD OF REVISIONS

Rev.	Description	Prepared by Date	Checked by Date	Reviewed by Date	Approved by Date
0	Original Issue	K. J. Fuhr 3/23/15 K. J. Fuhr Associate Engineer	M. Burkardt 3/23/2015 M. Burkardt Associate Engineer	G.A. White 3/23/2015 G. A. White Principal Engineer	G.A. White 3/23/2015 G. A. White Principal Engineer

The last revision number to reflect any changes for each section of the technical note is shown in the Table of Contents. The last revision numbers to reflect any changes for tables and figures are shown in the List of Tables and the List of Figures. Changes made in the latest revision, except for Rev. 0 and revisions which change the technical note in its entirety, are indicated by a double line in the right hand margin as shown here.

CONTENTS

LIST OF FIGURES

ACRONYMS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
AWS	American Welding Society
BWC	Babcock & Wilcox Canada
CEDM	Control Element Drive Mechanism
CGR	Crack Growth Rate
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CRDM	Control Rod Drive Mechanism
CT	Compact Tension
DEI	Dominion Engineering, Inc.
EPRI	Electric Power Research Institute
FOI	Factor of Improvement
GE-GRC	General Electric Global Research Center
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
ICI	In-Core Instrumentation
K	Stress Intensity Factor
MRP	Materials Reliability Program
NRC	Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
PPU	Partial Periodic Unloading
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
RIY	Re-Inspection Year
RV	Reactor Vessel
RVCH	Reactor Pressure Closure Head
UNS	Unified Numbering System

1 INTRODUCTION

The purpose of this DEI technical note is to examine laboratory crack growth rate (CGR) data for primary water stress corrosion cracking (PWSCC) compiled for Alloys 690, 52, and 152 to assess factors of improvement (FOI) for these replacement alloys relative to the CGR behavior for Alloys 600 and 182 as documented in MRP-55 [1] and MRP-115 [2]. In addition, an assessment is made of the available laboratory CGR data for the potential concern of elevated CGRs for specific categories of nozzle and weld materials.

Per ASME Code Case N-729-1 [3], the volumtric inspection interval for Alloy 600 RV head nozzles is based on operating time adjusted for operating temperature using the temperature sensitivity for PWSCC crack growth. The normalized operating time between inspections, called the Re-Inspection Years (RIY) parameter, represents the potential for crack growth between successive volumtric examinations. Thus, the FOI for Alloys 690/52/152 exhibited by laboratory CGR data can be used to support appropriate volumetric inspection intervals for RV heads with Alloy 690 nozzles. On the basis of the RIY = 2.25 limit of Code Case N-729-1 for Alloy 600 RV head nozzles, an FOI of 12 corresponds to an inspection interval of 20 years for Alloy 690 RV head nozzles operating at 613°F.[1] A temperature of 613°F is expected to bound the head operating temperature for the U.S. pressurized water reactor (PWR) fleet.

As discussed in Section 3 of Electric Power Research Institute (EPRI) Materials Reliability Program (MRP) report MRP-375 [2], a conservative approach was taken in MRP-375 to develop the factor of improvement (FOI) values describing the primary water stress corrosion cracking (PWSCC) crack growth rates applicable to Alloy 690 reactor vessel (RV) top head penetration nozzles. The crack growth rate data points presented in Figures 3-1, 3-3, and 3-5 of MRP-375 represent the values reported by individual researchers, without any adjustment by the authors of MRP-375 other than to normalize for the effect of temperature. The data in these figures represent essentially all of the Alloys 690, 52, and 152 data points reported by the various

[1] To calculate the implied FOI for the bounding RV top head operating temperature of 613°F, the re-inspection year (RIY) parameter for a requested examination interval of 20 years is compared with the N-729-1 interval for Alloy 600 nozzles of RIY = 2.25. The representative head operating temperatures of 613°F corresponds to an RIY temperature adjustment factor of 1.38 (versus the reference temperature of 600°F) using the activation energy of 31 kcal/mol (130 kJ/mol) for crack growth of ASME Code Case N-729-1. Conservatively assuming that the effective full power years (EFPY) of operation accumulated since RV top head replacement is equal to 98% of the calendar years since replacement, the RIY for a requested extended period of 20 years would be (1.38)(19.6) = 27.0. The FOI implied by this RIY value is (27.0)/(2.25) = 12.0.

laboratories. No screening process was applied to the data on the basis of test characteristics such as minimum required crack extension or minimum required extent of transition along the crack front to intergranular cracking. Instead, an inclusive process was applied to conservatively assess the factors of improvement apparent in the data for specimens with less than 10 percent added cold work.

The approach was conservative in that no effort was made to screen out data points reflecting tests that are not applicable to plant conditions. Instead, the data were treated on a statistical basis in Figures 3-2, 3-4, and 3-6 of MRP-375,[2] and compared to the crack growth rate variability due to material variability for Alloy 600 in MRP-55 [1] and Alloy 182 in MRP-115 [2]. A comparison between the cumulative distributions of the crack growth rates for Alloys 690/52/152 and Alloys 600/82/182 treats the full variability in both original and replacement alloys, rather than comparing the variability of the replacement alloy against a conservative mean (75^{th} percentile) growth rate for the original alloys. By considering the cumulative distributions, a fuller perspective of the improved resistance of Alloys 690/52/152 emerges where over 70% of the data in each of Figures 3-2, 3-4, and 3-6 of MRP-375 indicate a factor of improvement beyond 20 and all of the data[3] correspond to a factor of improvement of 12 or greater.

It is emphasized that the deterministic MRP-55 and MRP-115 crack growth rate equations were developed not to describe bounding crack growth rate behavior but rather reflect 75^{th} percentile values of the variability in crack growth rate due to material variability. Twenty-five percent of the material heats (MRP-55) and test welds (MRP-115) assessed in these reports on average showed crack growth rates exceeding the deterministic equation values. Thus, the most appropriate FOI comparisons are made on a statistical basis (e.g., Figures 3-2, 3-4, and 3-6 of MRP-375). Comparing the crack growth rate for Alloys 690/52/152 versus the deterministic crack growth rate lines in Figures 3-1, 3-3, and 3-5 of MRP-375 represents an unnecessary compounding of conservatisms. Essentially none of the data presented lies within a statistical FOI of 12 below the MRP-55 and MRP-115 distributions of material variability. The technical basis for the inspection requirements for heads with Alloy 600 nozzles ([5], [6], [7]) are based on the full range of crack growth rate behavior, including heat-to-heat (weld-to-weld) and within-heat (within-weld) material variability factors. Thus, the Re-Inspection Year (RIY) = 2.25 inspection interval developed for heads with Alloy 600 nozzles reflects the possibility of crack

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[2] Figures 3-2, 3-4, and 3-6 of MRP-375 show cumulative distribution functions of the variability in crack growth rate normalized for temperature and crack loading (i.e., stress intensity factor). Each ordinate value in the plots shows the fraction of data falling below the corresponding normalized crack growth rate. Thus, the cumulative distribution function has the benefit of illustrating the variability in crack growth rate data for a standard set of conditions.

[3] Excluding data points that reflect fatigue pre-cracking conditions and are not relevant to PWSCC.

growth rates being many times higher than the deterministic 75th percentile values per MRP-55 and MRP-115. Nevertheless, as described below, the large majority of the data points for the conditions directly relevant to plant conditions (e.g., constant load conditions) are located more than a factor of 12.0 below the deterministic (75th percentile) MRP-55 and MRP-115 equations.

2 DISCUSSION OF DATA POINTS FROM MRP-375 [2]

2.1 Data Points Above a Hypothetical 12.0 Factor of Improvement Line in Figure 3-1, 3-3, and 3-5 of MRP-375

- *Figure 3-1 of MRP-375.* Figure 3-1 shows the complete set of data points compiled by the PWSCC Expert Panel organized by EPRI at the time MRP-375 was completed for Alloy 690 specimens with less than 10% added cold work. The following points are within a factor of 12.0 below the MRP-55 deterministic crack growth rate for Alloy 600:
  - There are 16 points within a factor of 12.0 below the MRP-55 75th percentile curve, out of a total of 75 points shown in Figure 3-1 of MRP-375.
  - These data represent test segments from six distinct Alloy 690 compact tension (CT) specimens that were tested by Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) and two that were tested by Argonne National Laboratory (ANL).
  - Two of the points tested by CIEMAT are from specimen 9ARB1, comprised of Alloy 690 plate material, loaded to 37 MPa(m)$^{0.5}$, and tested at 340°C and 15 cc H_2/kg H_2O [8]. Both of these data are for the first half of segments that exhibited a crack growth rate that was an order of magnitude lower in the second half of the segment. A plot of crack growth rate versus crack-tip stress intensity factor (K) for the Alloy 690 data from MRP-375 for plate material tested by CIEMAT is provided here as Figure 1. These two points have minimal implications for the requested inspection interval extension for several reasons:
    - As illustrated in Figure 1 and subsequent figures using open symbols, one of the two points was generated under partial periodic unloading (PPU) conditions. As discussed below in Section 2.2, PPU conditions may result in accelerated crack growth rates that are not directly representative of plant conditions, especially for the case of alloys with relatively high resistance to environmental cracking like Alloy 690.
    - U.S. PWRs operate with a dissolved hydrogen concentration per EPRI guidelines in the range of 25-50 cc/kg for Mode 1 operation. Testing at 15 cc/kg results in accelerated crack growth rates versus that for normal primary water due to the proximity of the Ni-NiO equilibrium line [2].
    - Specimens fabricated from Alloy 690 plate material are not as relevant to plant RV top head penetration nozzles as specimens fabricated from control rod drive mechanism (CRDM) / control element drive mechanism (CEDM) nozzle

material. CRDM and CEDM nozzles in U.S. PWRs are fabricated from extruded pipe or bar stock material. Note that term CRDM nozzle is used henceforth to refer to both CRDM and CEDM nozzles (CEDM is the terminology used by plants designed by Combustion Engineering).

- The wide variability in crack growth rate within even the same testing segment indicates that significant experimental variability exists. Thus, there is a substantial possibility that a limited number of elevated growth rate data points do not reflect the true characteristic behavior of the material tested.

– The remaining 11 CIEMAT points are from specimens comprised of Valinox WP787 CRDM nozzle material that was cold worked by a 20% tensile elongation (9.1% thickness reduction) [9]. One datum was for specimen 9T3—tested at 310°C, 22 cc H_2/kg H_2O, and 39 MPa(m)$^{0.5}$—but was from the test period immediately following a reduction in temperature from 360°C to 310°C [9]. The next period of constant load growth had a factor of 10 lower CGR. The other 10 data are for testing at 325°C and 35 cc H_2/kg H_2O, and seven of these points are for PPU testing (which may accelerate growth beyond what would be expected for in-service components). Four of the data are for specimens 9T1 and 9T2 (loaded to roughly 36 MPa(m)$^{0.5}$), and the remaining six data are from specimens 9T5 or 9T6 (loaded to roughly 27 MPa(m)$^{0.5}$). The results for 9T1 and 9T2 are contained in Reference [9]; the final data for 9T5 and 9T6 are contained in EPRI MRP-340, but have not been openly published. As discussed later in Section 2.4, the addition of cold work may result in a material that is substantially more susceptible than the as-received material. The extent of transition along the crack front to intergranular cracking for these data was extremely low ($\leq$ 10%) for the ten points from specimens tested at constant temperature. A plot of crack growth rate versus K for the Alloy 690 data from MRP-375 for heat WP787 is provided here as Figure 2. As in Figure 1, there is significant growth rate variability within the data for the same heat of material. The median for the CIEMAT specimens is more than a factor of 12 below the MRP-55 curve. Additionally, the Pacific Northwest National Laboratory (PNNL) data indicate that the specific laboratory that produces the data can significantly influence the reported growth rate, such that there is a substantial possibility that a small number of reported data points with relatively high crack growth rates from a single laboratory are not characteristic of the true susceptibility of a specific heat of Alloy 690 material.

– The three ANL data points are for CT specimens C690-CR-1 and C690-LR-2, comprised of Valinox heat number WP142 CRDM nozzle material that were not cold worked and were tested at 21 to 24 MPa(m)$^{0.5}$, 320°C, and 23 cc H_2/kg H_2O [10]. The intergranular engagement for these specimens was extremely low (almost entirely transgranular). A plot of crack growth rate versus K for the Alloy 690 data from MRP-375 for heat WP142 is provided here as Figure 3. As in Figure 2, PNNL data indicate that the specific laboratory that produces the data can significantly influence the reported growth rate.

