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

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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 (75th 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 75th 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

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 (≤ 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 75^{th} 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 75^{th} 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

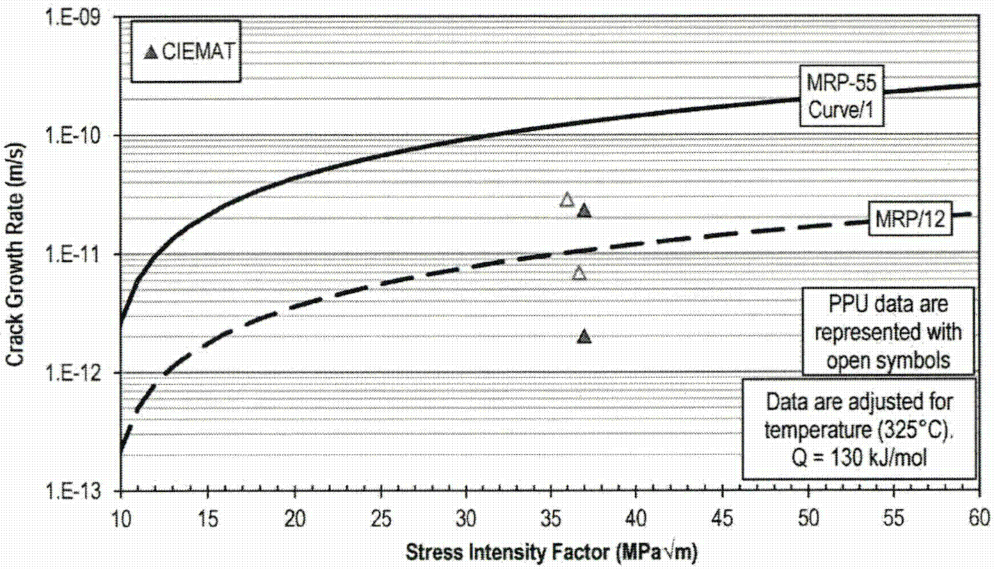

Figure 1. Plot of Crack Growth Rate (da/dt) versus Stress Intensity Factor (K_I) for Alloy 690 Data from Plate Material Tested by CIEMAT

