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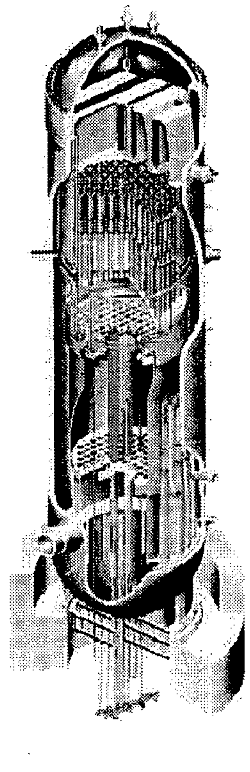
BWRVIP-138NP, Revision 1: BWR Vessel and Internals Project

Updated Jet Pump Beam Inspection and Flaw Evaluation Guidelines



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1016574NP

Final Report, January 2009

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This report is based on the following previously published report:

BWRVIP-138: BWR Vessel and Internals Project, Updated Jet Pump Beam Inspection and Evaluation Guidelines. EPRI, Palo Alto, CA: 2004. 1008213, authored by GE-Hitachi.

REPORT SUMMARY

This report, a revision to BWRVIP-138 (EPRI Report 1008213) provides updated inspection guidelines for boiling water reactor (BWR) jet pump holddown beams designed by General Electric. This report is intended to supplement the previous recommendations of BWRVIP-41, Revision 1: *BWR Vessel and Internals Project, BWR Jet Pump Assembly Inspection and Flaw Evaluation Guidelines*. EPRI, Palo Alto, CA: 2005 (EPRI report 1012137).

Background

In January 2002, Quad Cities Unit 1 (GE BWR/3) experienced a failure of the No. 20 jet pump beam. The beam was of the BWR/3 design and was fabricated from X-750 in the equalized and aged condition. Analysis of the failed beam confirmed that the failure mechanism was intergranular stress corrosion cracking (IGSCC), consistent with past beam failures. This failure was significant in that it occurred in the tapered region of the beam, and inspection of this region was not included in the recommendations of BWRVIP-41, Revision 0. It was concluded that although the stress in the tapered region is much lower than the bolt hole and transition (arm) locations, IGSCC in the tapered region is possible. Consequently, inspection requirements needed to be defined for the tapered region of the beam. As a result of this failure, BWRVIP-41, Revision 0 was revised to include inspection of the BB-3 region. However, since water chemistry plays a key role in the IGSCC process, inspection intervals also needed to be established for both normal water chemistry (NWC) and effective hydrogen water chemistry (HWC).

Objectives

To develop an updated inspection strategy for jet pump beams to assure continued integrity of jet pump safety functions and to maintain the design basis.

Approach

Investigators compiled and evaluated information on jet pump beam design and configurations, field experience with cracking, and inspection capabilities. They performed stress and fracture mechanics analyses to determine critical flaw sizes for demonstrating nondestructive evaluation (NDE) techniques and for establishing appropriate inspection intervals. Researchers also investigated the benefits of crack mitigation in a HWC environment.

Results

Revised inspection intervals are presented for the Group 2 and the new Group 3 beam designs. The Group 3 design has lower peak stresses in the beam. The lower stresses increase the times to crack initiation and reduce the crack growth rates resulting in an increase in expected beam life and inspection intervals compared to the Group 2 beam design. The report specifies the regions required to be inspected for the bolt hole, tapered section, and beam ends. In the tapered section of the beam, a region has been established in which flaws are acceptable without repair for an additional cycle of operation.

EPRI Perspective

The specific safety functions of the jet pump assembly are to maintain the ability to reflood the reactor to two-thirds core height in an accident scenario and, for some plants, to provide a path for Low Pressure Coolant Injection (LPCI) to the core. The inspection recommendations in this report will assure that jet pump beam integrity is maintained.

Keywords

Boiling water reactor
Flaw evaluation
Jet pump assembly
Inspection strategy
Stress corrosion cracking
Vessel and internals

EXECUTIVE SUMMARY

The purpose of this report is to provide background understanding and to update the inspection guidelines for all of the jet pump holddown beam designs. This report is intended to supplement the previous recommendations of "BWRVIP-41, Revision 1: *BWR Vessel and Internals Project, BWR Jet Pump Assembly Inspection and Flaw Evaluation Guidelines.* EPRI, Palo Alto, CA: 2005. 1012137.

The report first describes the beam types installed in the plants, and provides a discussion for each beam type in regards to applied loading, as well as intergranular stress corrosion cracking (IGSCC) susceptibility. In addition, the probability of a beam failure is developed. Beam field experience is documented and used as the basis for defining inspection regions. The inspection techniques applicable to each region are presented, as well as defining the recommended inspection area.

Fracture mechanics techniques are applied to the holddown beam, in order to evaluate an acceptable flaw size, given the normal capabilities of the non-destructive examination techniques. This allowable flaw size is correlated with current understanding of Alloy X-750 IGSCC crack growth behavior in order to develop the recommended inspection intervals for normal and hydrogen water chemistry conditions.

RECORD OF REVISIONS

Revision Number	Revisions
BWRVIP-138	Original Report (1008213)
BWRVIP-138 Revision 1	BWRVIP-138 was revised to incorporate the results of comprehensive fracture mechanics evaluations performed on Group 2 and Group 3 jet pump beam designs. The evaluation established flaw tolerances of the jet pump beam designs upon which revised inspection intervals are based. All changes, except corrections to typographical errors, are marked with margin bars in the main report. Appendices A and B have been added to this report and are not marked with revision bars. Details of the revision can be found in Appendix C.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION AND BACKGROUND

1.1 Background

The BWR Vessels and Internals Project (BWRVIP) has issued an Inspection and Evaluation (I&E) Guideline for the jet pump assembly, "BWR Jet Pump Assembly Inspection and Flaw Evaluation Guidelines (BWRVIP-41, Revision 0)," EPRI TR-108728, October 1997 [1]. The scope of the guideline included all of the jet pump assembly locations and components. Based on susceptibility discussions, two regions of the jet pump beam were identified as recommended inspection locations. The two regions were the bolt hole region ('BB-1') and the transition region ('BB-2'). These regions were determined based on field experience and stress considerations, and included three styles of jet pump beams: (1) BWR/3; (2) BWR/4-6 (Group 1); and BWR/4-6 (Group 2).

In January 2002, Quad Cities Unit 1 (GE BWR/3) experienced a failure of the No. 20 jet pump beam. The beam was of the BWR/3 design, and was fabricated from X-750 in the equalized and aged condition. Analysis of the failed beam confirmed that the failure mechanism was IGSCC, consistent with past beam failures. This failure was significant in that it occurred in the tapered region of the beam, and inspection of this region was not included in BWRVIP-41, Revision 0. The beam evaluation was expanded to other beams removed from Quad Cities 1 and 2, and some of these beams were found to contain IGSCC indications in the tapered region as well. It was concluded that although the stress in the tapered region is much lower than the bolt hole and transition (arm) locations, IGSCC in the tapered region is possible. Consequently, inspection requirements, based upon fracture mechanics, need to be defined for the tapered region of the beam. As a result of this failure, BWRVIP-41, Revision 0 was revised to include inspection of the BB-3 region. Since water chemistry plays a key role in the IGSCC process, the inspection intervals also need to be established for normal water chemistry (NWC) and effective hydrogen water chemistry (HWC).

It was also recognized that jet pump beam designs in service varied from plant to plant and the earlier BWRVIP-41, Revision 0 report did not provide sufficient detail on the key design parameters, heat treatments and stress state, nor did it include the new GE holddown beam design.

1.2 Objectives and Scope

This report presents generic inspection and evaluation guidelines to assure continued integrity of the jet pump beam. The guidelines presented are supported by comprehensive fracture mechanics evaluation of the Group 2 and Group 3 jet pump beam designs. These evaluations were performed to establish the flaw tolerance of the designs currently installed in the BWR fleet. The flaw tolerances were used to determine the jet pump beam re-inspection intervals.

The specific safety functions of the jet pump assembly are to maintain the ability to reflood the reactor to 2/3 core height in an accident scenario, and for some plants, to provide a path for Low Pressure Coolant Injection (LPCI) to the core. It is the intent that, for BWRVIP members, this Guideline can be followed in place of the prior GE Service Information Letters (SILs) to assure the essential safety functions of the jet pumps (of which the beam bolt is an essential part).

This report includes the following:

- A discussion of the different jet pump beam designs;
- A discussion of the factors affecting the susceptibility of Alloy X-750;
- A summary of the field experience with cracking in jet pump beams to better identify the locations requiring inspection;
- A thorough discussion of the inspection regions as well as the capabilities of the NDE methods for inspecting jet pump beams;
- The flaw evaluation methodology used to establish the re-inspection interval;
- The calculated flaw acceptance limits and the re-inspection intervals as a function of location and operating environment (NWC and effective HWC);
- Inspection times and re-inspection intervals for the newer jet pump beam design;
- Group 2 and Group 3 jet pump beam fracture mechanics evaluations; included as Appendices A and B, respectively.

Table 1-1 shows the plant configurations and Table 1-2 shows the beam types and dates of installation for the plants addressed in this report. Plants are advised to confirm the accuracy of these configurations to evaluate the applicability of the inspection recommendations.

The information and the associated evaluations provided in this report have been performed in accordance with the requirements of 10CFR50 Appendix B.