- *Figure 3-3 of MRP-375*. Figure 3-3 shows the complete set of data points compiled for Alloy 690 heat affected zone (HAZ) specimens at the time MRP-375 was completed by the PWSCC Expert Panel that was organized by EPRI. The following points are within a factor of 12.0 below the MRP-55 deterministic crack growth rate for Alloy 600:

- There are eight points within a factor of 12.0 below the MRP-55 75th percentile curve, out of a total of 34 points shown in Figure 3-3 of MRP-375. All but one of the eight data points are for PPU testing, and all but two appear to have had very little to no intergranular engagement.
- Six of the points are from ANL testing of specimens comprised of Valinox CRDM nozzle material heat WP142 and Alloy 152 filler (Special Metals heat WC43E9), tested at 320°C and 23 cc H_2/kg H_2O [11]. Five of the points are from specimens CF690-CR-1 and CF690-CR-3 (loaded to roughly 28 to 32 MPa(m)$^{0.5}$) [11], and the other point is from specimen CF690-CR-4 (loaded to roughly 22 MPa(m)$^{0.5}$) [12]. A plot of crack growth rate versus K for all the Alloy 690 HAZ data from MRP-375 for heat WP142 is provided here as Figure 4. As discussed below, PPU conditions—under which five of these six points were obtained—may result in accelerated crack growth relative to plant conditions.
- The remaining two points are from CIEMAT testing of specimens 19ARH1 and 19ARH2, comprised of welded Alloy 690 plate material, tested at 340°C and 15 cc H_2/kg H_2O, and loaded to roughly 37 MPa(m)$^{0.5}$ [8]. A plot of crack growth rate versus K for the Alloy 690 HAZ data from MRP-375 for plate material tested by CIEMAT is shown in Figure 5. As discussed later, the orders of magnitude difference between these two PPU points and the constant load testing for this HAZ is indicative of the substantial accelerating effect that PPU testing can have beyond what would be expected in service environments.

- *Figure 3-5 of MRP-375.* Figure 3-5 shows the complete set of data points compiled by the PWSCC Expert Panel organized by EPRI at the time MRP-375 was completed for Alloy 52 and 152 weld metal specimens. The following points are within a factor of 12.0 below the MRP-115 deterministic crack growth rate for Alloy 182:
  - There are 19 points within a factor of 12.0 below the MRP-115 75th percentile curve, out of a total of 212 points shown in Figure 3-5 of MRP-375. Five of these points are not relevant to PWR conditions and should not be considered further, as discussed in the following bullets.
    - One of these points is from PNNL testing of the dilution zone of a dissimilar metal weld between 152M (Special Metals heat WC83F8) and carbon steel, tested at 360°C and 25 cc H2/kg H2O [13]. This material condition is not applicable to the wetted surfaces of CRDM nozzle J-groove welds because the dilution zone where Alloy 52/152 contacts the low-alloy steel RV head is below the stainless steel cladding. A plot of crack growth rate versus K for the Alloy 152 data from MRP-375 for heat WC83F8 is provided here as Figure 6.
    - Four of the remaining points, including the point closest to the MRP-115 curve, are for environmental fatigue pre-cracking test segments [14]. The status of these four data points, which are shown in black in Figure 7, as being fatigue pre-cracking test segments irrelevant to PWSCC conditions was clarified subsequent to publication of MRP-375.
  - The remaining 14 data points represent four specimens from Alloy 152 weld material (Special Metals heat WC04F6) that were tested by ANL at 320°C and 23 cc H_2/kg H_2O ([15] and [10]). Ten of these points are for specimen A152-TS-5 at loads of about 28, 32, and 48 MPa(m)$^{0.5}$ [14]. The other four points were obtained at loads of

27 MPa(m)$^{0.5}$ for specimen N152-TS-1 and 30 MPa(m)$^{0.5}$ for specimens A152-TS-2 and A152-TS-4. The Alloy 152 specimens all came from welded plate material. A plot of crack growth rate versus K for the Alloy 152 data from MRP-375 for heat WC04F6 is provided here as Figure 7. All but three of these points were for PPU conditions, which may result in accelerated crack growth rates that are not directly representative of plant conditions. Figure 7 shows a very large variability in the crack growth rate reported by different laboratories for this heat of Alloy 152 weld material. Roughly one third the ANL data (specimen N152-TS-1), all of the General Electric Global Research Center (GE-GRC) data, and all the PNNL data for this heat are for specimens from a single weld made by ANL [16], illustrating the role of experimental variability. A small number of elevated data points for a weld produced by a single laboratory may not be representative of the true material susceptibility.

2.2 Data Most Directly Applicable to Plant Conditions

As described above, Section 3 of MRP-375 took an inclusive approach to statistical assessment of the compiled data. A conservative approach was applied in which both constant load data and data under PPU conditions were plotted together. In addition, weld data reflecting various levels of weld dilution adjacent to lower chromium materials was included in the data for Alloys 52/152. An assessment of the crack growth rate data points most applicable to plant conditions is presented in Figure 8 through Figure 13. The assessment shows very few points located within a factor of 12.0 below the deterministic MRP-55 and MRP-115 lines, with such points only slightly above the line representing a factor of 12.0:

- Figure 8 for Alloy 690 with Added Cold Work Less than 10%.
  - Only seven of the 55 points are within a factor of 12.0 below the MRP-55 deterministic crack growth rate for Alloy 600.
  - Figure 9 shows that the data are bounded by an FOI of more than 12 relative to Alloy 600 data on a statistical basis.
- Figure 10 for Alloy 690 HAZ.
  - Only one of the 24 points is within a factor of 12.0 below the MRP-55 deterministic crack growth rate for Alloy 600.
  - Figure 11 shows that the data are bounded by an FOI of more than 12 relative to Alloy 600 data on a statistical basis.
- Figure 12 for Alloys 52/152.
  - Only three of 83 points are within a factor of 12.0 below the MRP-115 deterministic crack growth rate for Alloy 182.
  - Figure 13 shows that the data are bounded by an FOI of more than 12 relative to Alloy 182 data on a statistical basis.

As discussed above, the technical basis for heads with Alloy 600 nozzles assumes the substantial possibility of crack growth rates substantially greater than that predicted by the deterministic

equations of MRP-55 and MRP-115. The MRP-55 and MRP-115 deterministic crack growth rate equations are not bounding equations, but rather reflect the 75th percentile of material variability. Thus, the perspective provided in Figure 9, Figure 11, and Figure 13 is most relevant to drawing conclusions regarding FOI values applicable to inspection intervals for heads fabricated using Alloy 690, 52, and 152 materials.

The data presented in Figure 8 through Figure 13 were included on the basis of the following considerations:

- As demonstrated and discussed in MRP-115, certain PPU conditions will act to accelerate the crack growth rate. PPU conditions, which include a periodic partial reduction in load, are often used in testing to transition from initial fatigue conditions toward constant load conditions with the crack in a state most representative of stress corrosion cracks if they had initiated in plant components over long periods of time. The periodic load reductions and accompanying load increases may rupture localized crack ligaments along the crack front, facilitating transition of the crack to an intergranular morphology. In MRP-115, data with hold times less than 1 hour were screened out of the database for Alloys 82/182/132. The greater resistance of Alloys 690/52/152 to cracking is expected to result in a greater sensitivity of the crack growth rate to partial periodic unloading conditions. Figure 14 and Figure 5, in particular, show that there is an apparent significant bias for the data for Alloy 690 in which the data for partial periodic unloading conditions are substantially higher than for constant load conditions. Thus, the data presented in Figure 8 through Figure 13 have been restricted to the constant load (or constant K) conditions that are most relevant to plant conditions for growth of stress corrosion cracks.
- The Alloy 52/152 weld metal data shown in Figure 3-5 and Figure 3-6 of MRP-375 include data reflecting a range of weld dilution levels. The data presented in Figure 12 and Figure 13 exclude the weld dilution data points because of the limited number of data points available, the variability in results, and the limited area of continuous weld dilution for potential flaws to grow through. The weld dilution data are not reflective of the full chromium content of Alloy 52/152 weld metal.
- The data presented in Figure 12 and Figure 13 exclude a small number of data points that reflect cracking at the fusion line with carbon or low-alloy steel material. Some of these data reflect cracking in the adjacent carbon or low-alloy steel material that was not post-weld heat treated as would be the case in plant applications.
- The data presented in Figure 12 and Figure 13 eliminate the few data points that in fact reflect fatigue pre-cracking rather than stress corrosion cracking. The status of these data points was clarified subsequent to publication of MRP-375.

The limited number of remaining points in Figure 8 and Figure 12 that lie within a factor of 12.0 below the deterministic MRP-55 and MRP-115 lines represent the upper end of material and/or experimental variability. Figure 9, Figure 11, and Figure 13 consider the variability in crack growth rate among different heats/welds of Alloys 600/82/182 and compare this against the full variability of the Alloy 690/52/152 data most applicable to plant conditions. The lack of *any*

points within a factor of 12 when accounting for variability in Alloy 600/82/182 crack growth rates supports a reexamination interval longer than the requested interval corresponding to an FOI of 12.0. The volumetric or surface inspection interval for heads with Alloy 600 nozzles reflects consideration of crack growth rates on a statistical basis, with crack growth rates often higher than that given by the deterministic equations of MRP-55 and MRP-115.

2.3 Data Specific to Argonne National Laboratory (ANL) and Pacific Northwest National Laboratory (PNNL)

The U.S. NRC is most familiar with the crack growth data for Alloys 690/52/152 that have been generated by ANL and PNNL, so the data specific to these national laboratories have also been evaluated separately. Based on the compilation of ANL and PNNL crack growth rate data recently released by NRC [17][4], the results are shown in Figure 15 through Figure 20. These data reflect Alloy 690 test specimens with up to 22% added cold work. The data in Reference [17] are consistent with the ANL and PNNL data in the wider database presented in MRP-375. As shown in Figure 15, Figure 17, and Figure 19, only 10 of the total of 86 constant load (or constant K) data points generated by ANL and PNNL are within a factor of 12.0 below the deterministic MRP-55 and MRP-115 lines. Only one of these points is within a factor less than 9.0 below the deterministic MRP-55 and MRP-115 lines. Furthermore, among the constant load data, only five of the 55 points with less than 10% cold work are within a deterministic factor of 12.0. Finally, when the statistical variability in material susceptibility is considered for the reference material (Alloys 600 and 182) as well as for the subject replacement alloys, all the data points for constant load conditions show a factor of improvement greater than 12.0. This favorable result is clearly illustrated in Figure 16, Figure 18, and Figure 20.

2.4 Data for Alloy 690 Wrought Material Including Added Cold Work up to 20% for CRDM Nozzle and Bar Material Product Forms

An assessment of the crack growth rate data points for Alloy 690 CRDM nozzle and bar material product forms for cold work levels up to 20% is presented in Figure 21 and Figure 22. Equivalent plots for Alloy 52/152 material for the purpose of including the limited number (i.e., five) of weld metal data points generated for added cold work conditions are shown in Figure 23

[4] The data in Reference [16] are augmented by the crack growth rate data for Alloys 52/152 produced by PNNL and previously published in an NRC NUREG contractor report [17]. While these PNNL data are shown graphically in Enclosure 3 of Reference [16], the enclosures of tabular data in this NRC document omitted all of the PNNL data for Alloys 52/152. It is also noted that contrary to the enclosure titles of Reference [16], Enclosure 2 contains the PNNL tabular data, and Enclosure 4 contains the ANL tabular data.

and Figure 24. Added cold work for weld metals is not directly relevant to plant material conditions.

For Alloy 690 control rod drive mechanism (CRDM) / control element drive mechanism (CEDM) nozzles and other RV head penetration nozzles, the effective cold-work level in the bulk Alloy 690 base metal is expected to be no greater than roughly 10%. This is based on fabrication practices specific to replacement heads, i.e., material processing and subsequent nozzle installation via welding [19]. Furthermore, the crack growth rate data presented for Alloy 600 in MRP-55 do not include cases of added cold work. Comparing cold worked Alloy 690 data against non-cold worked Alloy 600 data results in a conservatism in the factor of improvement for Alloy 690 material as the cold worked material condition for Alloy 600 would be expected to result in a somewhat increased deterministic crack growth rate for Alloy 600, and thus a greater apparent factor of improvement. Nevertheless, the assessment in Figure 21 through Figure 24 is included in this document to illustrate the effect of higher levels of cold work. These data show the potential for modestly higher crack growth rates for such elevated cold work levels for the material product forms most relevant to RV top head nozzles.