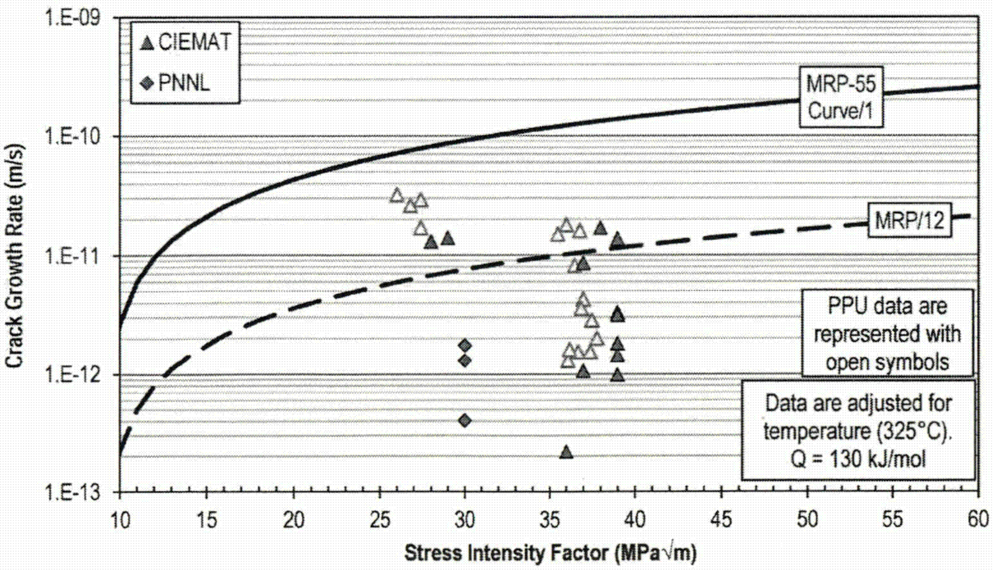

Figure 2. Plot of da/dt versus K_I for Alloy 690 Data from Heat WP787

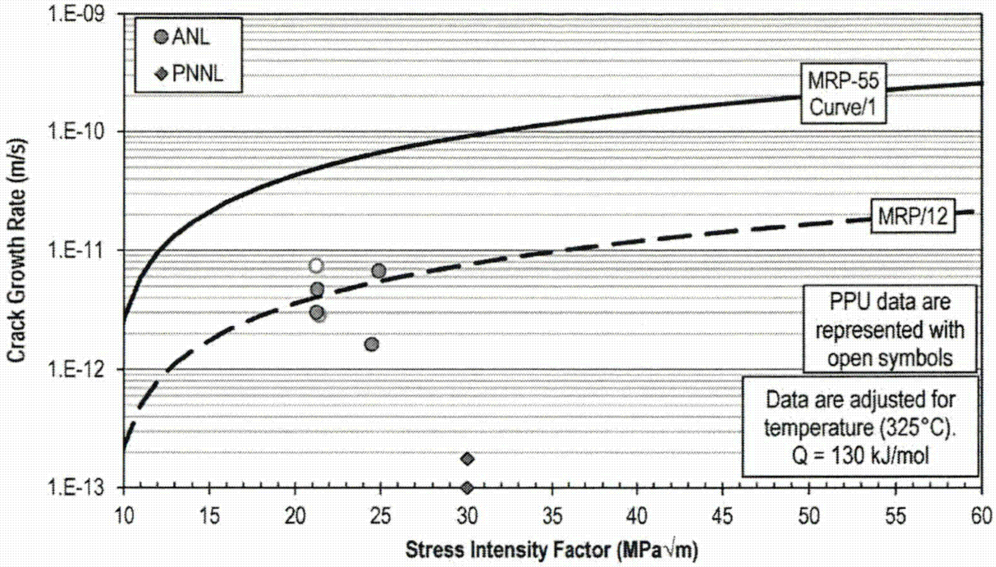

Figure 3. Plot of da/dt versus K_I for Alloy 690 Data from Heat WP142

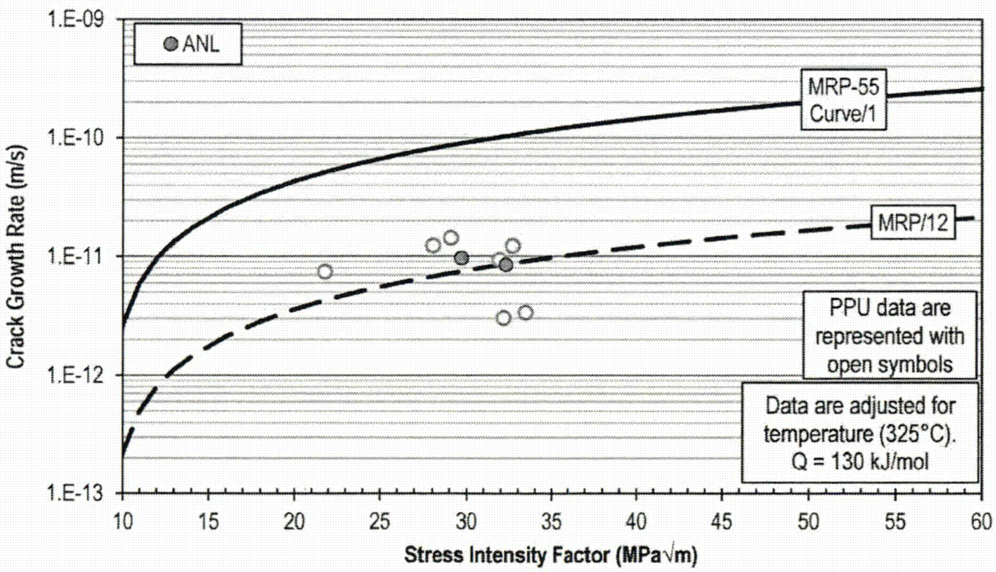

Figure 4. Plot of da/dt versus K_I for Alloy 690 HAZ Data from Heat WP142

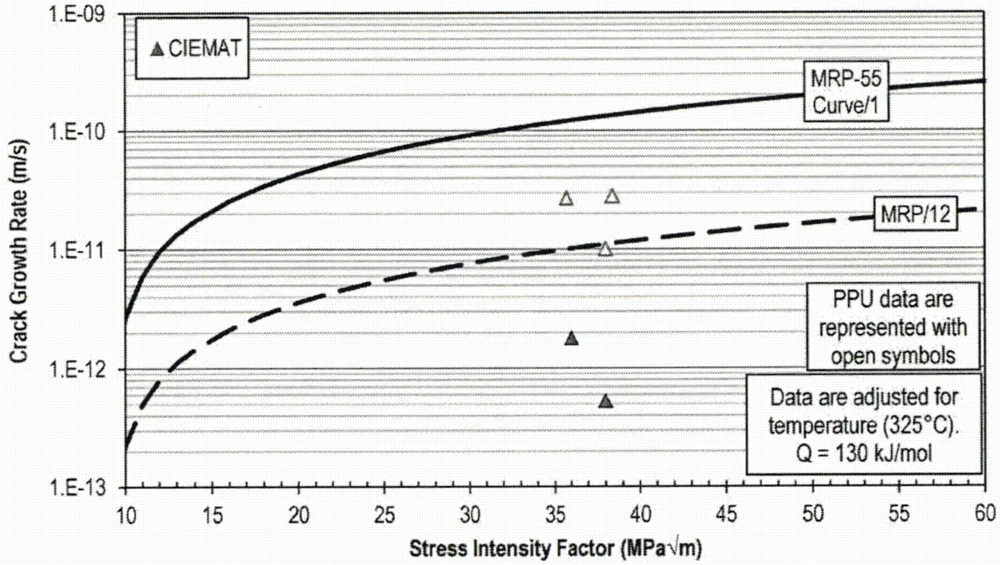

Figure 5. Plot of da/dt versus K_I for Alloy 690 HAZ Data from Plate Material Tested by CIEMAT