Table 1-1
Plant Configurations Evaluated

Plant Type	Plant Name
BWR/3	Dresden 2/3, Monticello, Pilgrim, Quad Cities 1/2, and Santa Maria de Garoña
BWR/4	Browns Ferry 1/2/3, Brunswick 1/2, Chinshan 1/2, Cooper, Duane Arnold, Fermi 2, FitzPatrick, Hatch 1/2, Hope Creek, KKM, Limerick 1/2, Peach Bottom 2/3, Susquehanna 1/2, Vermont Yankee
BWR/5	Columbia, Laguna Verde 1/2, LaSalle 1/2, Nine Mile Point 2
BWR/6	Clinton, Cofrentes, Grand Gulf, KKL, Kuosheng 1/2, Perry, River Bend

Table 1-2
Beam Installation Information (as of 6/1/2004)

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1.3 Implementation Requirements

In accordance with the requirements of Nuclear Energy Institute (NEI) 03-08, Guideline for Management of Material Issues, Section 4.3, Tables 7-1 and 7-2 of this report are "needed" and the remaining sections are for information only. The jet pump beam re-inspection guidance contained in this report supersedes previously documented BWRVIP guidance contained in preceding versions of BWRVIP-41: "BWR Vessel and Internals Project, BWR Jet Pump Assembly Inspection and Flaw Evaluation Guidelines".

2
BEAM SUSCEPTIBILITY

2.1 Jet Pump Beam Design and Configurations

The GE jet pump beam design has evolved since the original installation in BWR/3 plants. Although Alloy X-750 has been used exclusively since original installation, the heat treatment and dimensions have changed significantly. The basic designs are described in the following paragraphs. The BWR/3 design is included for historical interest. Since the BWR/4-6 design is interchangeable with the BWR/3 design, all BWR/3 replacement beams are of the newer designs.

2.1.1 BWR/3 Beam Design

The BWR/3 beam design was fabricated from a closed-die forging of Alloy X-750 material. The beams were subsequently equalized at 1625°F (885°C) for 24 hours, followed by aging at 1300°F (704°C) for approximately 20 hours. This heat treatment condition was referred to as 'equalized and aged'. Since the process used a closed die forging to achieve near net shape, only portions of the beam (the bolt hole region and the transition region) were machined. Most of the beam surface, including the tapered region, was left in the as-forged condition, although subsequent grinding of the surface was required by the fabrication drawing. Prior to final assembly, the beam was liquid penetrant examined. At the time of the publication of this report, no BWR/3 beams remain in service. Figure 2-1 shows the BWR/3 beam assembly.

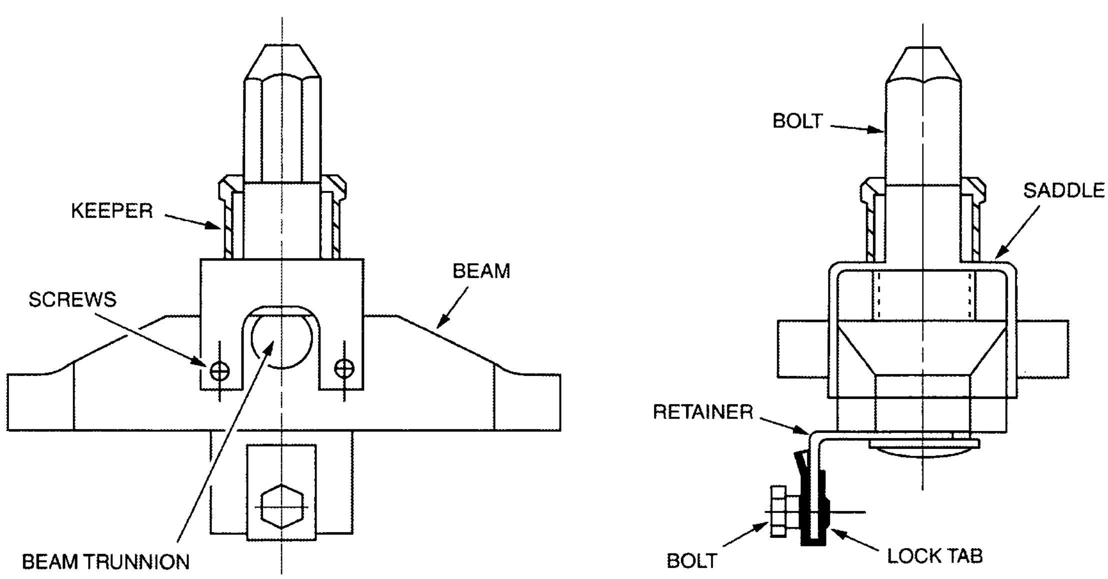

Figure 2-1
BWR/3 Beam Bolt Assembly

2.1.2 BWR/4-6 Beam Design – Group 1 (G001)

The Group 1 BWR/4-6 design beams used the same material and heat treatment as the BWR/3 design, and were also fabricated from closed die forgings. Similar to the BWR/3 design, the surfaces of the beam were both as-forged and machined. The final beam surfaces were also examined by liquid penetrant prior to final assembly. The major change in the beam design was dimensional - the beam depth increased from 2.02 to 2.30 inches (51.3 to 58.42 mm). In addition, the installation preload was increased from 25 to 30 kips (111 kN to 133 kN). At the time of the publication of this report, no G001 beams remain in service. Figure 2-2 shows the Group 1 BWR/4-6 beam assembly.

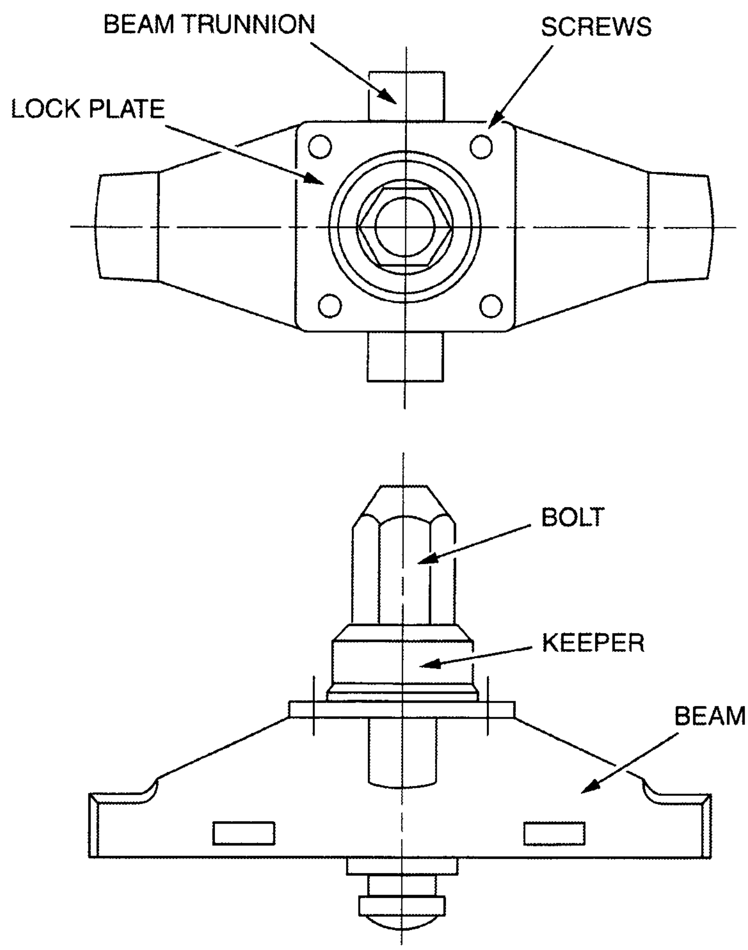

Figure 2-2
BWR/4-6 Beam Bolt Assembly (Groups 1 and 2)

2.1.3 BWR/4-6 Beam Design – Group 2 (G002)

As a result of the failures of the equalized and aged beams (see Section 3), the heat treatment of the beam material was changed. The heat treatment consisted of solution annealing at 2000°F (1093°C) for 1-2 hours, followed by water quench and then by aging at 1300°F (704°C) for approximately 20 hours. This heat treatment is referred to as the 'high temperature anneal and aged' (HTA). The change to the HTA heat treatment was combined with a reduced preload, from 30 kips to 25 kips (133 to 111 kN). The initial beams were manufactured from closed die forgings, with the attendant combination of machined and as-forged surfaces, followed by liquid penetrant examination of the final beam surfaces. Beginning in 1994, some of the Group 2 beams were supplied as open-die forgings and as a result were machined on all surfaces, removing any as-forged surfaces. Liquid penetrant examination of final machined surfaces was also performed. Another change that occurred in 1994 was the addition of a baseline inspection by ultrasonic techniques (UT) of the BB-1 and BB-2 regions prior to installation, as a result of the beam failure at Grand Gulf (see Section 3). Since the Group 1 and Group 2 beams are dimensionally identical, Figure 2-2 also includes the configuration of the Group 2 beam assembly.

2.1.4 BWR/4-6 Beam Design – Group 3 (G003)

Group 3 beams were introduced in 2001. The beam is fabricated from an "open die" bar forging. The beam is machined on all surfaces and subsequently liquid penetrant examined. The rectangular bar forging is fabricated from Alloy X-750 with the "HTA" heat treatment. The material is tested in accordance with MIL-DTL-24114F (the 'rising load test') as specified in BWRVIP-84 [2]. This beam-bolt assembly also incorporates a "ratchet" lock plate and keeper in place of the tack welded keeper used in the previous beam-bolt assembly designs. The beam has been made thicker in the center and the ends to reduce the mean stress in the beam after installation. Figure 2-3 shows the configuration of the Group 3 beam assembly.