2.5 Conclusion

The data presented above support factors of improvement greater than 12 for the CGR performance of Alloys 690/52/152. Thus, the available laboratory CGR data support a volumetric inspection interval of at least 20 years for Alloy 690 RV head nozzles.

3 POTENTIAL IMPLICATIONS OF SPECIFIC CATEGORIES OF NOZZLE AND WELD MATERIALS

Section 3 assesses the available laboratory CGR data for the potential concern of elevated CGRs for specific categories of nozzle and weld materials.

3.1 Potential Similarities for Laboratory Specimen Material Exhibiting a Deterministic Factor Less than 12.0

Any similarities between (a) the data points within a factor of 12.0 below the MRP-55/MRP-115 curve in Figure 3-1, 3-3, and 3-5 of MRP-375 and (b) the associated nozzles and weld material used in the RV heads in U.S. PWRs are as follows:

- *Figure 3-1 of MRP-375* [2]. The only Alloy 690 CRDM material for which crack growth rate data were available at added cold work of less than 10% (the threshold for inclusion in Figure 3-1 of MRP-375) was supplied by Valinox Nucleaire. The few data using CRDM material from other suppliers were obtained at cold works of 20% or higher and were not included in the assessment. The data do not indicate any correlation between material supplier and susceptibility to crack growth rate. Fourteen of the Alloy 690 crack growth data points within a factor of 12.0 below the MRP-55 [1] deterministic crack growth rate in Figure 3-1 of MRP-375 were produced for specimens of Alloy 690 CRDM nozzle material that was supplied by Valinox Nucleaire. However, for the reasons explained below (e.g., the variability among data from different laboratories, the variability among data for a single heat and laboratory, and the use of PPU for eight of these 14 data), this similarity in no way indicates any specific concern for elevated PWSCC susceptibility of the head nozzle material provided by any one supplier.
- *Figure 3-3 of MRP-375* [2]. Six of the Alloy 690 HAZ data points above a crack growth rate 12.0 times lower than the MRP-55 deterministic crack growth rate in Figure 3-3 of MRP-375 were also produced for specimens of Alloy 690 CRDM nozzle material that was supplied by Valinox Nucleaire. However, for the reasons explained below, this similarity in no way indicates any specific concern for elevated PWSCC susceptibility of head nozzles produced from Valinox material in comparison to Alloy 690 nozzles from another supplier. It is noted that the welding process used to produce the HAZ in the test specimens is not specific to any particular categories of replacement heads.
- *Figure 3-5 of MRP-375* [2]. There are no relevant similarities between (a) the Alloy 52 and 152 data points above a crack growth rate 12.0 times lower than the MRP-115 [2] Alloy 182 deterministic crack growth rate in Figure 3-5 of MRP-375 and (b) the Alloy 52/152 weld material used in any particular categories of replacement heads. The variability among test welds with respect to PWSCC crack growth susceptibility reflects a combination of how the weld was made (welding procedure, weld design, degree of constraint, etc.) and perhaps the material variability in the weld consumable (e.g., composition). The test welds used to produce the specimens that showed crack growth rates within a factor of 12.0 below the MRP-115 crack growth rate are not identified with any particular fabricator of replacement RV heads. Furthermore, the weld specimens used in the crack growth rate testing were machined from test welds in flat plates, not from actual J-groove welds. Thus, the test weld specimens should not be associated with particular fabrication categories of replacement heads.

3.2 Potential Implications

The material and welding similarities in no way indicate any specific concern for elevated PWSCC susceptibility of the head nozzles at any U.S. PWR or provided by any supplier in comparison to other heads with Alloy 690 nozzles or Alloy 690 nozzles supplied by any other supplier. It is emphasized that a small number of data points showing relatively high crack growth rates cannot readily be concluded to be characteristic of the true material behavior expected in the field. This conclusion is made considering the following:

- The only heats of Alloy 690 CRDM nozzle material that have been used in crack growth rate testing with less than 10% added cold work are supplied by Valinox. Consequently, there is no basis to suggest material from any one supplier is more susceptible than that from another based on the presence or absence of data points within a given factor of the deterministic crack growth rate curve from MRP-55.
- The data points showing the highest crack growth rates for the tested Valinox material reflect partial periodic unloading conditions. As discussed above, such conditions tend to result in accelerated crack growth rates that are not representative of plant conditions.
- Most of the crack growth rate data for heats that had points within a factor of 12.0 below the MRP-55 deterministic curve or MRP-115 deterministic curve were substantially lower. The best-estimate behavior for every heat or test weld of material presented in Figures 3-2, 3-4, and 3-6 of MRP-375 reflects a factor of improvement of 12 or greater. In addition, other factors being equal, one would expect a greater range of crack growth rates for a material heat for which a greater number of data points was produced. Some of the scatter likely reflects experimental uncertainty as opposed to true material variability. Experimental uncertainty is more of a factor for the data for Alloys 690/52/152 than for Alloys 600/82/182/132 considering the greater testing challenges associated with the more resistant replacement alloys.
- In some cases, different laboratories have reported large differences in crack growth rate for the same material heat or test weld. This behavior is illustrated in Figure 7 for the Alloy 152 heat WC04F6 and Figure 3 for the Alloy 690 heat WP142. Thus, individual data points showing relatively high crack growth rates might not reflect the true susceptibility of particular categories of nozzle or weld material. Consistent data from multiple laboratories may be needed before one can conclude that a particular category of nozzle or weld material has an elevated susceptibility to PWSCC growth.
- Some type of PWSCC initiation is necessary to produce a flaw that may grow via PWSCC. Laboratory and plant experience show that Alloys 690/52/152 are substantially more resistant to PWSCC initiation than Alloys 600/82/182 [2]. PWSCC has not been shown to be an active degradation mode for Alloys 690/52/152 components after use in PWR environments for over 25 years.
- The crack growth rate data compiled in MRP-375 [2] for Alloys 52 and 152 reflect the composition variants applicable to PWR plant applications. Data are included for the following variants: Alloy 52 (UNS N06052 / AWS ERNiCrFe-7), Alloy 52M (UNS N06054 / AWS ERNiCrFe-7A), Alloy 52MSS (UNS N06055 / AWS ERNiCrFe-13), Alloy 52i (AWS ERNiCrFe-15), Alloy 152 (UNS W86152 / AWS ENiCrFe-7), and Alloy 152M (UNS W86152 / AWS ENiCrFe-7). Considering the overall set of available crack growth rate data for the various variants of Alloy 52 and 152, there is no basis for concluding at this time any significant difference in the average behavior between the Alloy 52 and Alloy 152 variants in use at U.S. PWR RV heads with Alloy 690 nozzles.

In addition, it should be recognized that PWSCC of Alloy 690 RV head penetration nozzles or their Alloy 52/152 attachment welds is not an active degradation mode. Thus, it is premature to single out individual materials or fabrication categories of heads with Alloy 690 nozzles for additional scrutiny on the basis of subsets of laboratory crack growth rate data. In the case of

heads with Alloy 600 nozzles, for which PWSCC is an active degradation mode, materials and fabrication categories of heads with relatively high incidence of PWSCC are inspected in accordance with the same requirements as other heads.

Based on the additional information and discussion provided above, it is concluded that the available crack growth rate data do not indicate any susceptibility concerns specific to the nozzle or weld materials specific to any given replacement head or category of replacement heads.

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Data from Individual Heats

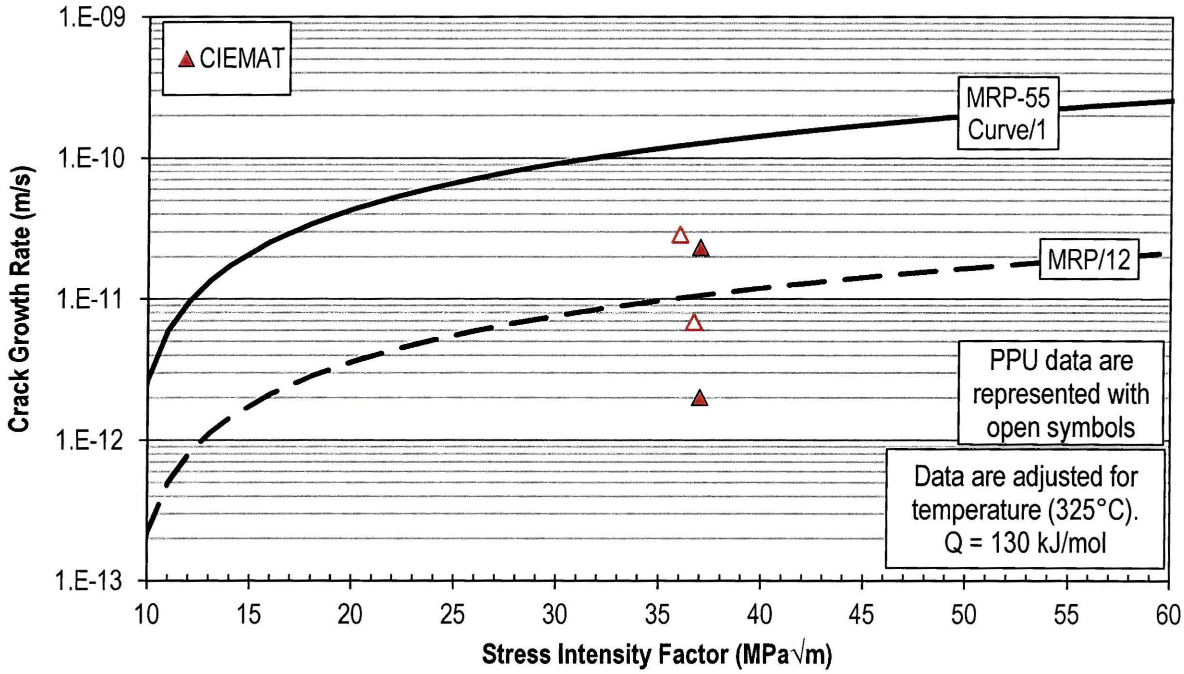

Figure 1. Plot of Crack Growth Rate (da/dt) versus Stress Intensity Factor (K_I) for Alloy 690 Data from Plate Material Tested by CIEMAT