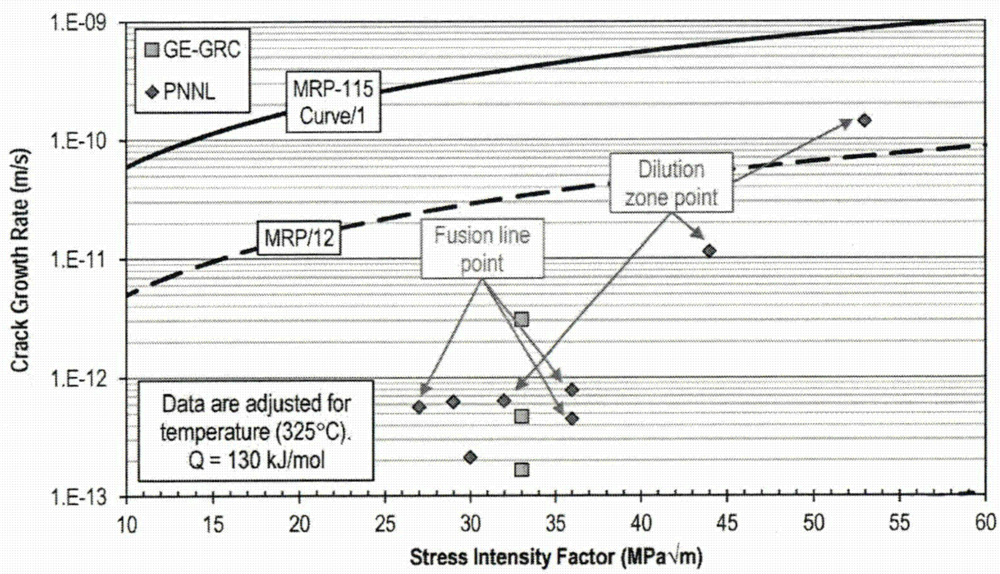

Figure 6. Plot of da/dt versus K_I for Alloy 152 Data from Heat WC83F8

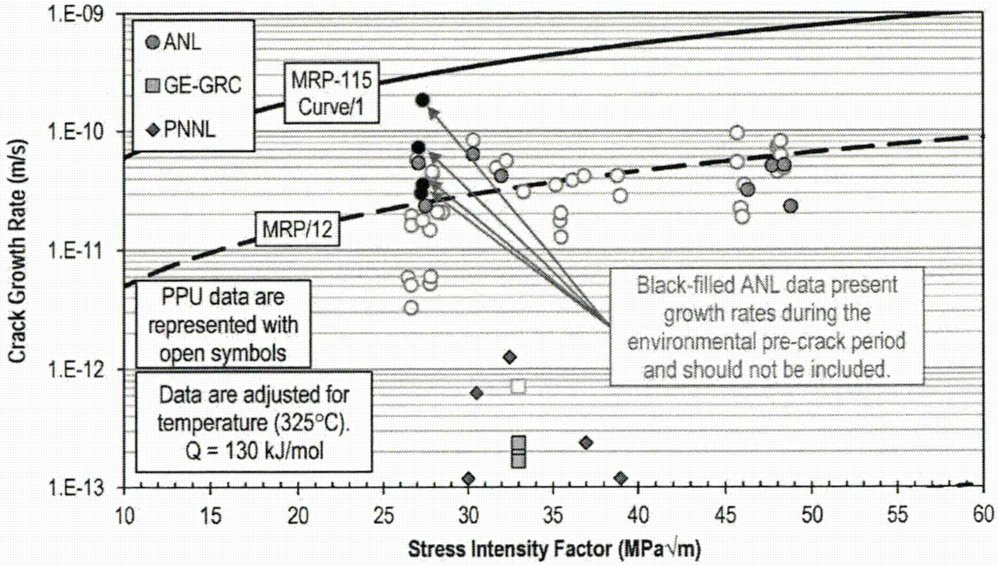

Figure 7. Plot of da/dt versus K_I for Alloy 152 Data from Heat WC04F6

Data Most Applicable to Plant Conditions

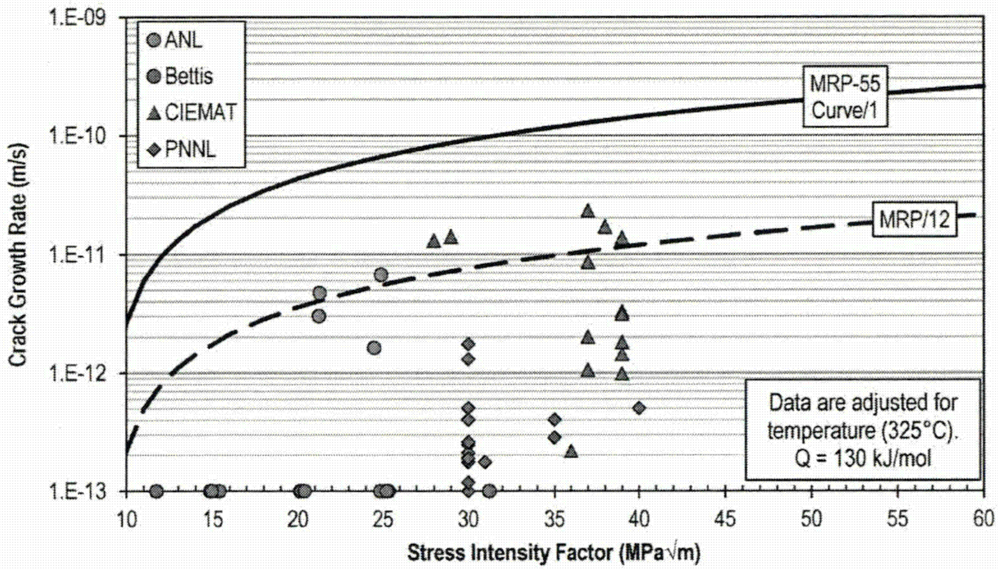

Figure 8. Plot of da/dt versus K_I for Alloy 690 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

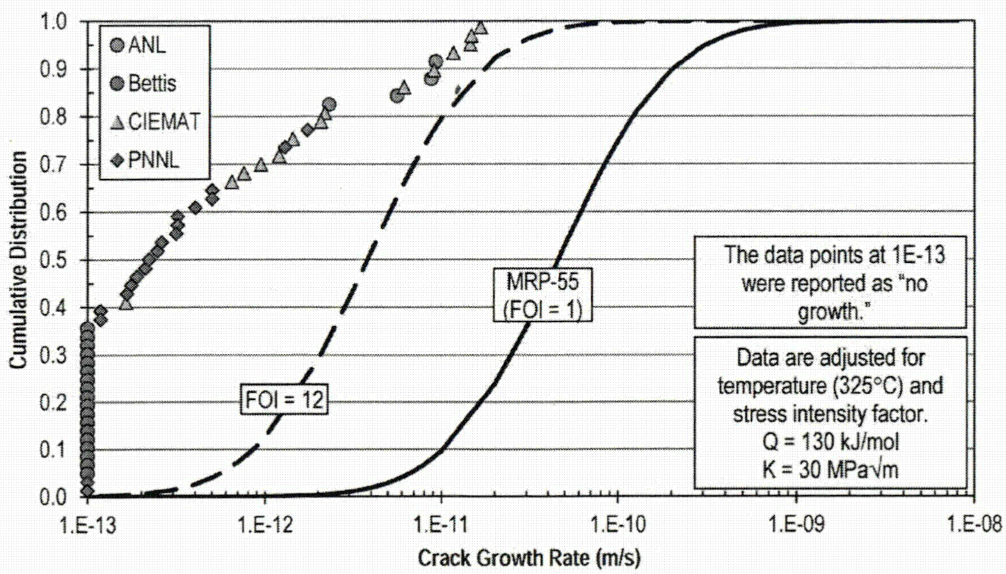

Figure 9. Cumulative Distribution Function of Adjusted da/dt for Alloy 690 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