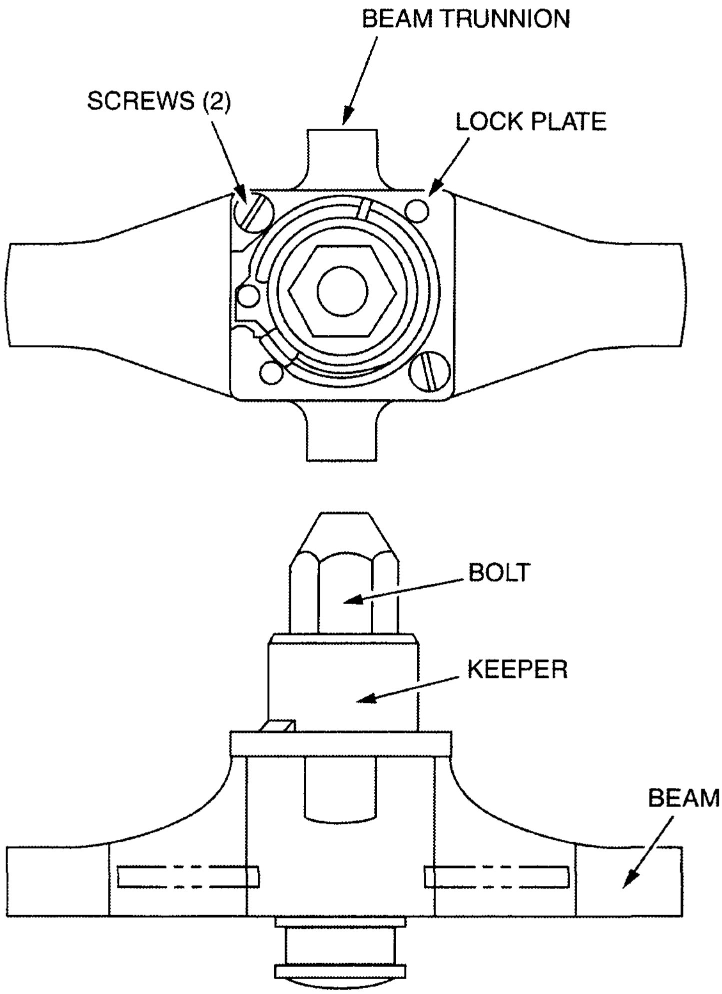

Figure 2-3
BWR/4-6 Beam Bolt Assembly (Group 3)

2.2 IGSCC Considerations

As described in BWRVIP-41, Revision 1 [17], the only significant failure mechanism associated with the jet pump beam is intergranular stress corrosion cracking (IGSCC). IGSCC is dependent on three factors: (1) tensile stress (applied or residual); (2) material; and (3) aggressive environment.

2.2.1 Environment

Under normal water chemistry (NWC) conditions, the environment in the annulus region is highly oxidizing in all BWRs. Radiolysis model calculations predict that the environment has a significant concentration of H_2O_2. Both the initiation and growth of cracks will be promoted by the high electro-chemical potential (ECP) that exists in the annulus region under NWC conditions.

Effective hydrogen water chemistry (HWC) reduces the amount of oxidizing species in the water, and hence, the ECP. This lowering of ECP is expected to result in an increase in time of initiation of cracking, as well as a reduction in crack growth rate (see Section 6.1 for more details on crack growth rate).

2.2.2 Material

All of the jet pump beams have been fabricated from Alloy X-750, although there are two types of heat treatments. BWR/3 and Group 1 beams received the EQA heat treatment, and the Group 2 and 3 beams received the HTA heat treatment. The EQA condition is known to be susceptible to IGSCC initiation and growth in the BWR environment. As described in Section 3, there have been several failures of beams in the EQA condition, including the recent Quad Cities failure in the BB-3 region.

The HTA condition was found to be more resistant to IGSCC initiation than the EQA condition under the same loading conditions. However, test data [3] indicate that the material will fail by IGSCC eventually; the major contributor is the applied stress. Therefore, as the beam age increases, the probability of IGSCC initiation increases.

2.2.3 Stress

As discussed in the previous section, the applied stress on the beam is a major contributor to determining the time to IGSCC failure. The various beam designs have different applied stresses, as shown in Table 2-1; all are shown for a 25 kip (111 kN) preload. The probability of IGSCC initiation in the jet pump beam X-750 material increases as the applied stress increases (in a particular heat treatment condition).

Table 2-1
Comparison of Maximum Principal Stress without Thermal Relaxation

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2.3 Design Susceptibility to IGSCC

2.3.1 BWR/3 Beam Design

Beams of this design have experienced multiple failures (in both the bolt hole and tapered regions) attributed to the EQA heat treatment condition. Under NWC conditions, the material should be considered highly susceptible to IGSCC. For HWC conditions, the less oxidizing environment will increase the time to initiation, but the high stress and material condition will likely result in failure. Therefore, these beams are considered susceptible to IGSCC under all water chemistry conditions.

2.3.2 BWR/4-6 Beam Design (Group 1)

The failure of this design occurred in the beam transition region, and has been attributed to the EQA heat treatment condition. Under NWC conditions, the material should be considered highly susceptible. For HWC conditions, the less oxidizing environment will increase the time to initiation, but the high stress associated with the transition region and the susceptible material condition could result in failure. Therefore, these beams are also considered susceptible to IGSCC under all water chemistry conditions.

2.3.3 BWR/4-6 Beam Design (Group 2)

The change from the EQA to HTA heat treatment process increased the resistance of the beam to IGSCC. For normal water chemistry conditions, these beams are considered resistant to IGSCC initiation, although IGSCC has occurred under high stress conditions. Under hydrogen water chemistry conditions, the time to initiation is greater and the crack growth rate is at least a factor of 2 less than for NWC conditions (See Section 6.3).

2.3.4 BWR/4-6 Beam Design (Group 3)

This design is considered the most resistant to IGSCC of the current jet pump beam designs. The material is in the HTA condition, and the applied stress has been reduced at the transition and center bolt hole locations. The reduced applied stress results in a longer expected time to initiation, even in the NWC environment. Under hydrogen water chemistry conditions, the time to initiation is expected to be even greater and the crack growth rate is further reduced by a factor of at least 2 (See Section 6.3).

2.4 IGSCC Initiation Life

Beams that are in the EQA condition are expected to exhibit SCC initiation much earlier than beams in the HTA condition. Given the high susceptibility of the EQA condition, no initiation predictions are provided for the BWR/3 and Group 1 beams. The recommendation from GEH has been to replace Group 1 beams at the first available opportunity. (Note: this recommendation has been carried out by the entire U.S. BWR fleet.)

Laboratory data for Alloy X-750 has shown a direct dependency of the time-to-initiation on the applied stress [2, 3]. The available initiation data used to confirm this dependency was obtained under NWC conditions. While effective HWC is expected to increase the initiation time, at this point in time, the effect of HWC on crack initiation is difficult to quantify (for the effects on crack growth, see Section 5.

For beams in the HTA condition and under NWC conditions, a statistical evaluation of the Group 2 and Group 3 beams (based on applied stress) has been used to quantify the significant differences in the initiation times in the jet pump beams. Based on available data, the mean time for SCC initiation in the Group 2 beams is 40 years. Decreasing the stress ratio from 0.74 to 0.58 results in a six-fold increase in mean beam initiation time (see Table 2-2). As initiation is a statistical process, crack initiation in a small population of beams can be expected to occur somewhat earlier than the mean predicted time. To provide a high confidence (~99%) that cracking in the beam would be detected by inspection, a value of 3σ was selected to develop the appropriate inspection interval. As discussed in Section 7, the initial recommended inspection of jet pump beams should be performed within twelve years, consistent with the recommendations of BWRVIP-41, Revision 1. For Group 2 beams, the initial inspection interval (12 years) is warranted based on three factors: (1) Field experience (no beam with the 25 kip preload has experienced cracking in the first ten years); (2) Water chemistry - the crack initiation data was originally developed based on high oxygen, high conductivity water; the typical water chemistry (including HWC) provides additional margin against IGSCC initiation and (3) Early crack extension of any small initiated flaw would not affect the beam's function (see section 6).

The lower applied stress on the Group 3 beam shows an approximate factor of 6.2 increase in time to first initiation at 3σ compared to the 3σ value for the Group 2 beam; thus a longer time to the first inspection is warranted. Specifically, delaying the first inspection until 20 years or longer is consistent with the significantly longer time to initiation shown in Table 2-2.

Table 2-2
Predicted Beam IGSCC Initiation Life

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3
FIELD EXPERIENCE

Over the last twenty-five years, there have been several instances of jet pump beam cracking, with some resulting in failure. These instances can be classified by the location of the crack: those initiating in the bolt hole region of the beam (BB-1), those initiating in the transition or arm region (BB-2) where the net section is a minimum, and the most recent failure initiating in the tapered region of the beam (BB-3). An overview of the failure history is presented in the following sections, although emphasis will be placed on the recent failure associated with the tapered region.

3.1 Bolt Hole Region (BB-1)

The first two jet pump beam failures occurred in 1979 and 1980 [1, 5]. Both occurred at GE BWR/3s (which had the longest operating time) and resulted in partial ejections of the inlet mixers. The beams were of the BWR/3 design and in the equalized and aged (EQA) condition. Intergranular stress corrosion cracking (IGSCC) was determined to be the failure mechanism. Subsequent inspections at other plants revealed crack indications in additional jet pump beams. The observed IGSCC cracks initiated in the thread region and then propagated across the beam, basically following the high stress trajectory (perpendicular to the beam axis). The cracking occurred on both sides of the beam bolt hole. Figure 3-1 schematically depicts the cracking orientation found in one beam. Other observations have shown that at least one of the two cracks propagated perpendicular to the centerline of the beam for its entire path. The other crack at least started from the thread with an initial path, also perpendicular.