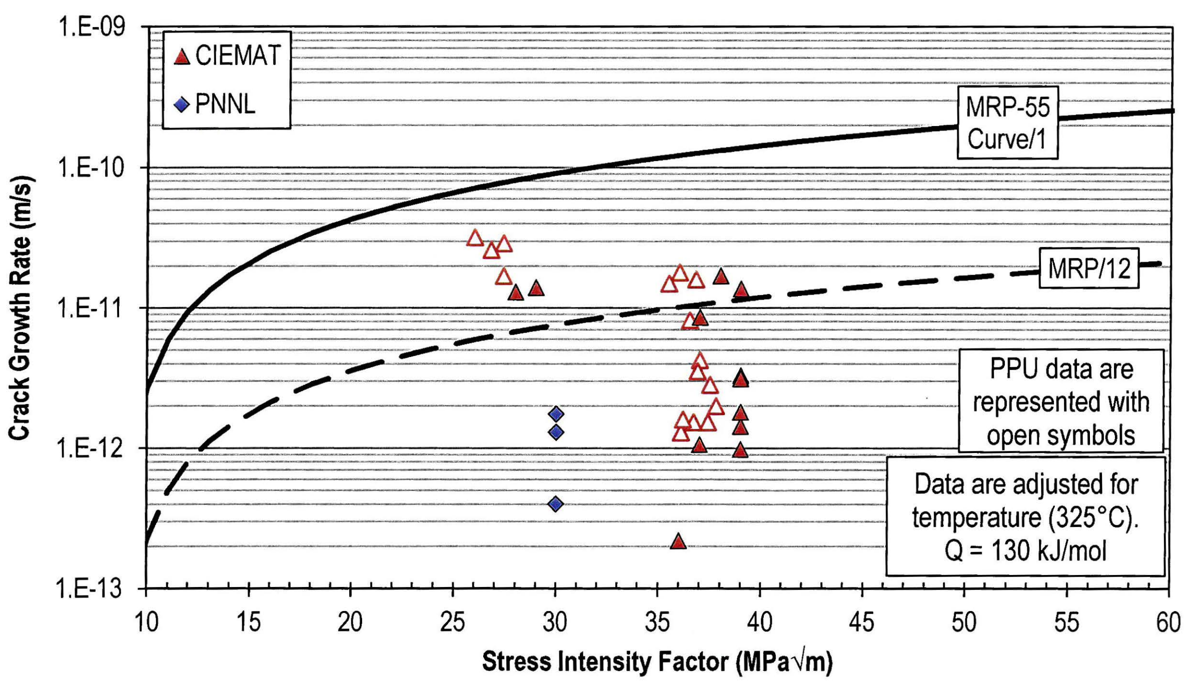

Figure 2. Plot of da/dt versus K_I for Alloy 690 Data from Heat WP787

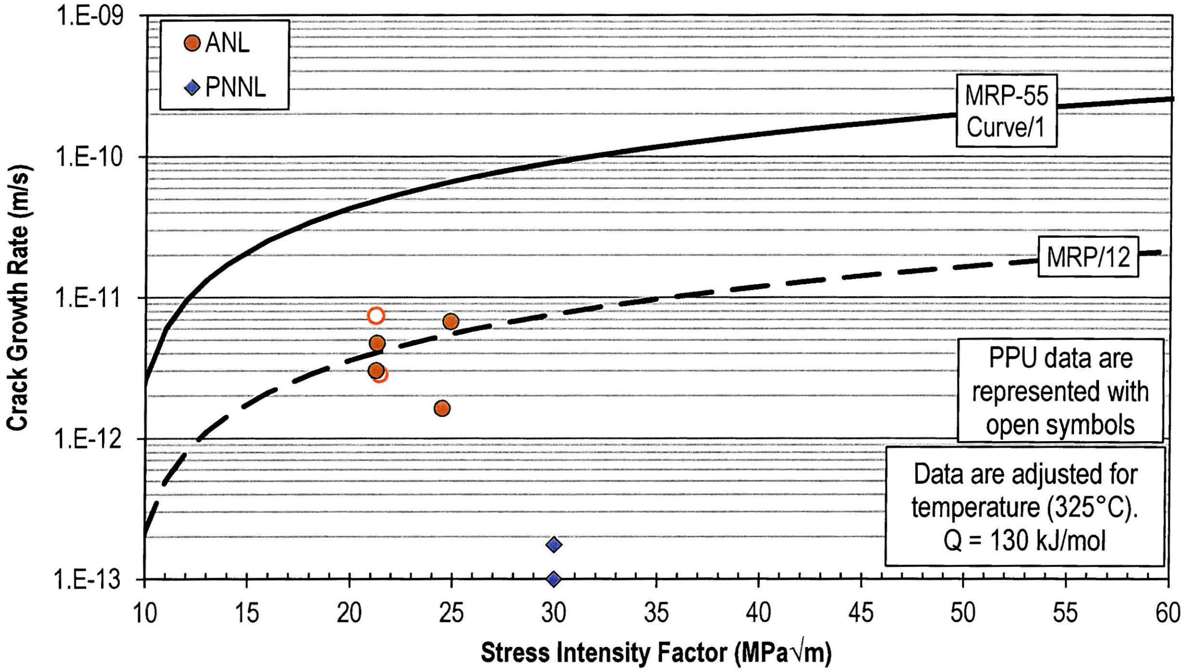

Figure 3. **Plot of da/dt versus K_I for Alloy 690 Data from Heat WP142**

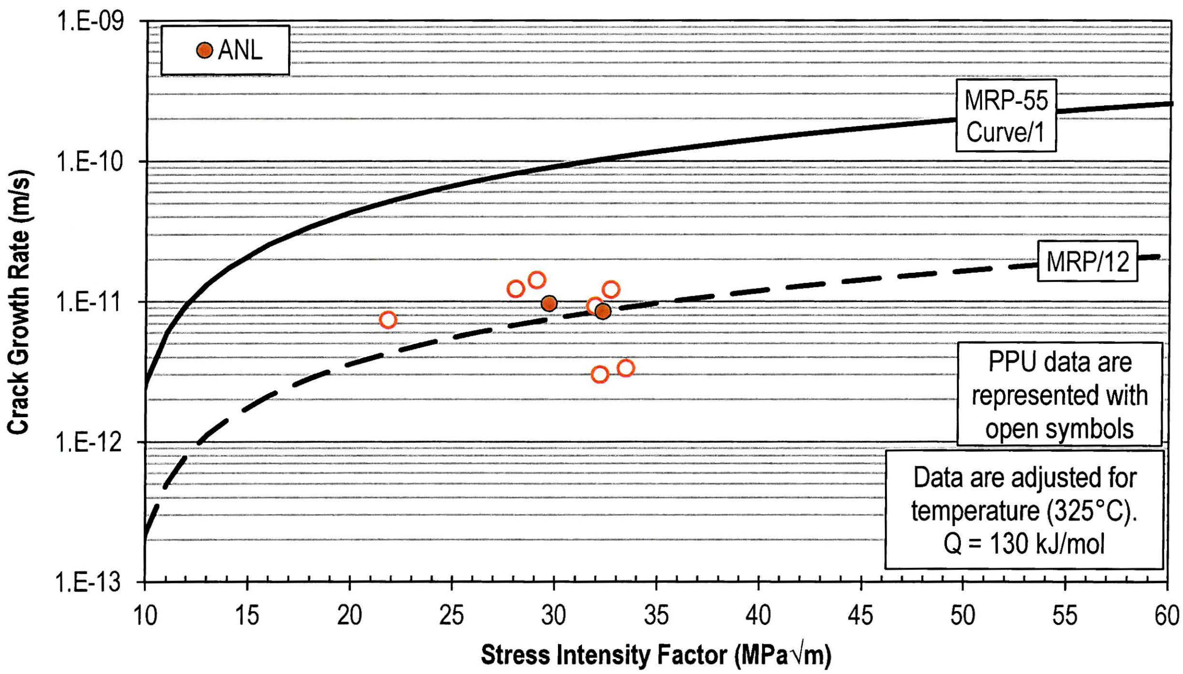

Figure 4. **Plot of da/dt versus K_I for Alloy 690 HAZ Data from Heat WP142**

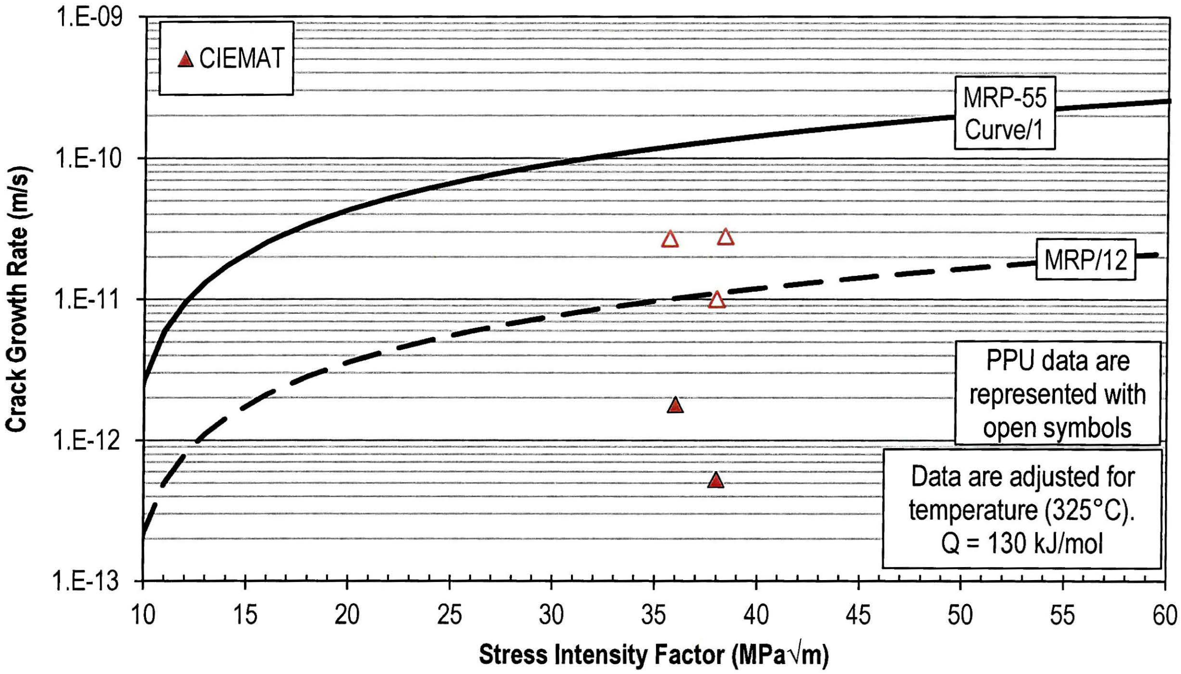

Figure 5. **Plot of da/dt versus K_I for Alloy 690 HAZ Data from Plate Material Tested by CIEMAT**