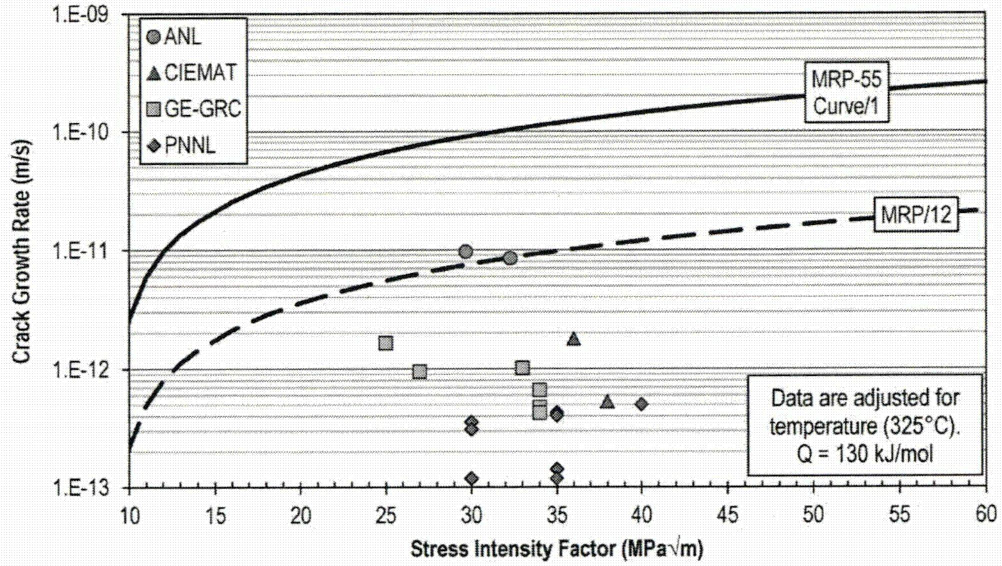

Figure 10. Plot of da/dt versus K_I for Alloy 690 HAZ Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

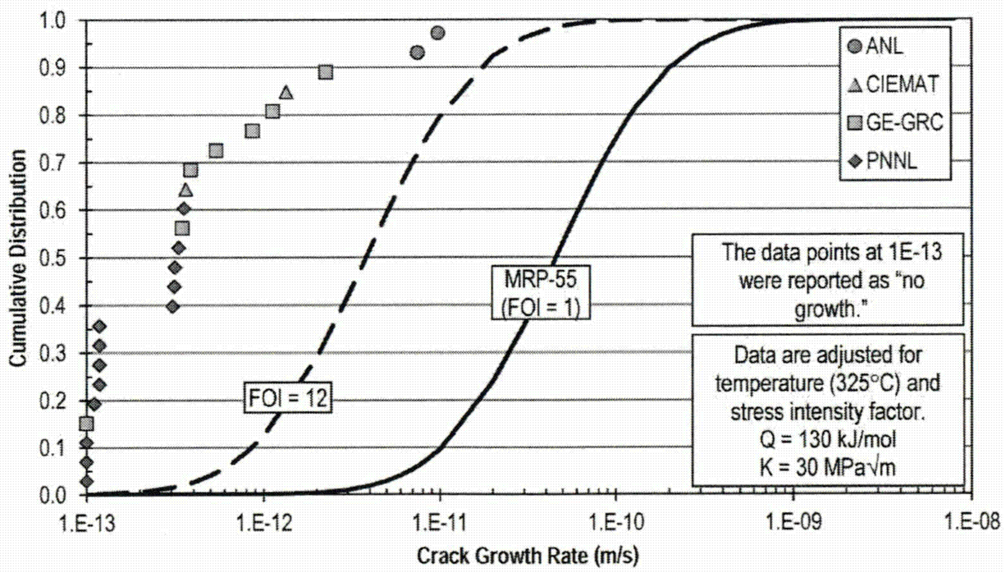

Figure 11. Cumulative Distribution Function of Adjusted da/dt for Alloy 690 HAZ Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

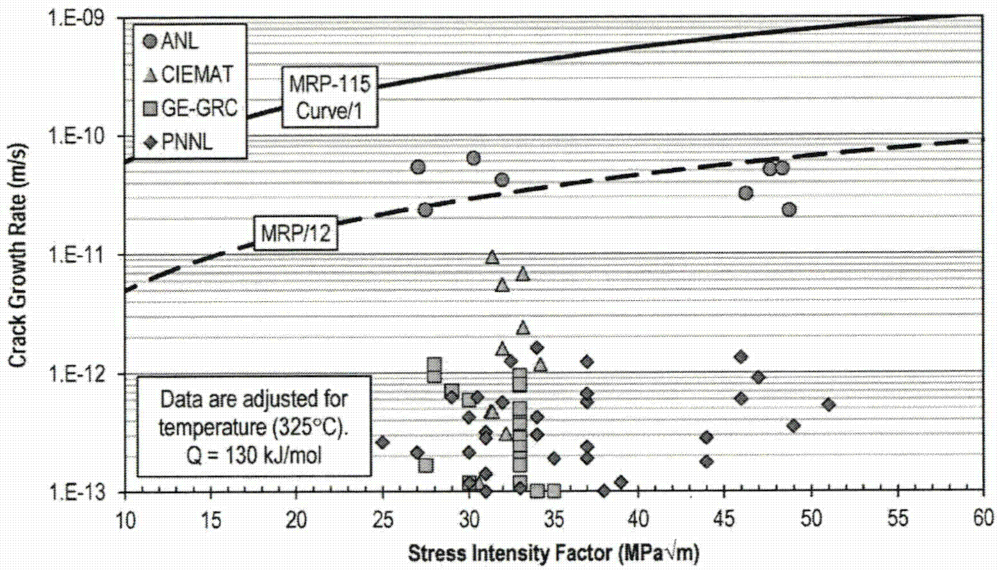

Figure 12. Plot of da/dt versus K_I for Alloy 52/152 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