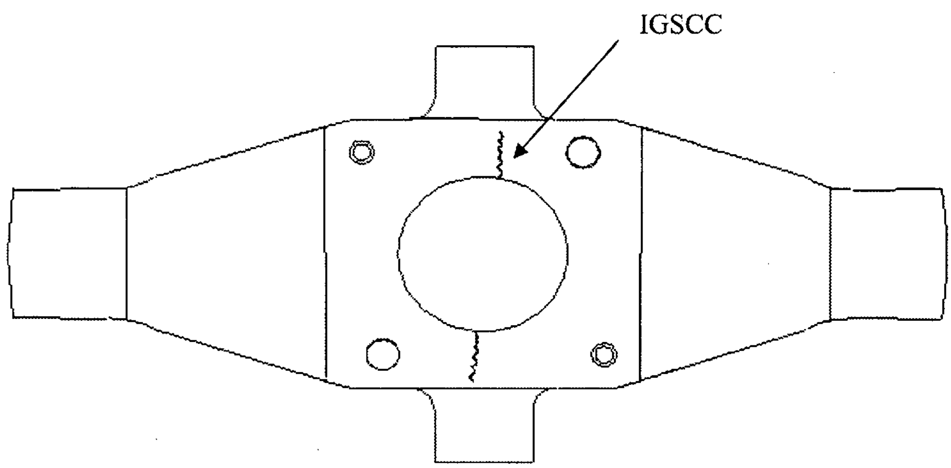


Figure 3-1
Schematic of the Typical Cracking in a BWR/3 Jet Pump Beam at the Bolt Hole Region. Cracking was Detected with UT and Confirmed Metallographically

In June 1980, GE issued the SIL No. 330 which established recommendations for utility actions including ultrasonic examinations (UT) during the next scheduled refueling outages, replacement of beams with detected indications and jet pump performance monitoring to avoid ejections without warning.

3.2 Transition Region (BB-2)

The second region of cracking was associated with the loss of a jet pump inlet mixer in a BWR/6 in September 1993 [5]. The reactor scrammed on high water level following initiation of the high pressure core spray (HPCS) system while the reactor was operating normally near rated power and core flow. An investigation subsequent to restarting the plant revealed that a jet pump failure caused a disturbance in a vessel level sensing line that taps into the vessel near the failed jet pump, initiating the HPCS system. The event was verified by further flow testing and confirmed by in–vessel inspection following reactor shutdown. The inspection confirmed that the beam failure was responsible for the event. The beam was of the Group 1 design, again being in the EQA heat treat condition. Subsequent metallurgical analysis established that the cracking mechanism was IGSCC, consistent with the past failures. Cracking was found to have been present in both transition regions with the second (non-failed) crack being ~50% through the section.

In May 1994, a second failure in the transition region occurred in an overseas plant after several years of operation. A failure analysis confirmed that the cracking mechanism was IGSCC. As opposed to all earlier failures, this beam had received the high temperature, single step aging treatment similar to that given the Group 2 beams in GE plants. The beam geometry is different than that of the GE designs, and the preload applied to the beam was approximately 30 kips (133 kN).

The location of cracking in these two failed beams was situated in the radius region. Figure 3-2 displays the schematic of the first failed beam. The documentation showed that the initiation locations were approximately mid-radius. Initiation also was associated with the edges of the beam.

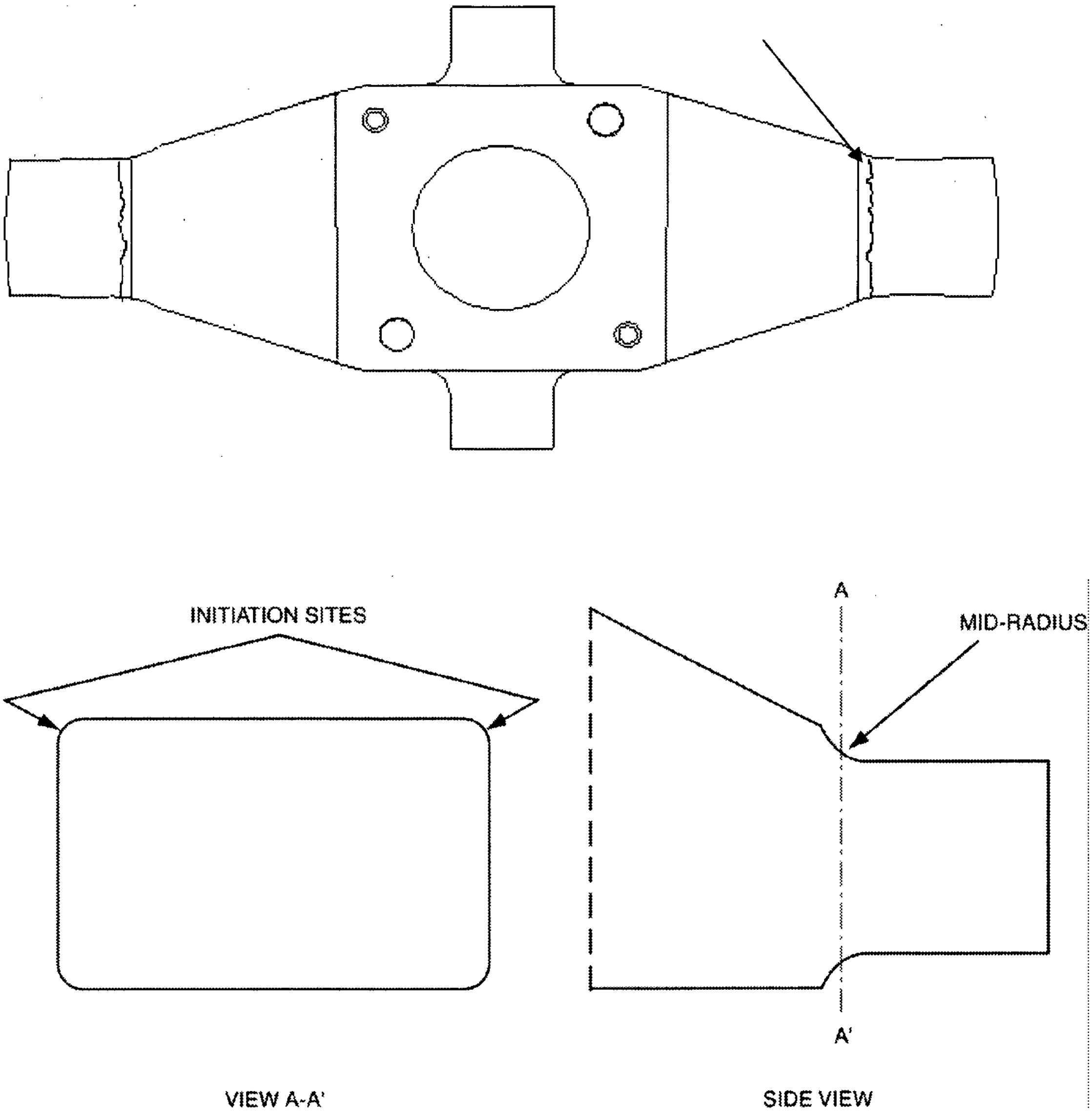


Figure 3-2
Schematic of the Typical Cracking in a BWR Jet Pump Beam at the Transition Region. The Initiation Location was Determined to be in the Radius Region

3.3 Tapered Region (BB-3)

3.3.1 Jet Pump Beam Failure

In January 2002, a new jet pump beam failure occurred at Quad Cities Unit 1, a GE BWR/3 in a beam region that has not previously experienced cracking and that is not normally inspected [6]. The plant was operating at full power when a jet pump flow anomaly was observed. The anomaly was judged to be characteristic of a jet pump beam failure, based on prior industry experience. The unit was shut down and disassembled to allow investigation of the condition. It was confirmed that a jet pump hold-down beam had severed. Subsequent inspection of the vessel internals revealed that the No. 20 inlet mixer was displaced and leaning against the shroud wall and that the beam had broken into two separate parts with the fracture occurring on the vessel side of the beam. The smaller of the two fracture parts, comprised mostly of the machined ear of one end of the beam, was located next to the access hole cover. The larger fractured part was drawn into the Recirculation Loop "B" suction line damaging four of the six vanes on the rotating element of the recirculation pump. The beam fractured in the as-forged and ground tapered area of the beam, approximately one third of the way between the bolt-hole and the end of the beam. The beam was an original BWR/3 equipment component (Alloy X-750 in the EQA heat treatment condition) that had been in service approximately 30 calendar years. However, the location of this new failure was significantly different from those described in Sections 3.1 and 3.2. This failure was located approximately at the mid-point of the tapered region, between the thick center part of the beam and the thinner ends (see Figure 3-3). Figure 3-4 shows the photograph of the fractured end of the beam. It was heavily discolored except for a very small ligament that was associated with the final fracture. Stress analyses would not have predicted this transition region to be a highly stressed region in the beam. Previous failures and crack incidents were coincident with the locations of highest stress. The existence of the crack for a significant period of time was confirmed from re-review of videotapes taken four years prior to the failure. Figure 3-5 displays the enhanced inspection photo.