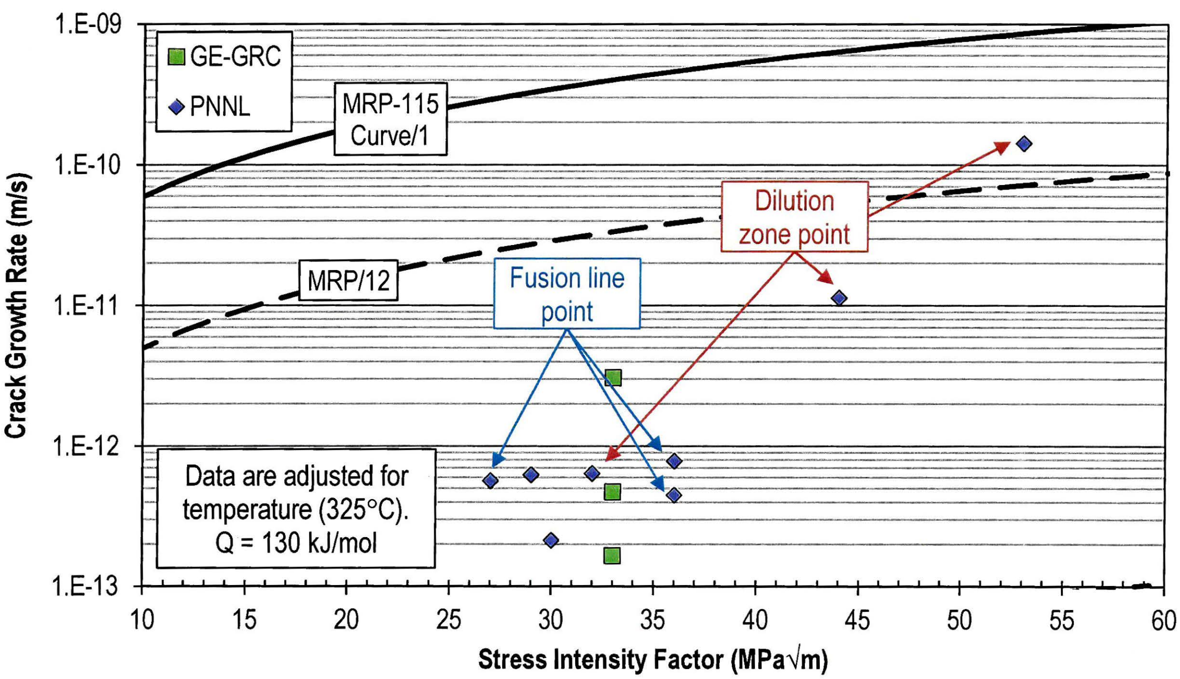

Figure 6. **Plot of da/dt versus K_I for Alloy 152 Data from Heat WC83F8**

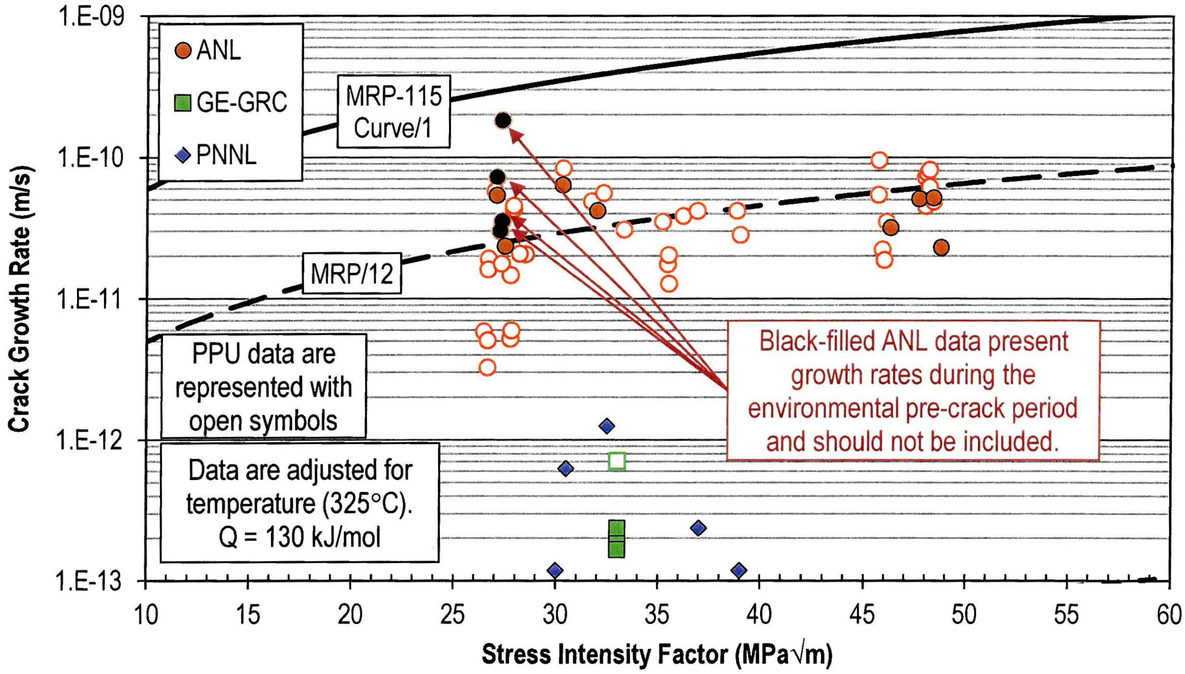

Figure 7. Plot of da/dt versus K_I for Alloy 152 Data from Heat WC04F6

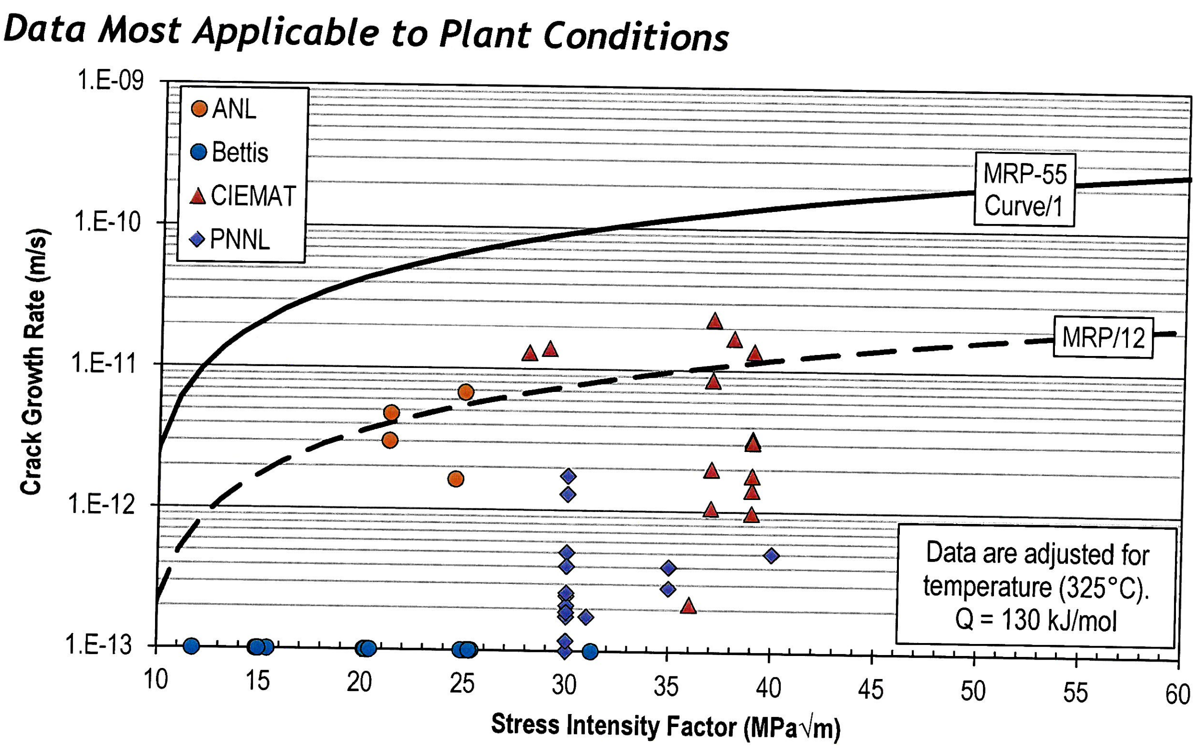

Figure 8. Plot of da/dt versus K_I for Alloy 690 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

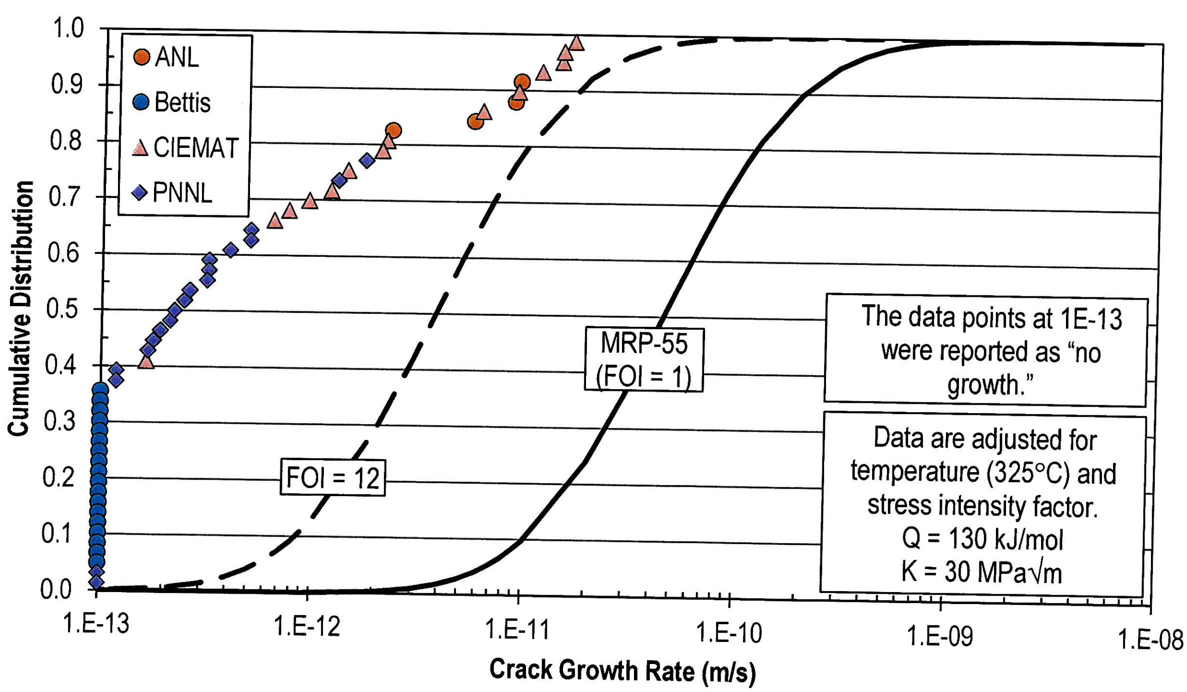

Figure 9. Cumulative Distribution Function of Adjusted da/dt for Alloy 690 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

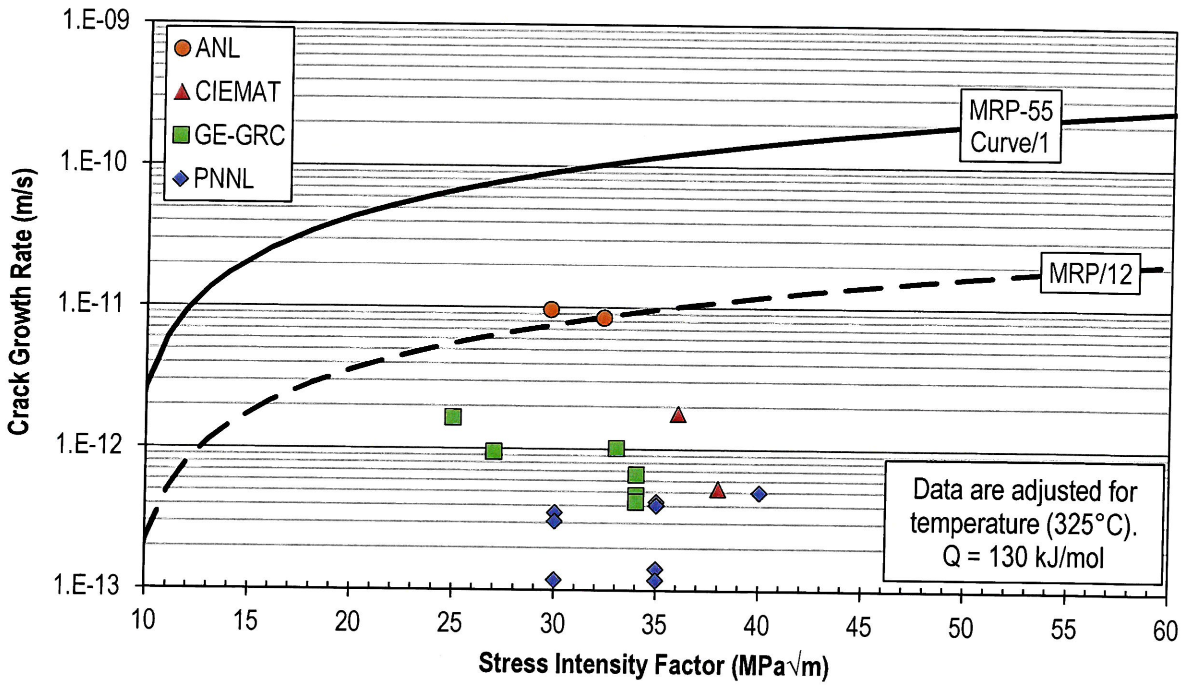

Figure 10. **Plot of da/dt versus K_I for Alloy 690 HAZ Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I**

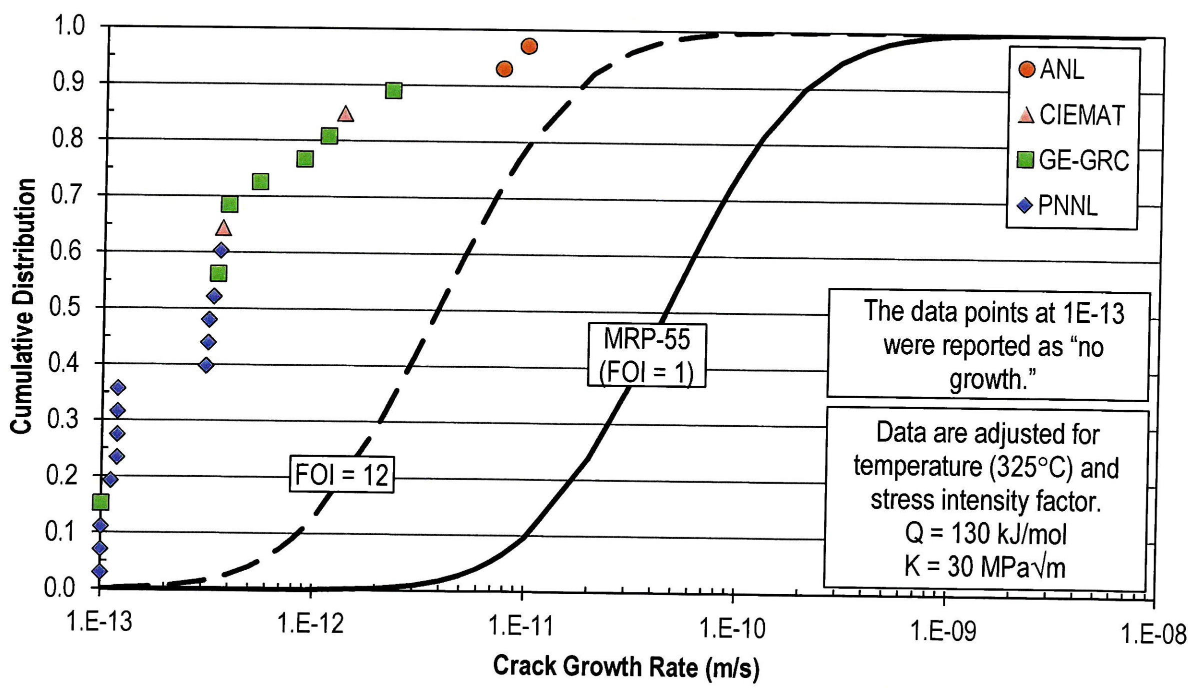

Figure 11. **Cumulative Distribution Function of Adjusted da/dt for Alloy 690 HAZ Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I**