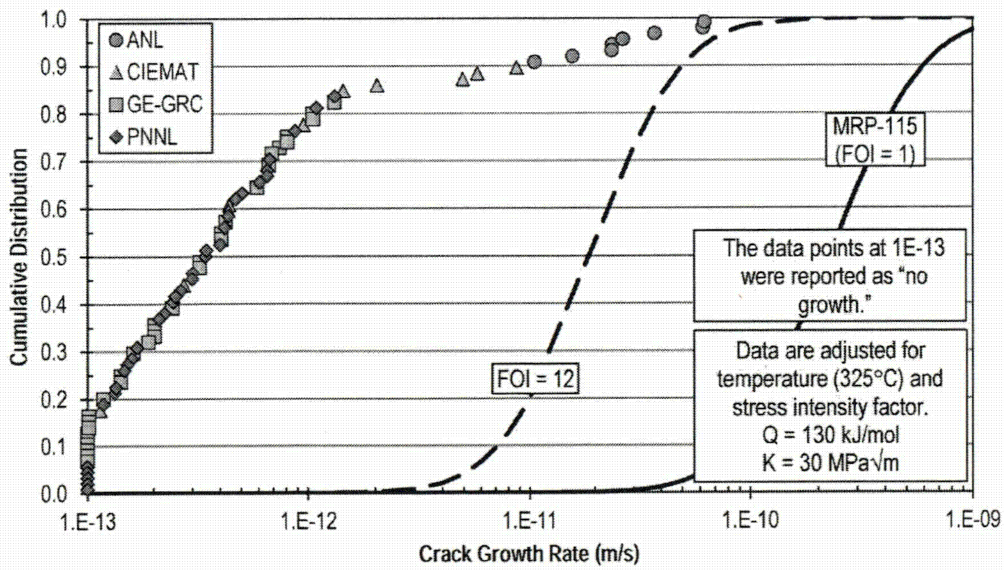

Figure 13. Cumulative Distribution Function of Adjusted da/dt for Alloy 52/152 Data from All Laboratories, ≤ 10% Cold Work, Constant Load or K_I

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

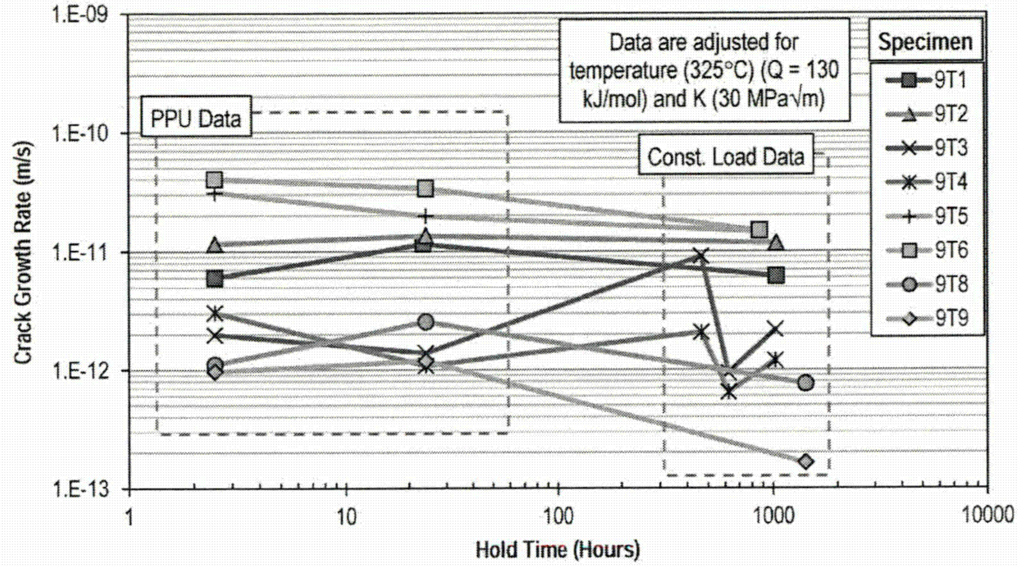

Figure 14. Plot of da/dt versus Loading Hold Time (for PPU testing) or Test Segment Duration (for Constant K_I/Load Testing) from Heat WP787

Compilation of ANL and PNNL Data

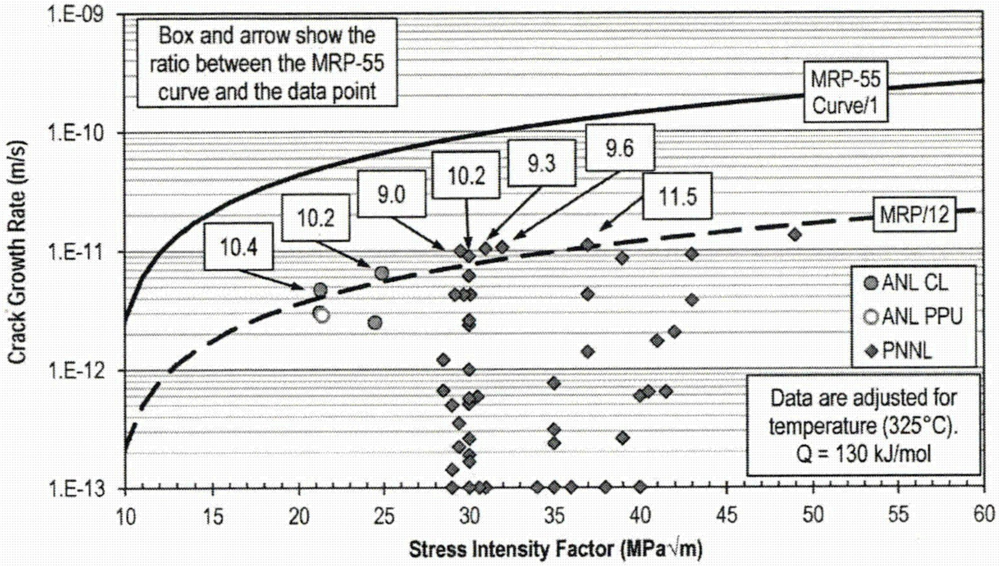

Figure 15. Plot of da/dt versus K_I for Alloy 690 Data Produced by ANL and PNNL and Available in Reference [17]; ≤ 22% Cold Work