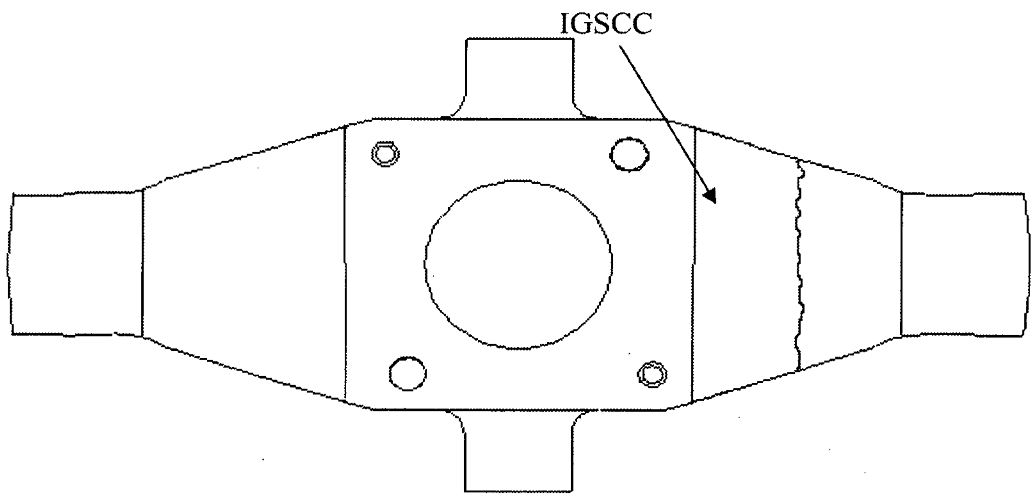


Figure 3-3
Schematic of the Typical Cracking in a BWR Jet Pump Beam at the Tapered Region. The Initiation Location was Determined to be in the Radius Region

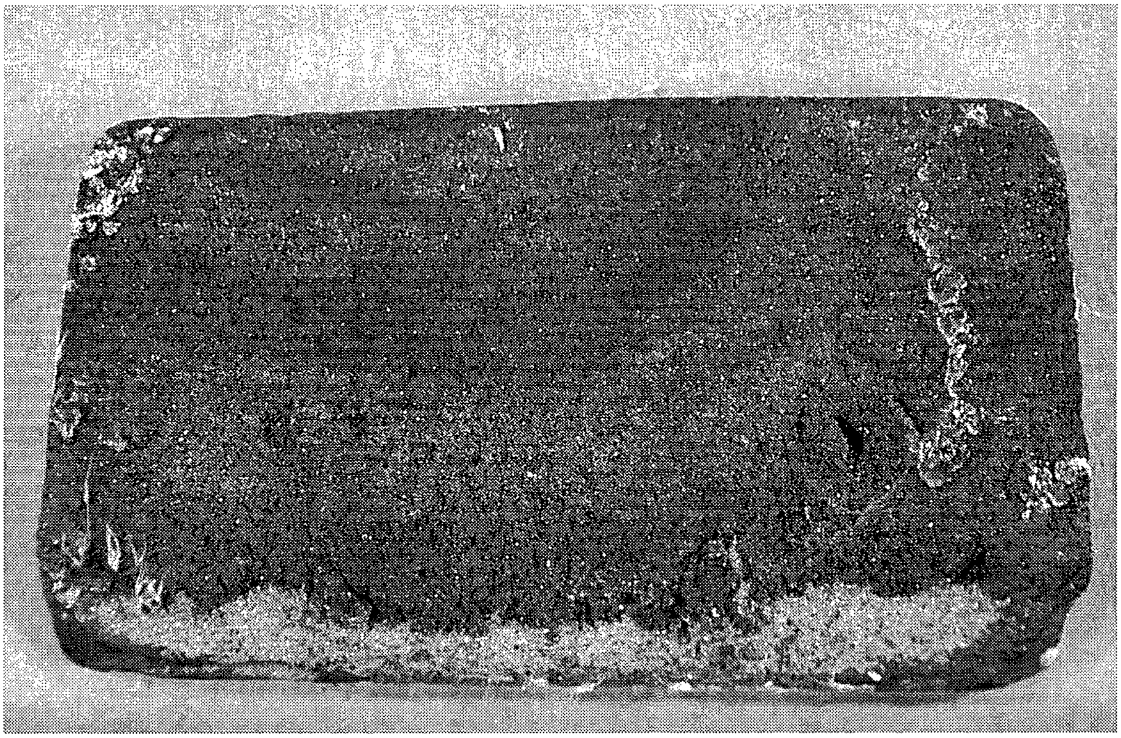


Figure 3-4
Cross-Section of the Broken Jet Pump Beam from the Quad Cities Unit 1 Plant. The Surface Shows Different Discoloration Consistent with the Slow Crack Growth Rates. The Light Section at the Bottom is the Final Fracture Region

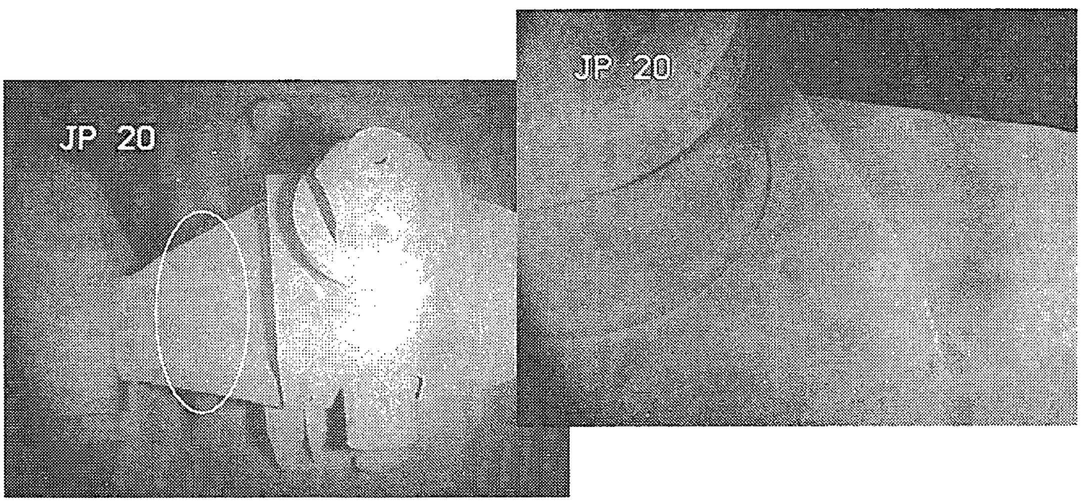


Figure 3-5
Enhanced Visual Inspection Photographs from 1998 Inspection. The Existence of Cracking on Both the Top and Side Surface is Apparent

A detailed laboratory evaluation of the failed beam was conducted [7]. The visual observations as well as the metallographic examination established the cracking to be IGSCC. Based on detailed evaluation of the fracture surface (Figure 3-4), the pattern of cracking supported slow crack growth up to a depth of approximately 0.4 inch (10 mm) followed by more rapid crack propagation until a point was reached where final ductile rupture of the remaining ~10% of the beam occurred. Metallographic evaluation confirmed that the cracking mode was IGSCC. Figure 3-6 displays fracture surface at different magnifications. An assessment of the material properties confirmed that the forging material met the specifications. The evaluation did not establish a specific initiation location. However, it did establish that the surface had been ground, which occurred during initial fabrication per the fabrication drawing.

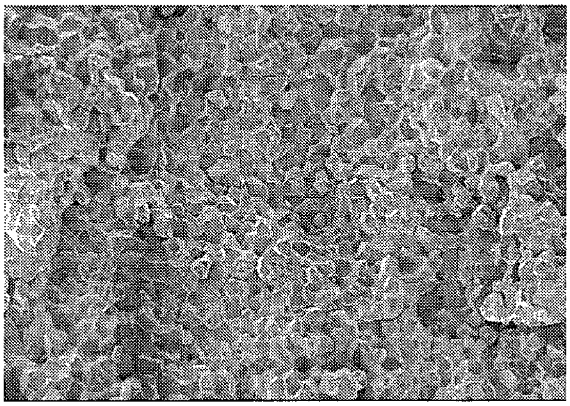
3.3.2 Results of Additional Failure Investigations of BWR/3 Group 1 Jet Pump Beams

In conjunction with the replacement of all the original equipment BWR/3 beams at two BWR/3s, 34 beams were shipped to a laboratory and examined using liquid penetrant (PT) to evaluate the existence of IGSCC. Based on the PT results, selected beams with indications were sectioned to confirm the depth and characteristics of observed indications. The goal of these evaluations was to better understand the nature of cracking in this tapered region and to attempt to identify the cause of initiation. Eight of the beams were found to contain surface cracking. The existence of transverse cracking was confirmed in two of the eight beams with reportable indications[1]. One beam contained an indication approximately 1.7 inches (43.2 mm) in length and 0.17 inches (4.32 mm) in depth; it was located on the as-forged tapered area, mid-way between the hold-down bolt-hole and the end of the beam. A second indication was identified on the corner radius of the as-forged tapered area approximately 0.8-inch (20 mm) from the flat center section surrounding the hold-down bolt-hole. These indications were also confirmed to be IGSCC. As part of the examination, efforts were made to characterize the top surface of the taper in an attempt to better understand the cause of crack initiation. Figure 3-7 displays the surface of a typical tapered region, showing evidence of grinding. However, as in the actual crack initiation region, there was no evidence of a defect acting as a site for the IG crack to start.

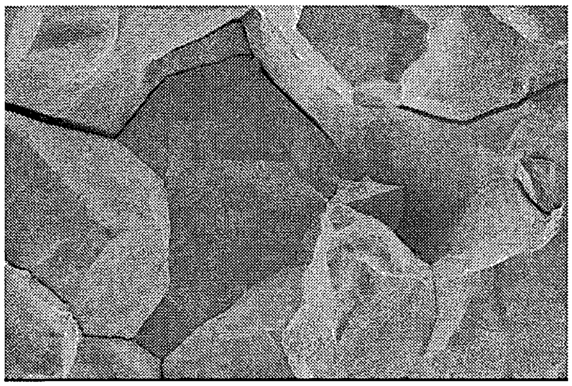
3.3.3 Summary of Tapered Region Cracking

The failure analyses substantiated that cracking was transverse to the beam and aligned with the bending stresses. There was no evidence that there was a manufacturing defect that acted as the initiation site, and there was no evidence that the Alloy X-750 material was out of specification, as confirmed by hardness measurements and chemical analysis. The field data established that the crack growth rates were slow, with visual inspection information confirming that the beam had significant life even with a very deep crack. For these beams, the surface conditions were such that the available visual inspection results did not fully correlate with the laboratory findings.