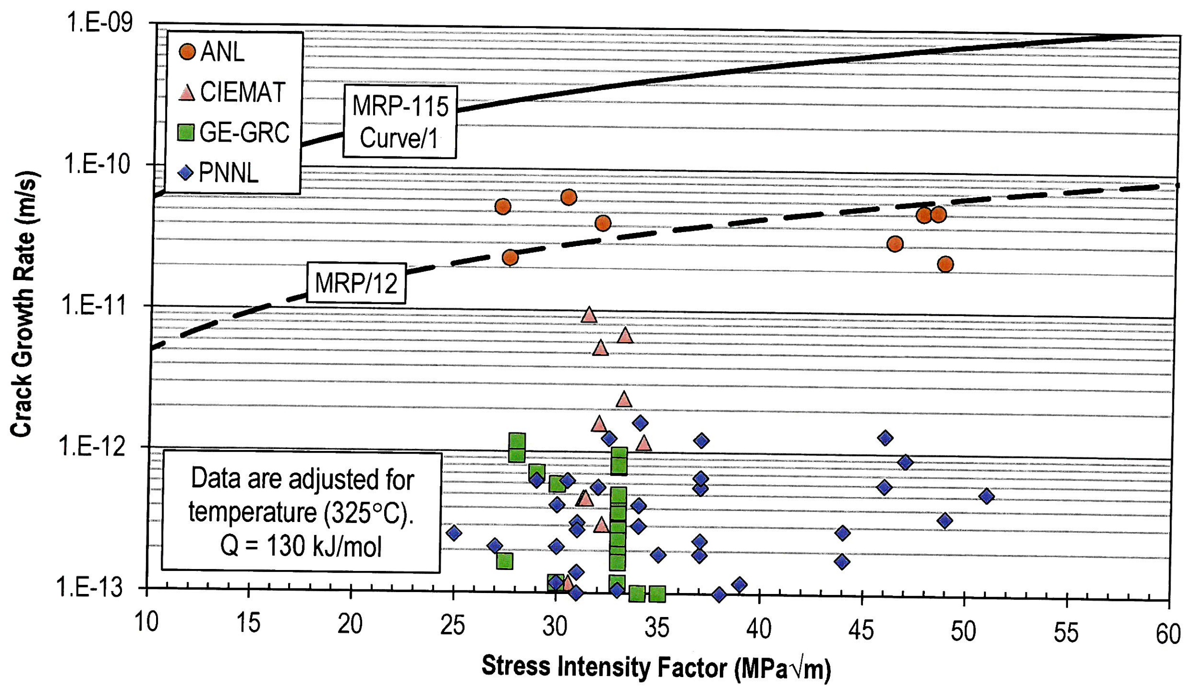

Figure 12. Plot of da/dt versus K_I for Alloy 52/152 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

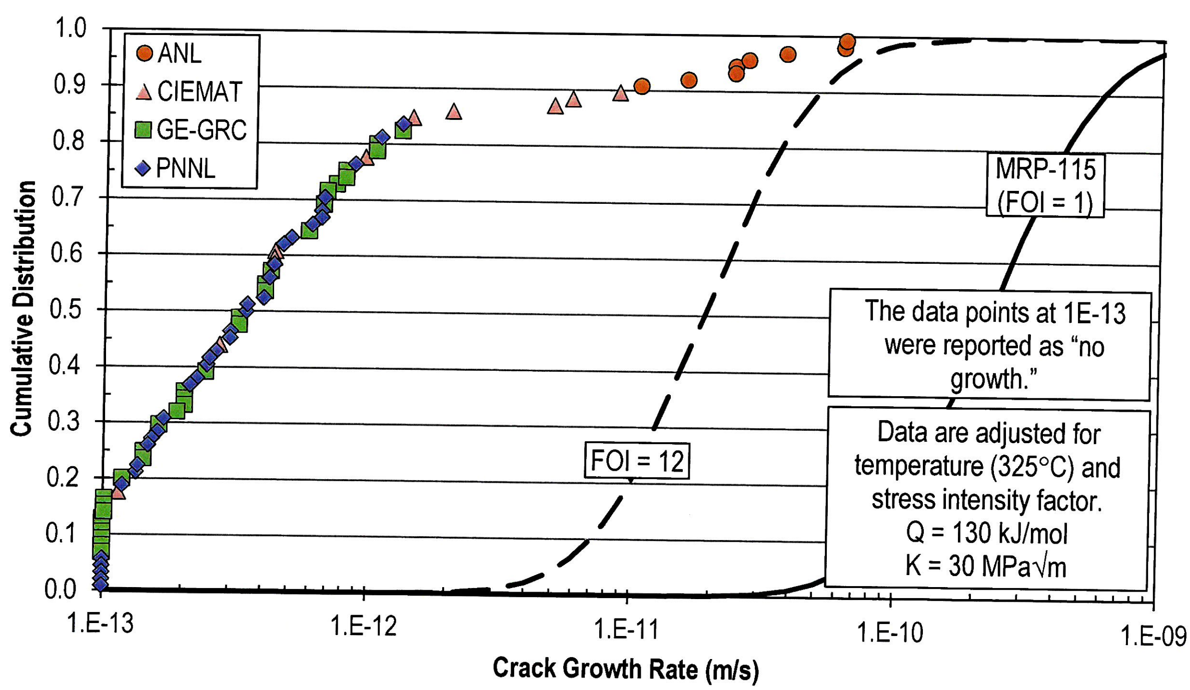

Figure 13. Cumulative Distribution Function of Adjusted da/dt for Alloy 52/152 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

Comparison of Partial Period Unloading (PPU) Conditions vs. Constant Load Conditions

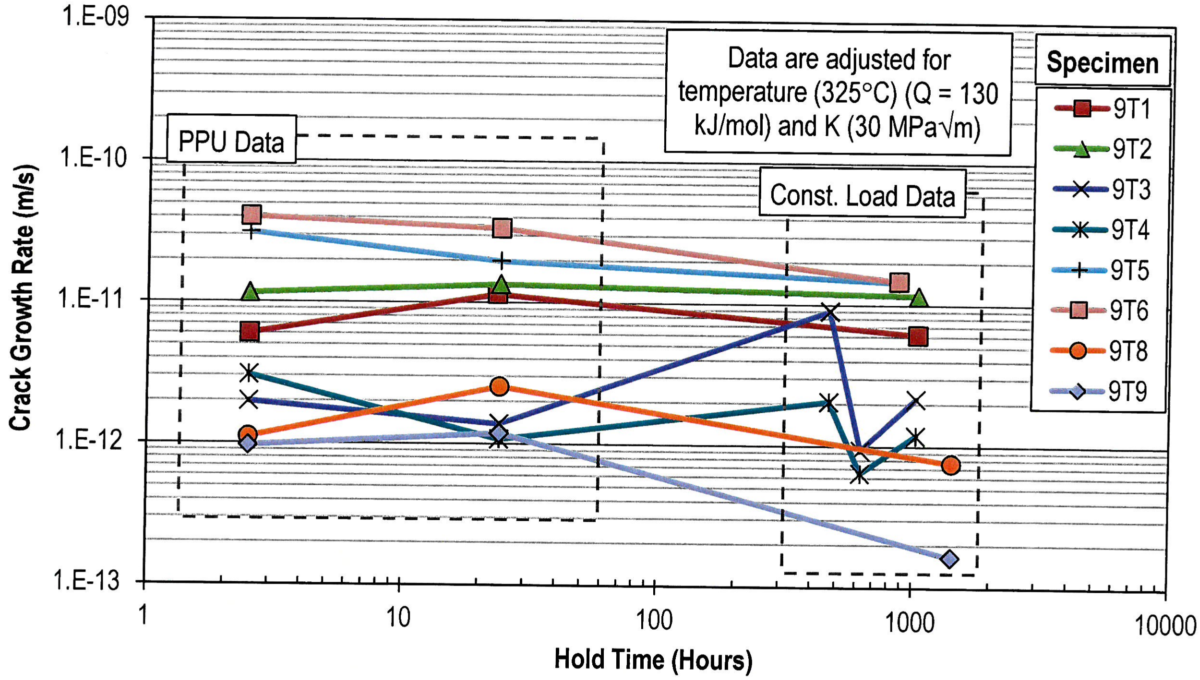

Figure 14. **Plot of da/dt versus Loading Hold Time (for PPU testing) or Test Segment Duration (for Constant K_I/Load Testing) from Heat WP787**

Compilation of ANL and PNNL Data

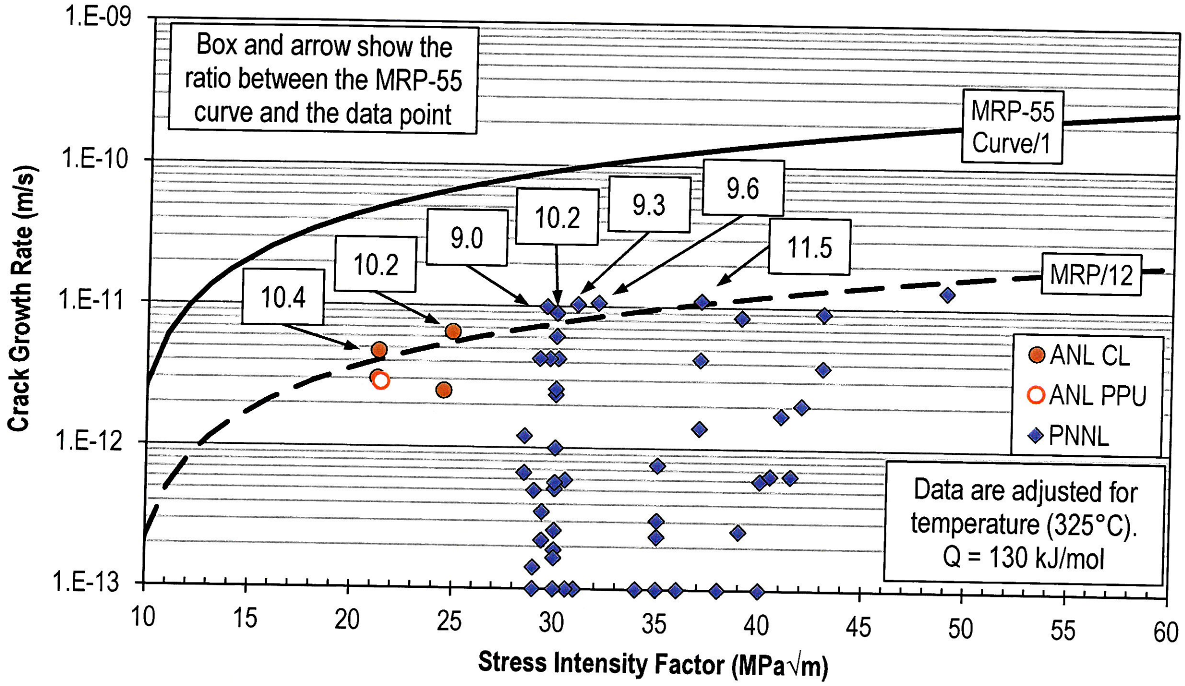

Figure 15. **Plot of da/dt versus K_I for Alloy 690 Data Produced by ANL and PNNL and Available in Reference [17]; ≤ 22% Cold Work**