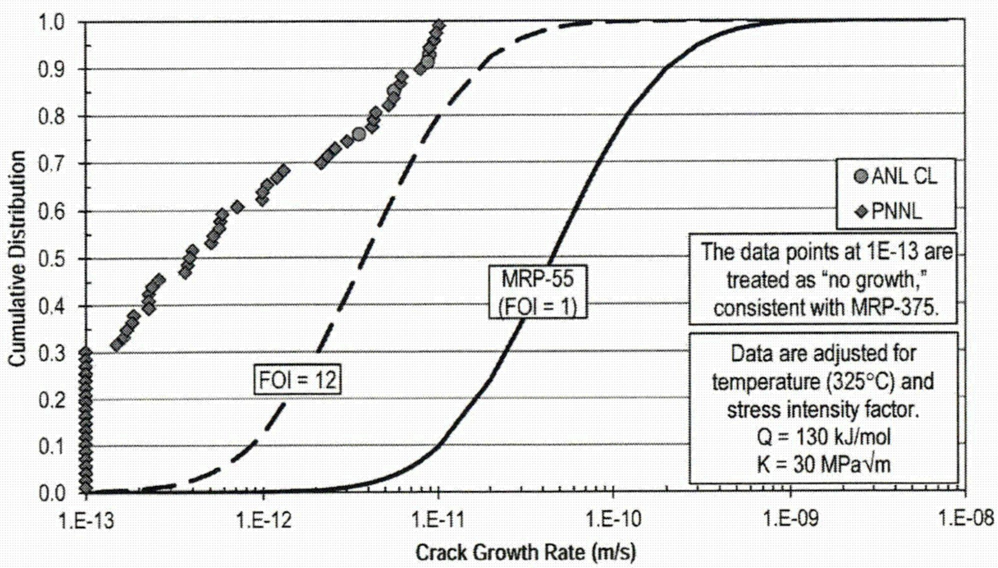

Figure 16. Cumulative Distribution Function of Adjusted da/dt Alloy 690 Data Produced by ANL and PNNL in References [17]; ≤ 22% Cold Work and Constant Load/K_I

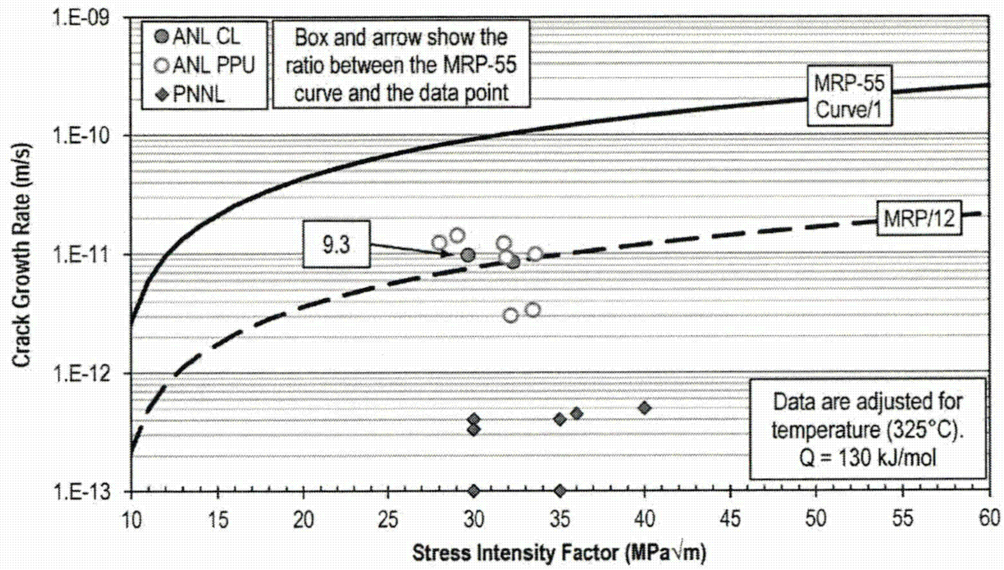

Figure 17. Plot of da/dt versus K_I for Alloy 690 HAZ Data Produced by ANL and PNNL and Available in Reference [17]; ≤ 22% Cold Work

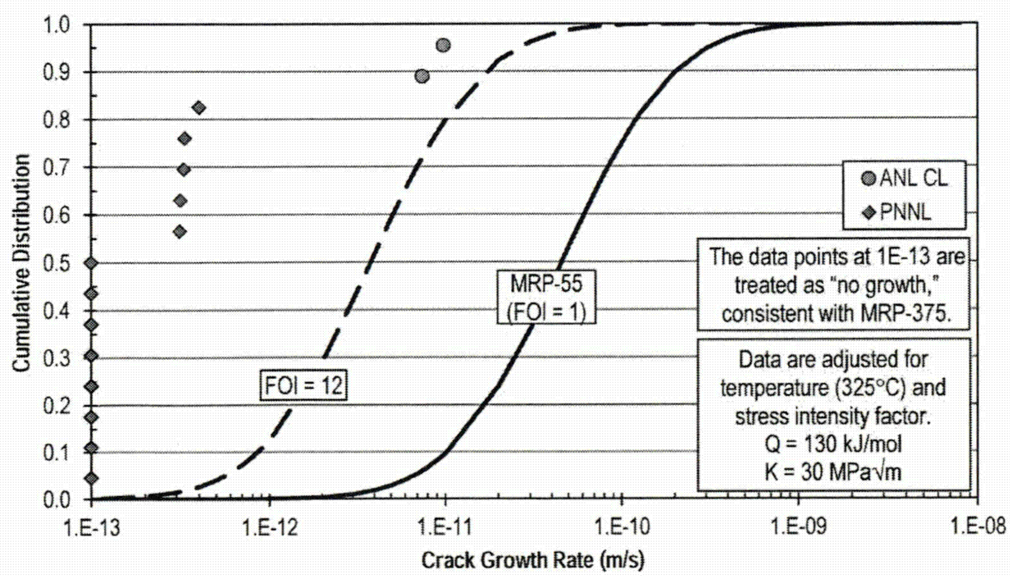

Figure 18. Cumulative Distribution Function of Adjusted da/dt Alloy 690 HAZ Data Produced by ANL and PNNL [17]; ≤ 22% Cold Work and Constant Load/K_I