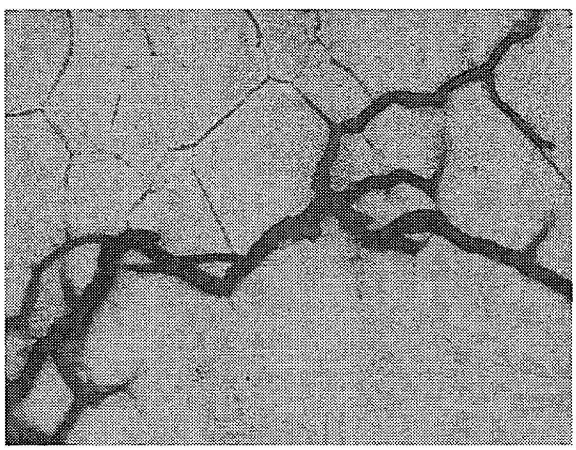
[1] Random cracking was also found in 6 beams. These cracks were not evaluated further.



(a)



(b)



(c)

Figure 3-6
(a) Jet Pump Beam IGSCC Failure at Low Magnification, (b) IGSCC at Higher Magnification and (c) Metallographic Confirmation of IGSCC Cracking Mode

Figure 3-7
Ground Surface Condition Evaluated on BWR/3 Beam Removed from Quad Cities Unit 1 Beam. Typical of all Removed Beams

4
INSPECTION REGIONS

4.1 Definition of Examination Region

As discussed in Section 3, jet pump beam cracking has occurred in all cases (with one exception) in the IGSCC-susceptible EQA beams. The key issue is that the failures have occurred in three different locations, warranting inspection of all three regions where cracking has occurred. In order to evaluate the inspection regions of interest, it is appropriate to review the beam shape. The total jet pump beam length is 10.5" (267 mm) and is symmetrical about the center point at 5.25" (134 mm) from the end. The loading, as discussed in detail in Section 6 and Appendices A [15] and B [16], produces a bending stress profile from one end of the beam to the center point. It is symmetric and thus can be mirrored to complete the bending stress profile over the beam's entire length. There are three regions of interest for JP beam non-destructive examination (NDE):

1. BB-1: the bolt-hole region covering the center of the beam (~4.00" to 6.50" (100 to 165 mm);
2. BB-2: the two beam ends or, transition regions, extending from the end at 0.00" to ~1.50" (0 to 38 mm) toward the beam center;
3. BB-3: both tapered regions starting at ~1.25" (31 mm) and extending to ~4.00" (100 mm) as measured from the ends.

Since the loading results in a bending stress that is tensile on the top surface of the beam and compressive on the bottom surface, IGSCC originating on the bottom surface of Alloy X-750 beam is highly unlikely. In addition, any IGSCC that may form would preferentially orient in the transverse direction due to the bending stress. It is therefore important that the inspection technique be directed towards cracking with significant transverse orientation. Any transverse oriented beam cracking detected during an examination should result in the beam's replacement prior to restarting the plant unless the flaw can be demonstrated to be wholly located in the "exclusion zone" as shown in Figure 4-3. For this case only, the beam is acceptable for continued service for one additional operating cycle and must be reinspected at the next refueling outage.

The candidate NDE methods for examination of the jet pump beam are EVT-1, ET and UT. Prior to discussion of these examination techniques, the definition of the important areas of interest for each of the three regions will be detailed.

4.1.1 Examination of the Bolt-Hole Region (BB-1)

The bolt-hole region of the beam extends from approximately 4.00" (100 mm) from the ends to the beam center line at 5.25" (134 mm). This is the region of maximum bending stress where historically the majority of cracked beams have been found. The bending stress in this section will be a maximum at the center of the beam normal to the longitudinal axis. Since the bending stress is the primary driving force for IGSCC, flaws in this region would be transversely oriented (previously shown in Figure 3-1). The stress in the thread region provides the initiation site. The examination of this region, originally developed during the timeframe of the first failures, should cover a large portion of the top surface around the bolt-hole extending toward the corners of both sides as well as the bolt-hole circumference. The cracks have always initiated transverse to the beam centerline and usually have propagated with little deviation on at least one of the two sides.

4.1.2 Examination of the Transition and Beam Ends (Ear) Region (BB-2)

The transition (or ear) regions of the beam extend approximately 1.50" (38 mm) in from the ends. The top surface of the ends make contact with holddown arms that are attached to the inlet riser pipe which in turn is attached to the reactor vessel wall. The contact area between the holddown arms and the beam can be up to 0.75" (19 mm) from the beam end. Since this area is under compressive load, it is not necessary to inspect the surface or volume directly under the contact area. It is however, necessary to consider inspecting from the end of the contact area at approximately ~0.75" (19 mm) from the end, to the transition into the tapered region which starts to occur at about 1.50" (38 mm) from the end. The examination region is along the length of the beam from the end of arm contact (~0.75", 19 mm) to the beginning of the tapered section (~1.50", 38 mm) on both beam ends; see Figure 4-1. Corners are typically stress-risers and would most likely be the originating point of IGSCC. In consideration of this issue, it would be desirable for the examination to extend around the corners and along the sides of this region. Since initiation and growth of cracks is stress dependent, cracks initiating at a corner would inevitably grow at a greater rate on the top surface than along the sides.

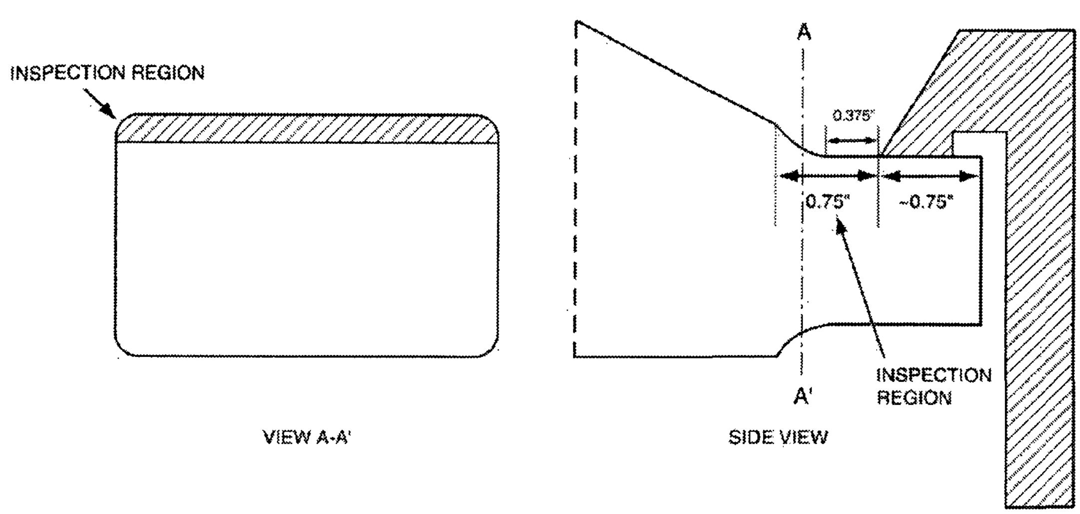


Figure 4-1
Inspection Regions for BB-2

4.1.3 Examination of the Tapered Region (BB-3)

The tapered region of the beam extends from approximately 1.50" to 4.00" (38 to 100 mm) from the ends. Although this region has lower bending stress compared to the other regions, the recent failure has confirmed that this region can be vulnerable to IGSCC. The examination should cover the entire top surface extending to the side corners (See Figure 4-2). Corners are typically stress-risers and would most likely be the originating point of IGSCC. In consideration of this issue, it would be desirable for the examination to extend around the corners and along the sides of this region. Since initiation and growth of cracks is stress dependent, cracks initiating at a corner would inevitably grow at a greater rate on the top surface than along the sides.