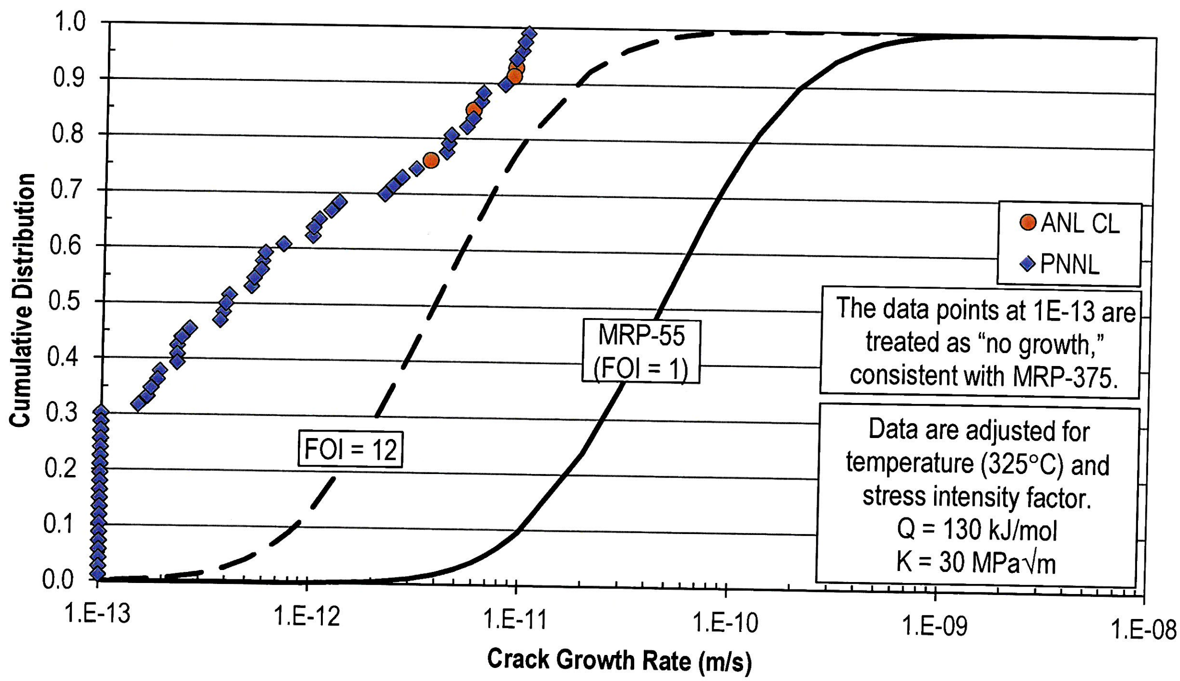

Figure 16. **Cumulative Distribution Function of Adjusted da/dt Alloy 690 Data Produced by ANL and PNNL in References [17]; ≤ 22% Cold Work and Constant Load/K_I**

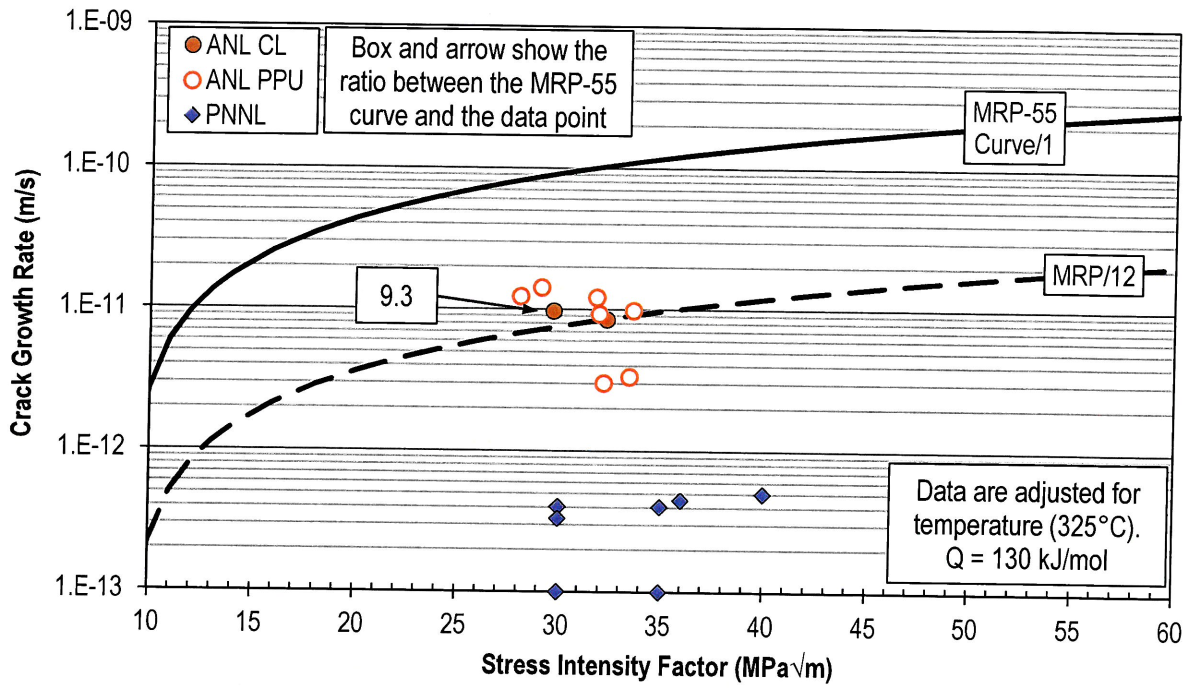

Figure 17. Plot of da/dt versus K_I for Alloy 690 HAZ Data Produced by ANL and PNNL and Available in Reference [17]; ≤ 22% Cold Work

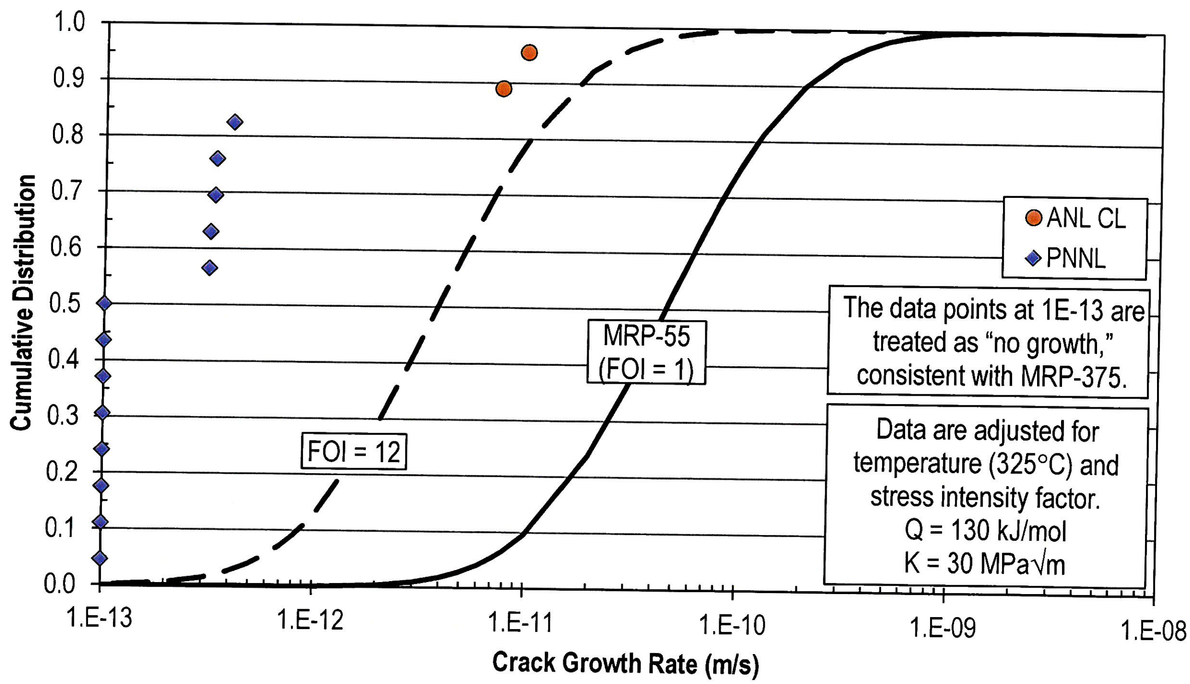

Figure 18. Cumulative Distribution Function of Adjusted da/dt Alloy 690 HAZ Data Produced by ANL and PNNL [17]; ≤ 22% Cold Work and Constant Load/K_I

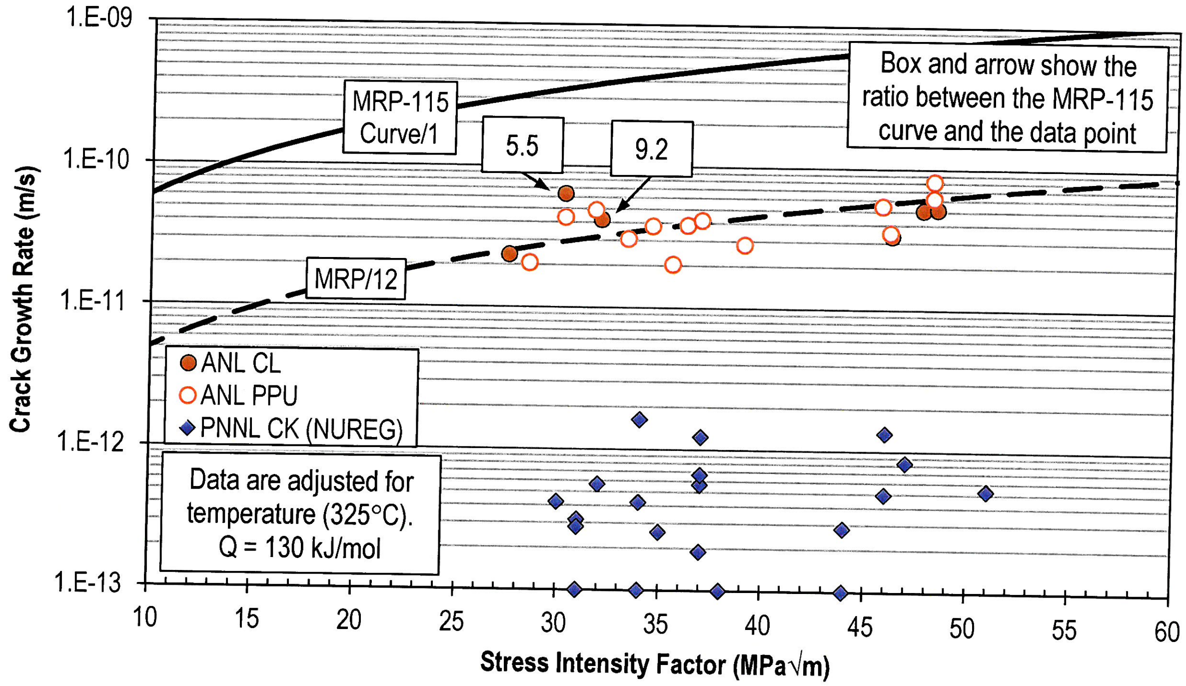

Figure 19. Plot of da/dt versus K_I for Alloy 52/152 Data Produced by ANL and PNNL and Available in References [17] and [18]; ≤ 22% Cold Work

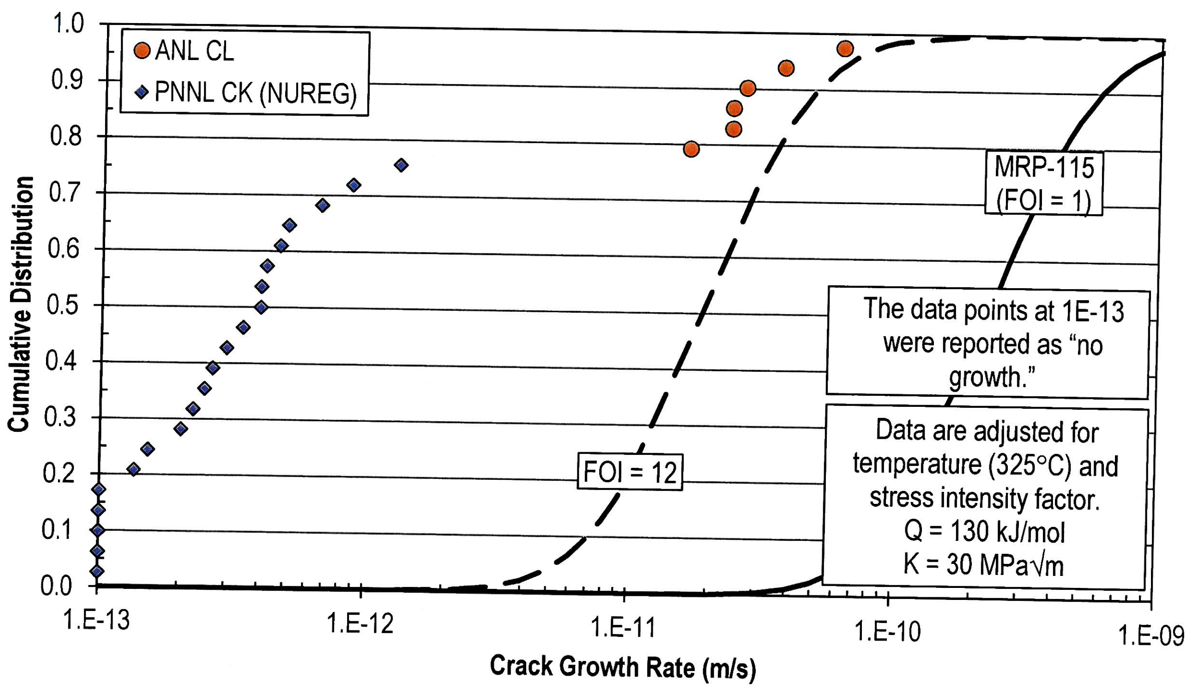

Figure 20. Cumulative Distribution Function of Adjusted da/dt Alloy 52/152 Data Produced by ANL and PNNL ([17] and [18]); ≤ 22% Cold Work and Constant Load/K_I