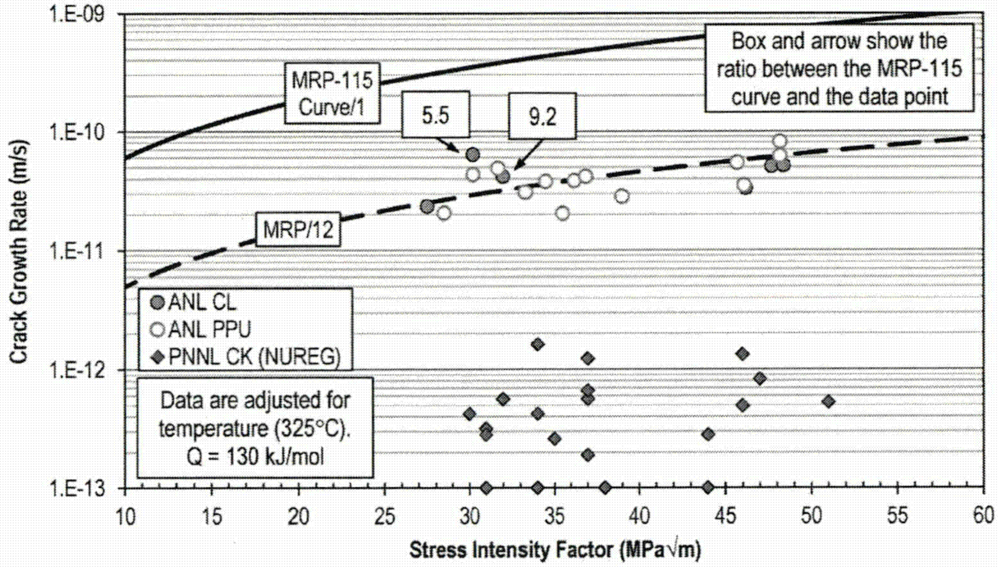

Figure 19. Plot of da/dt versus K_I for Alloy 52/152 Data Produced by ANL and PNNL and Available in References [17] and [18]; ≤ 22% Cold Work

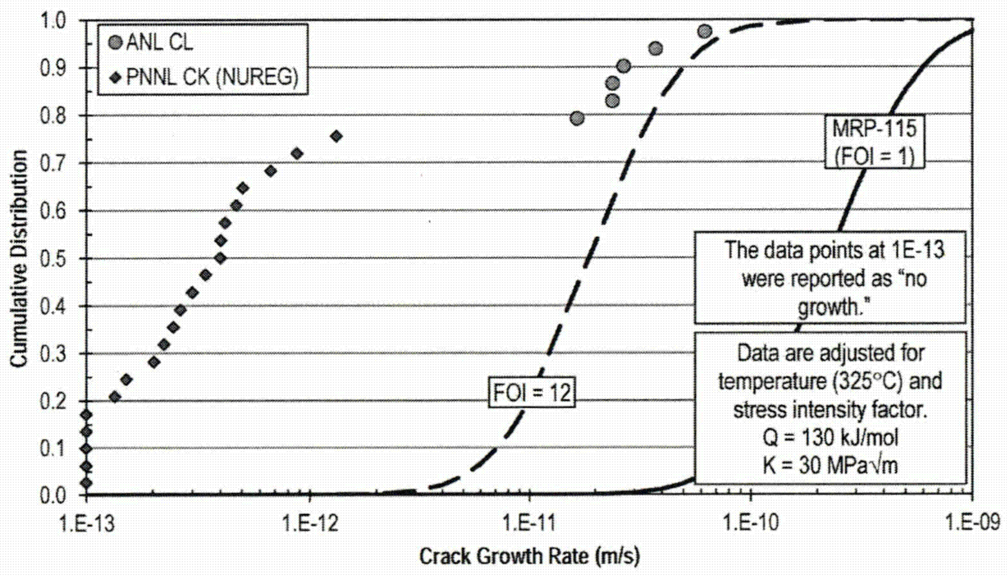

Figure 20. Cumulative Distribution Function of Adjusted da/dt Alloy 52/152 Data Produced by ANL and PNNL ([17] and [18]); ≤ 22% Cold Work and Constant Load/K_I

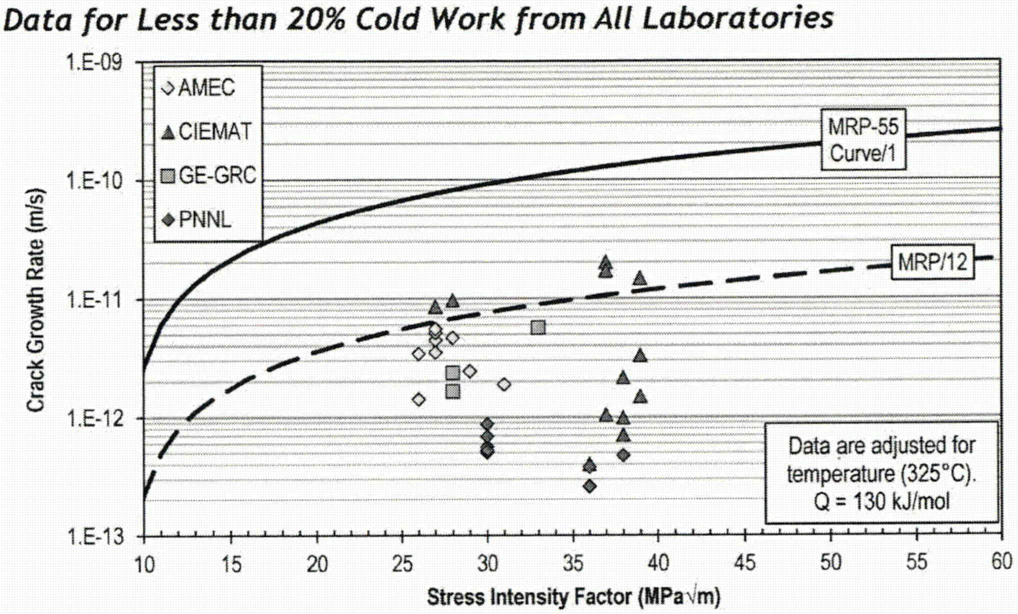

Figure 21. Plot of da/dt versus K_I for Alloy 690 Data from All Laboratories, > 10 & ≤ 20% Cold Work, CRDM and Bar Material, Constant Load or K_I Testing