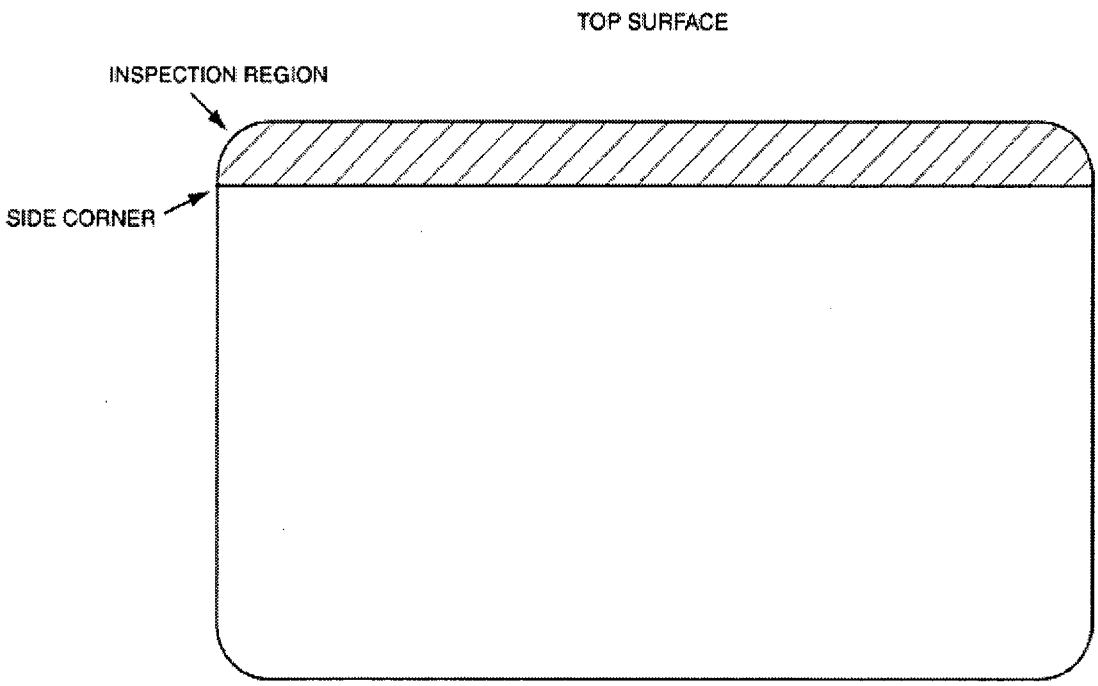


Figure 4-2
Inspection Regions for BB-3 Showing Cross Section with Corner Regions of Interest

4.2 Inspection Techniques

4.2.1 UT Examination of the Jet Pump Beams

UT is currently the primary technique used to inspect the BB-1 and BB-2 regions as called out in BWRVIP-41, Revision 1. There are several ways to accomplish the UT examination. In general, standard immersion transducers in the range of 1.0 to 5.0 MHz can be used to launch surface waves in the taper and beam end regions. Since the top surface of the bolt-hole region has a cover plate, examining this region could be accomplished with alternative pitch-catch or pulse-echo methods. The presence of the cover plate precludes the generation of surface waves and therefore an alternate exam method must be employed to examine this region (BB-1) compared to the beam end (BB-2) and taper (BB-3) regions.

The UT methods can interrogate the tapered region (BB-3) with the exception of a dead-zone immediately adjacent to the bolt-hole region. The dead-zone occurs at the thickest end of the taper region, which may extend an estimated 0.25" to 0.50" to (6 to 12 mm) from the beginning of the taper. This is where the sound energy is incident to the beam and converted to surface waves. This inspection limitation is mitigated by the fact that the dead-zone occurs in the region of lowest susceptibility due to the very large material cross-section. It should also be noted that future improvements in inspection techniques may reduce or eliminate this UT dead zone.

The transition region (BB-2) presents regions of difficulty. The holddown contact in the beam end region could cause interference with the UT signal response. Generally, this interference would be minimal and therefore not have a significant degrading effect on inspecting the remaining 0.50" of the end regions. There are two reasons for the effect to be minimal: (1) The signal interference diminishes quickly, generally within 0.100" (~ 2.5 mm); and (2) the bending stress quickly diminishes as the point of holddown contact is approached. Therefore the transition region can be considered to extend the critical region from the end of the taper to the point of contact with the holddown arm.

As with all NDE methods, care must be taken to achieve the best possible detection sensitivity while avoiding both false-positives and false-negatives. Sizing indications with UT is confounded due to several factors: (1) geometry of the beam design, (2) surface wave attenuation, (3) limited access for the transducers to impart sound energy, and (4) variable flaw morphology and orientation. These factors would make it very difficult to size an indication with any reasonable accuracy.

Recently, an encoded (automated) phased array technique has been demonstrated for the BB-2 and BB-3 regions. The scanner manipulates a single phased array probe across the width of the beam while a series of six active elements sweeping along the length of the 64-element probe performed an electronic scan up and down the length of the beam. The combination of mechanical and electronic scan motion displays the acquired data in a two-axis display. Similar to previously demonstrated conventional techniques the phased array technique has some ability to size the length of indications, but the accuracy is a function of the overall length of the flaw. The capability for depth sizing has not been demonstrated. Consequently, the results need to be carefully evaluated if length sizing is to be used to justify continued operation for an additional cycle.

4.2.2 Eddy Current Examination of the Jet Pump Beams

Eddy current testing (ET) is widely used for early detection of surface cracking. Because it is a surface inspection method, ET only rarely provides surface crack depth information, and then only for very shallow cracks. ET can be used where direct contact of the probe with the surface can be achieved; edge effects limit examination coverage at corners.

In the case of installed beams, the beams ends and taper regions are accessible. The bolt-hole region is covered with a plate which prevents access to its top surface. For this application a driver-pickup probe configuration would generally be the most suitable, although sensitivity is greatly impaired due to the presence of the plate. This configuration maximizes the ability to discriminate against responses from geometric variations and probe liftoff. Since the sensitivity of driver-pickup probes is dependent on crack orientation, the probe's coil configuration should be optimized for transversely oriented cracking.

4.2.3 EVT-1 Examination of the Jet Pump Beams

Although both UT and ET have the capability to detect IGSCC initiating from the top surface, it is also acceptable to inspect the jet pump assembly with high resolution visual inspection methods. If used, these processes must follow EVT-1 visual examination procedures as defined in the latest version of BWRVIP-03 [14]. It should be noted that EVT-1 can not be used for the BB-1 location (the surface is hidden by the cover plate), nor can it be used for the BB-2 location, due to the presence of the hold down. Therefore, EVT-1 inspection is only applicable to the BB-3 tapered region. See Section 4.3.3 for the specific inspection recommendations. In this location the EVT-1 level of sensitivity could provide adequate information about the presence of IGSCC originating on the top surface. However, visual examination has the inherent limitation of only providing surface information and can be subject to both false-positive and false-negative dispositions. For example, false-positives could occur because of scratches, surface oxides and stains. False negatives may occur if the surface of a crack has not opened sufficiently for the visual system to resolve it. This condition would most likely be present if the depth of cracking was small. The intergranular nature of the crack could provide additional information in aiding detection. The fact that a crack will follow grain boundaries typically results in irregular and jagged propagation thereby providing distinguishing characteristics of a real crack versus scratches, machining marks or stains. The examples of cracking found in the tapered region establish that deep cracks with significant length were indeed detectable.

4.3 Examination Recommendations for the Jet Pump Beam Regions

The examination recommendations for the jet pump beam are based upon a combination of field experience, laboratory data and susceptibility evaluations. Each region of the jet pump beam has separate recommendations. This section only defines the recommended inspection regions; the recommended inspection frequencies are described in Section 6. Figure 4-3 is an overall top view of the beam showing the inspection regions.

4.3.1 Bolt Hole Region (BB-1)

As shown in Section 3, the majority of the failures have occurred in this region. Based on the field experience and the stress analysis that indicates significant stresses are present in this location, continued inspection is warranted. The observed field cracking pattern is consistent with the applied stress field, resulting in flaws perpendicular to the beam axis.

Given that flaws are not expected parallel to the beam axis, the region of inspection can be limited. The recommended region is ±22.5° (total of 45°) from an axis perpendicular to the beam axis, on both sides of the beam. All beam designs have significant stress present in this location, and therefore, all beams should be inspected in this location. Figure 4-3 shows the region (hatched) requiring inspection.

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Figure 4-3
Schematic Diagram of the Inspection Regions for the Group 2 Jet Pump Beam

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4.3.2 Transition Region (BB-2)

The transition region of the beam has reported failures in this location, in both the original EQA condition and the improved (HTA) heat treatment condition. The BB-2 failures have occurred in the radius region, but, as the recent failure has shown, IGSCC can occur in regions that are located away from the peak stress.

The area underneath the hold downs is considered to be in compression, and therefore, no inspection is recommended at the ends of the beam.

The transition region inspection area is recommended to cover the entire radius region and extends to the hold down locations (see Figure 4-1). The differences in the beam designs for this region are minor, and therefore, this inspection region applies to all designs.

4.3.3 Tapered Region (BB-3)

The tensile stress in this location extends across the entire upper surface of the beam. The results of the tapered region failure analysis indicate the failed beam had crack initiation in the corner of the beam; subsequent examinations of other beams also identified IGSCC flaws on the top surface of the beams. The failure analysis and the stress results indicate that the entire region has the potential for cracking, and is therefore recommended for inspection. Figure 4-3 (right side) displays this as the "un-shaded" BB-3 region.

There may be times, however, when inspection of the entire upper surface is not practical. Based on the fracture mechanics analysis (see Section 6 and Appendices A and B), the crack growth rate is such that any flaws on the upper surface of the beam will propagate to the edges of the beam before penetrating to a sufficient depth to be of concern. As such, a visual inspection of the edges of the beam (the area within 0.5 inches (13 mm) of the edge), is sufficient to justify operation for one additional cycle of operation without inspection of the entire region. Figure 4-3 (left side) displays the exclusion zone as the vertically hatched region. The intent of the exclusion zone is to define a region where any visual indications can be accepted for one additional cycle of operation (up to 24 months).

5
ALLOY X-750 CRACK GROWTH RATES

5.1 Background

Alloy X-750 is an austenitic (γ) nickel-chromium-iron alloy that is precipitation-hardenable mainly due to the additional alloying elements of aluminum and titanium. When heat treated, these two elements combine with nickel to form gamma prime (γ′), an ordered intermetallic compound, which can be simply expressed as $Ni_3(Al,Ti)$. The physical and mechanical properties and the oxidation and the stress corrosion cracking propensities of the alloy are dependent on the compositions, distribution and volume fractions of its various phases includingγ, γ′ as well as the carbides which can be present as well. Like most alloys, the microstructure of Alloy X-750, which is determined by the heat treatment sequence, has a marked effect of the resistance to intergranular stress corrosion crack initiation. The equalized and aged heat treated condition (1625°F (885°C)/24 h + air cool + 1300°F (704°C)/20 h + air cool) Alloy X-750 which was used in the original jet pump beams exhibited shorter times to failure in comparison to the direct aged condition (2000°F (1093°C)/1 h + rapid cool + 1300°F (704°C/20 h + air cool) which has been used in replacement beams.