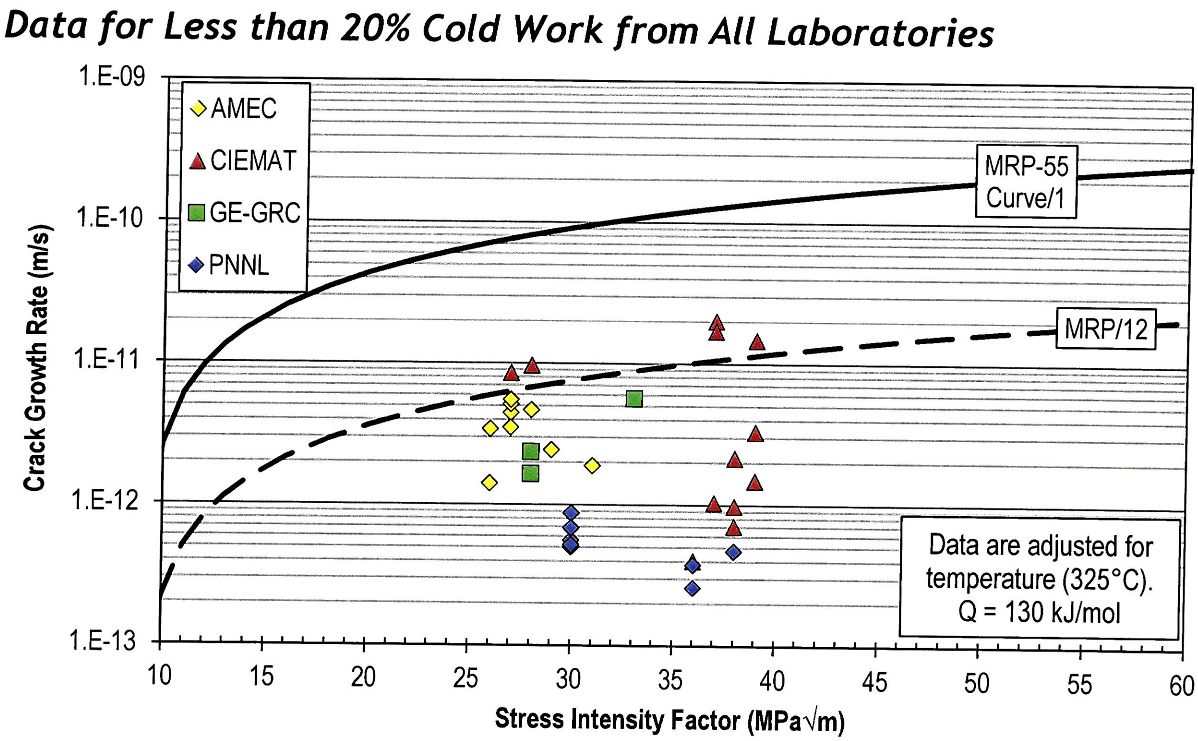

Figure 21. Plot of da/dt versus K_I for Alloy 690 Data from All Laboratories, > 10 & ≤ 20% Cold Work, CRDM and Bar Material, Constant Load or K_I Testing

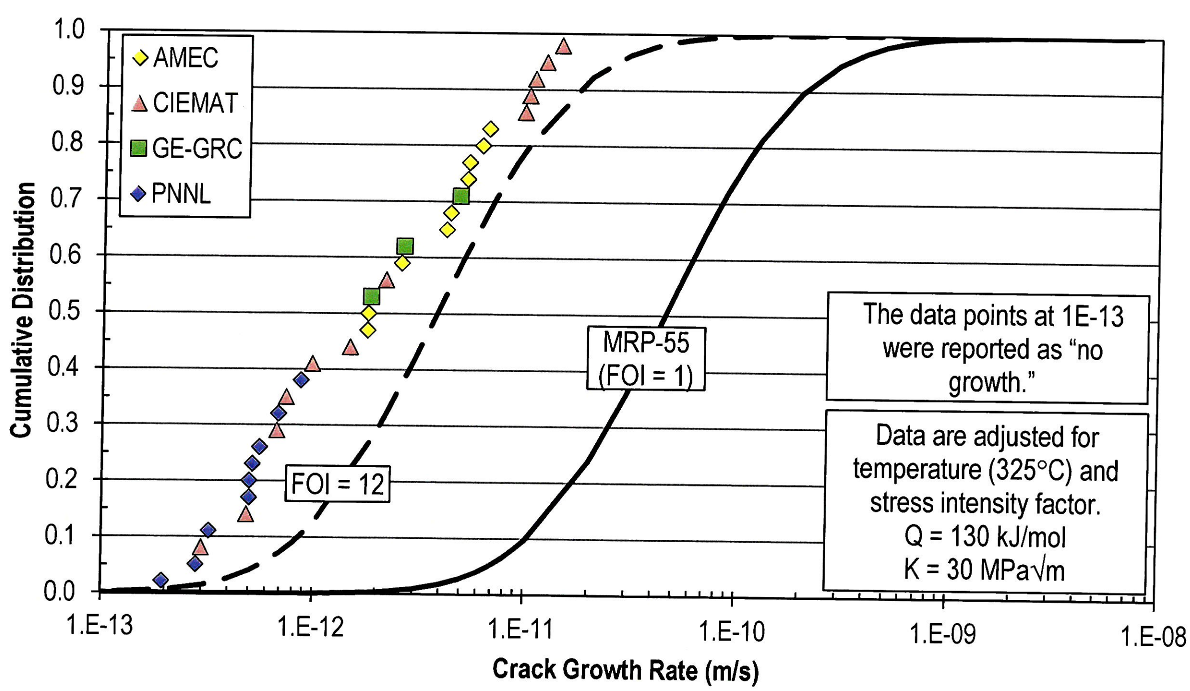

Figure 22. Cumulative Distribution Function of Adjusted da/dt Alloy 690 Data from All Labs, ≤ 20% Cold Work, CRDM and Bar Material, Constant Load or K_I

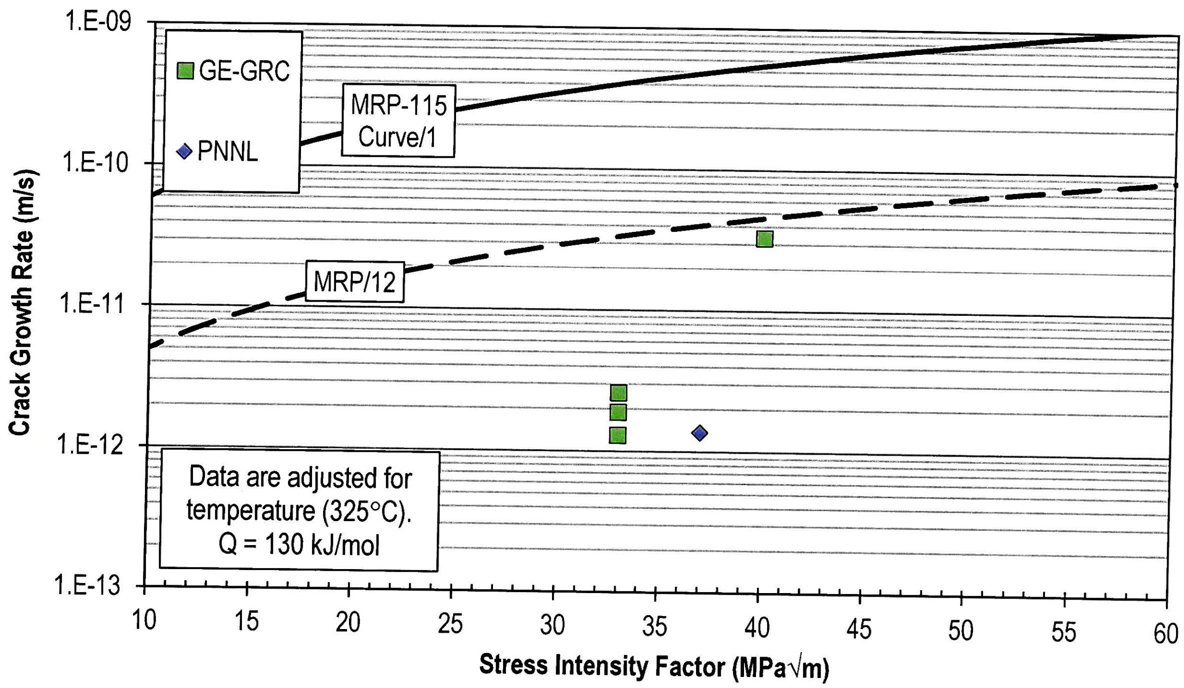

Figure 23. **Plot of da/dt versus K_I for Alloy 52/152 Data from All Laboratories, > 10 & ≤ 20% Cold Work, Constant Load or K_I**

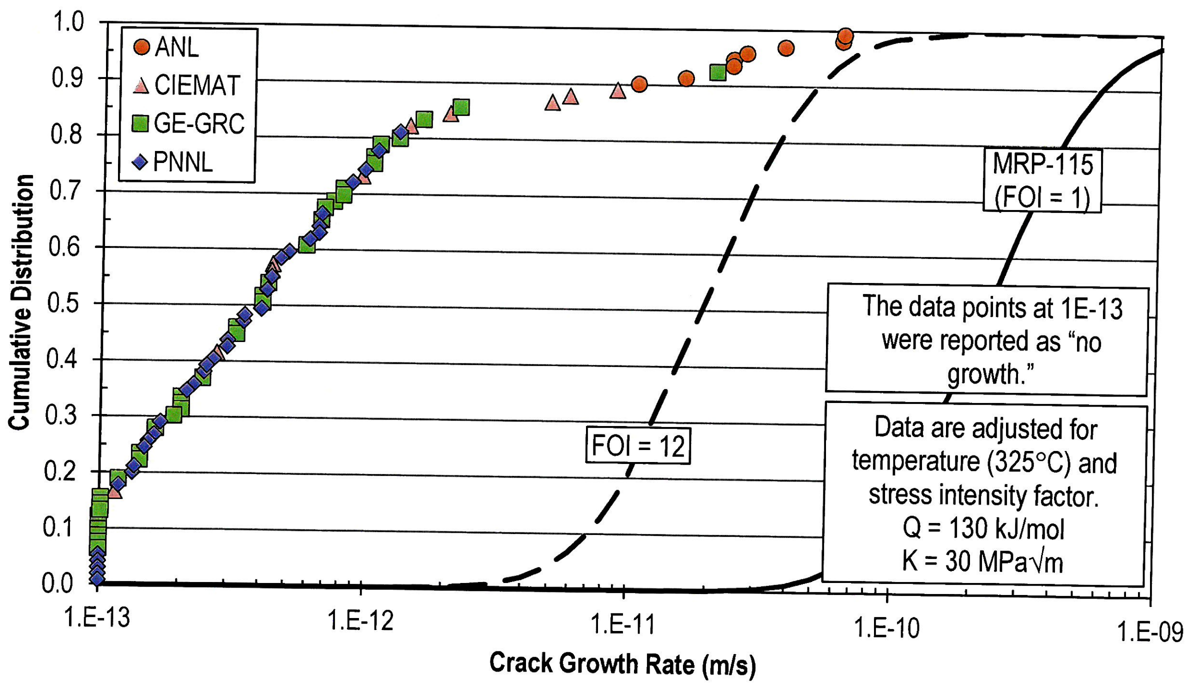

Figure 24. **Cumulative Distribution Function of Adjusted da/dt Alloy 52/152 Data from All Laboratories, ≤ 20% Cold Work, Constant Load or K_I**