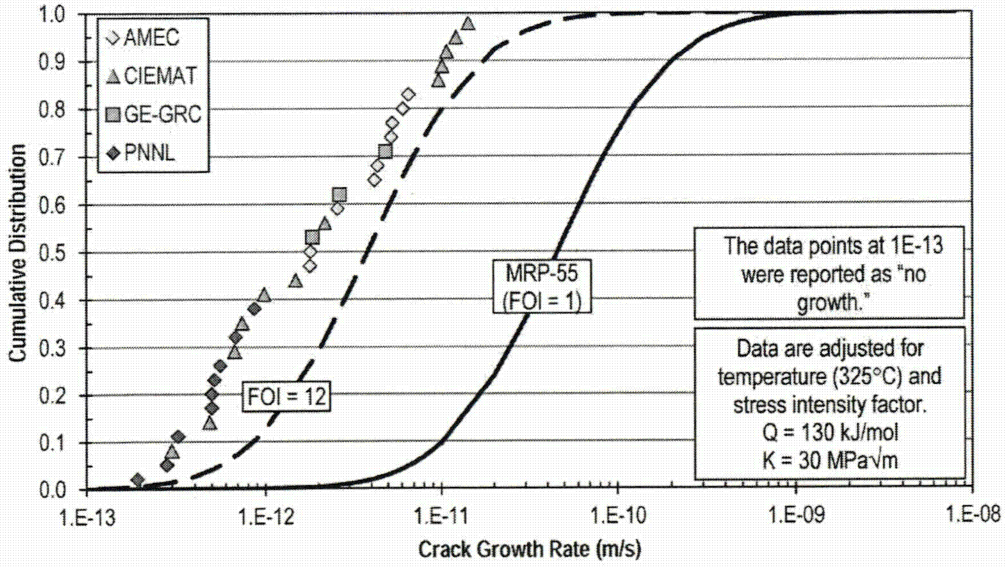

Figure 22. Cumulative Distribution Function of Adjusted da/dt Alloy 690 Data from All Labs, ≤ 20% Cold Work, CRDM and Bar Material, Constant Load or K_I

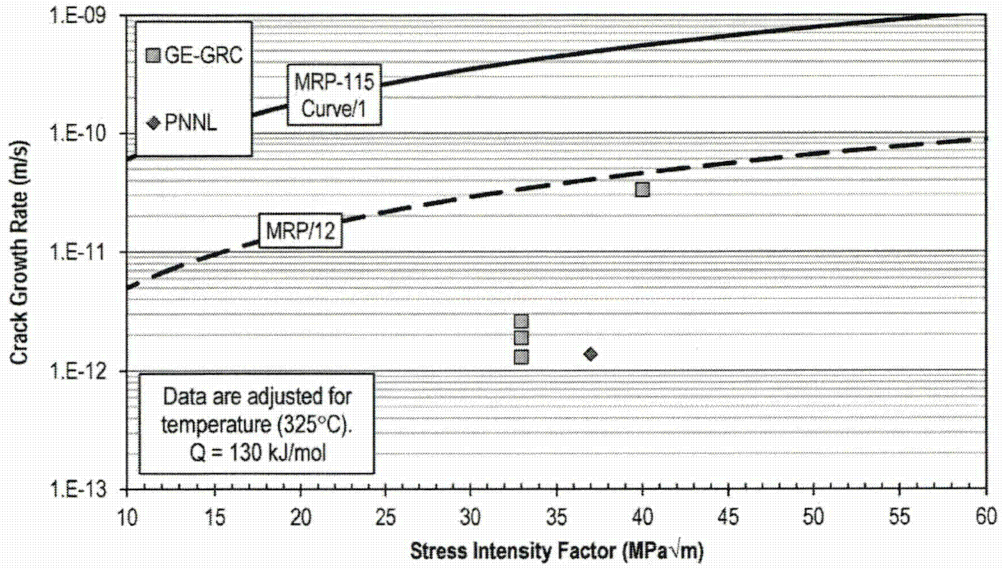

Figure 23. Plot of da/dt versus K_I for Alloy 52/152 Data from All Laboratories, > 10 & ≤ 20% Cold Work, Constant Load or K_I

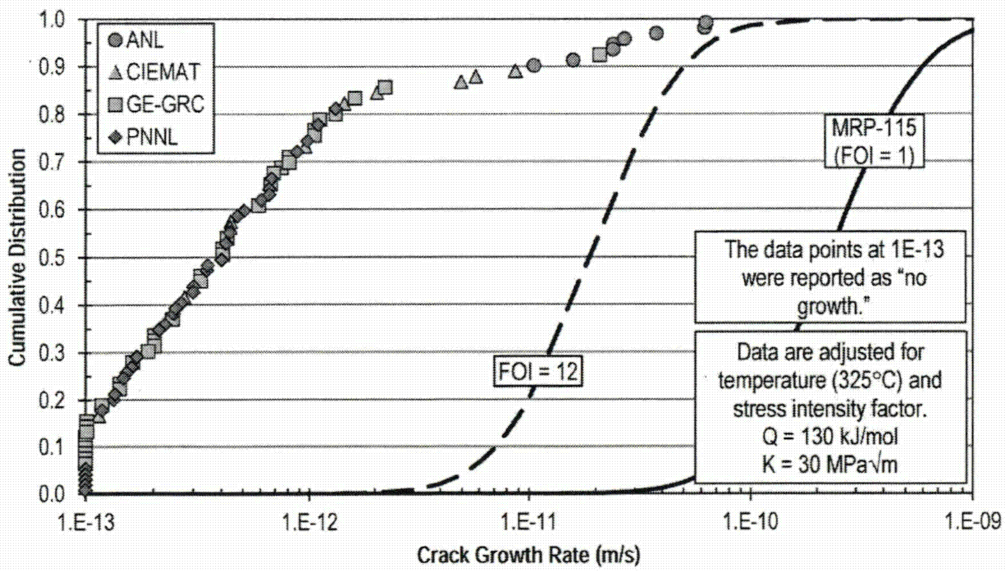

Figure 24. Cumulative Distribution Function of Adjusted da/dt Alloy 52/152 Data from All Laboratories, ≤ 20% Cold Work, Constant Load or K_I