While crack initiation data was used as the basis for determining relative IGSCC resistance, the crack growth behavior is needed to predict the rate of crack advance if initiation has occurred. Even though initiation likelihood increases with operating exposure, crack growth rates for X-750 beams are independent of service time. The calculated growth rates are expected to be dependent on the applied stresses, the water chemistry and the strength of the material, with less dependence on the amount of grain boundary precipitates. In this respect, the different heat treatment conditions have similar strength characteristics at the BWR operating temperature. Therefore, the important factors are the applied stresses, hot operating time, and the water chemistry.

In order to predict the crack depth as a function of operating time, crack growth rates for the Alloy X-750 need to be developed. These crack growth rates or dependencies can be then used to assess the time for an initiated crack to reach a critical crack size. Most of the limited data was measured under high oxygen conditions in tests performed at GE NE, GE GRC or available to GE NE. The effort must also make use of the extensive understanding of the behavior of other cold worked austenitic materials to benchmark the limited X-750 data and to support the projected benefit imparted by the effective HWC (HWC/NMCA) environment that is present in many of the operating BWRs.

5.2 Review of Existing Alloy X-750 Crack Growth Rate Data

There is very limited crack growth rate data on Alloy X-750 material, and much of the existing data was developed in the 1980's timeframe. The testing at that time was performed under deadweight applied loads or using servo-hydraulic systems in conjunction with compliance measurement techniques. These methods were later replaced with reversing DC potential drop crack growth monitoring techniques. All methods were capable of measuring the rates on growth that were later substantiated with actual lengthening measurements. The environments used in this time period were high oxygen, high conductivity, conditions that would favor higher growth rates. Recent tests were performed in representative environments with much lower conductivity levels, ~0.1 μS/cm, typical of operating power plants. Specifically, the first crack growth tests were performed on fatigue pre-cracked Alloy X-750 fracture mechanics wedge-open-load (WOL) specimens by using a lever-loaded type machine at 300° (572°F). The dissolved oxygen content was controlled to 7 to 8 ppm and the conductivity was <1 μS/cm. Several different Alloy X-750 heat treatments were evaluated with one being the EQA and one being the HTA direct aged condition. Most treatments were similar to the HTA condition. Crack extension was obtained by fracture surface examination and by the partial unloading compliance technique. The data was measured for stress intensity levels of ~40 ksi-in$^{1/2}$ to ~70 ksi-in$^{1/2}$ (44 to 77 MPa-m$^{1/2}$). There was no significant difference in crack growth rates between the heat treat conditions. It can be seen that the rates are affected by the K level with rates ranging from 1 x 10^{-5} in/hr at ~40 ksi-in$^{1/2}$ to 1 x 10^{-4} in/hr at ~70 ksi-in$^{1/2}$ (7 x 10^{-8} mm/s at ~44 MPa-m$^{1/2}$ to 7 x 10^{-7} mm/s at 77 MPa-m$^{1/2}$).

Additional Alloy X-750 crack growth testing was performed by GE NE using a fatigue pre-cracked Alloy X-750 fracture mechanics WOL specimen exposed to 200 ppb oxygenated water at 288°C (550°F) [9]. The direct aged specimen was subjected to alternating periods of slow cyclic loading (SCL), slow rising load (SRL) and constant active load (CL). The SCL and SRL phases were designed to assure that an active environmental crack was present at the start of each CL test phase wherein the desired time-based crack growth data were obtained. Crack growth was measured by the compliance measurement technique. Measurements were made at 31 and 38 ksi-in$^{1/2}$ (34 and 42 MPa-m$^{1/2}$) with the maximum rate measured to be 5.6 x 10^{-5} in/hr (4 x10^{-7} mm/s). These data are displayed in Figure 5-1.

Finally, recent crack growth rate measurements were made using reversing potential drop techniques at the GE GRC lab. These data were developed using modern measurement techniques as opposed to the other tests. These tests were conducted in both representative NWC environments and HWC environments. They were also conducted on the EQA and HTA heat treat conditions. One of these sets of the data is shown in Figure 5-2. The rates in NWC are higher than those measured in lower strength austenitic stainless steel. However, the data do clearly exhibit reduced rates in HWC.

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**Figure 5-1
Existing X-750 Crack Growth Data Measured in NWC Environments**

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Figure 5-2
Recent Data from GE GRC on Alloy X-750 [10]

5.3 Comparison with Other Austenitic Crack Growth Rate Data in Other High Strength Austenitic Materials

While there is currently limited data on the crack growth rates in X-750 material, there are data on other austenitic materials in BWR type high temperature water environments. These materials include cold worked stainless steel, cold worked Alloy 600 and cold worked Alloy 182 weld metal. GE GRC has tested a variety of materials in both NWC and HWC environments. GE GRC has observed a definite dependence of rate with accompanying yield strength [11, 12]. Figure 5-3 displays data for these materials in a NWC environment. As the yield strength is increased toward 700 MPa (~100 ksi), the observed crack growth rate rises. This data is measured at levels similar to the other data on X-750 (shown as a range). The figure also shows that theory of SCC and the associated modeling is consistent with the measured data.

There are a large number of observations that demonstrate the importance of corrosion potential on SCC of structural materials in high temperature water environments [11, 12]. In addition to extensive slow strain rate testing, more carefully controlled and quantitative fracture mechanics crack growth rate studies show that corrosion potential is the strongest factor in controlling SCC kinetics. GE GRC also evaluated the high strength materials at low corrosion potential (ECP). Figure 5-4 displays crack growth rate data as a function of strength level for similar austenitic materials [11, 12] in an HWC environment. Comparing Figures 5-3 and 5-4, it can be seen there is a significant reduction in growth rates for the high strength materials at low potential. For the higher strength material at low ECP, the improvement is up to a factor of 10. For the lower strength material, the improvement is in excess of a factor of 20.

5.4 Proposed Crack Growth Rates for Fracture Mechanics Evaluation

Based on the X-750 data as well as the understanding of SCC and the confirmatory data from other austenitic alloys, particularly stainless steel and alloy 600, crack growth rates can be proposed for use in evaluating postulated indications in jet pump beams. Figure 5-5 displays the proposed crack growth rates for X-750 in NWC and HWC along with the X-750 lab data. The NWC curve bounds all of the data up to a K level of 70 ksi-in$^{1/2}$ (77 MPa-m$^{1/2}$). The curve uses a K-dependence similar to that used in previous studies [12, 13] and uses a plateau rate of 1 x 10^{-4} in/hr (7 x 10^{-8} mm/s) beyond a K level of 50 ksi-in$^{1/2}$ (55 MPa-m$^{1/2}$).

For the effective HWC environment, a factor of improvement of 2 is used. This is conservative based on the measured benefit for the data from other high strength materials displayed in Figure 5-4.

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Figure 5-3
Relationship of Crack Growth Rates in NWC as a Function of Yield Strength. X-750 Data Range Also Shown

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Figure 5-4
Relationship of Crack Growth Rates in HWC or HWC/NobleChem as a Function of Yield Strength. X-750 Data Range also Shown

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Figure 5-5
Proposed Crack Growth Rate Relationship for X-750 Material for HWC and NWC Environments

6
FLAW EVALUATION METHODOLOGY

A comprehensive fracture mechanics evaluation of the Group 2 and Group 3 jet pump beam designs was performed to establish the flaw tolerance of the designs currently installed in the BWR fleet. The flaw tolerances were used to determine the jet pump beam re-inspection intervals. The flaw evaluations are not intended to be used to justify continued operation of jet pump beams with existing flaws unless the flaws are wholly contained within the exclusion zone of the BB-3 region of the beam as stated in section 4.3.3. The evaluations are contained in their entirety in this report as Appendices A and B, respectively. Portions of these reports are included in this section to communicate the general methodology used in the fracture mechanics evaluations of the jet pump beams. Refer to Appendices A and B for detailed descriptions of the methods, assumptions and results. The following items are discussed in this section: Stress Analysis, Allowable Flaw Size Calculations, Compliance Analysis, Linear Elastic Fracture Mechanics Analysis (LEFM). The results of the flaw tolerance evaluations are used to establish re-inspection intervals that are summarized in Section 7.

6.1 Stress Analysis

A three dimensional (3-D) linear elastic finite element analysis (FEA) was performed for each jet pump beam design rather than assuming a simplified stress distribution for the jet pump beam. This approach provides an accurate and detailed stress distribution along any desired crack plane which can be used as input to a LEFM analysis. The fracture mechanics methodology selected for this evaluation considers either a 1-D or 2-D stress gradient from an un-cracked finite element model (FEM) at the location of the postulated crack.

The 3-D FEA of the jet pump beams was performed using the ANSYS computer program. The geometry was modeled with linear 3-D SOLID45 elements. A regular hexahedral mesh was developed from which the resultant nodal stresses could be directly extracted along each postulated crack plane. The applicable bolt load is applied to the nodes at the bottom of the jet pump beam bolt hole. A single line of nodes is restrained in the vertical direction, at the support location, to react the applied load. A single node is restrained in the remaining translational degrees of freedom to prevent rigid body motion. The stress gradient along the surface of each crack plane is extracted from the nodal stress results and used as input into the LEFM analysis. Figure 6-1 illustrates the FEM mesh and boundary conditions used for the jet pump beam stress analyses.

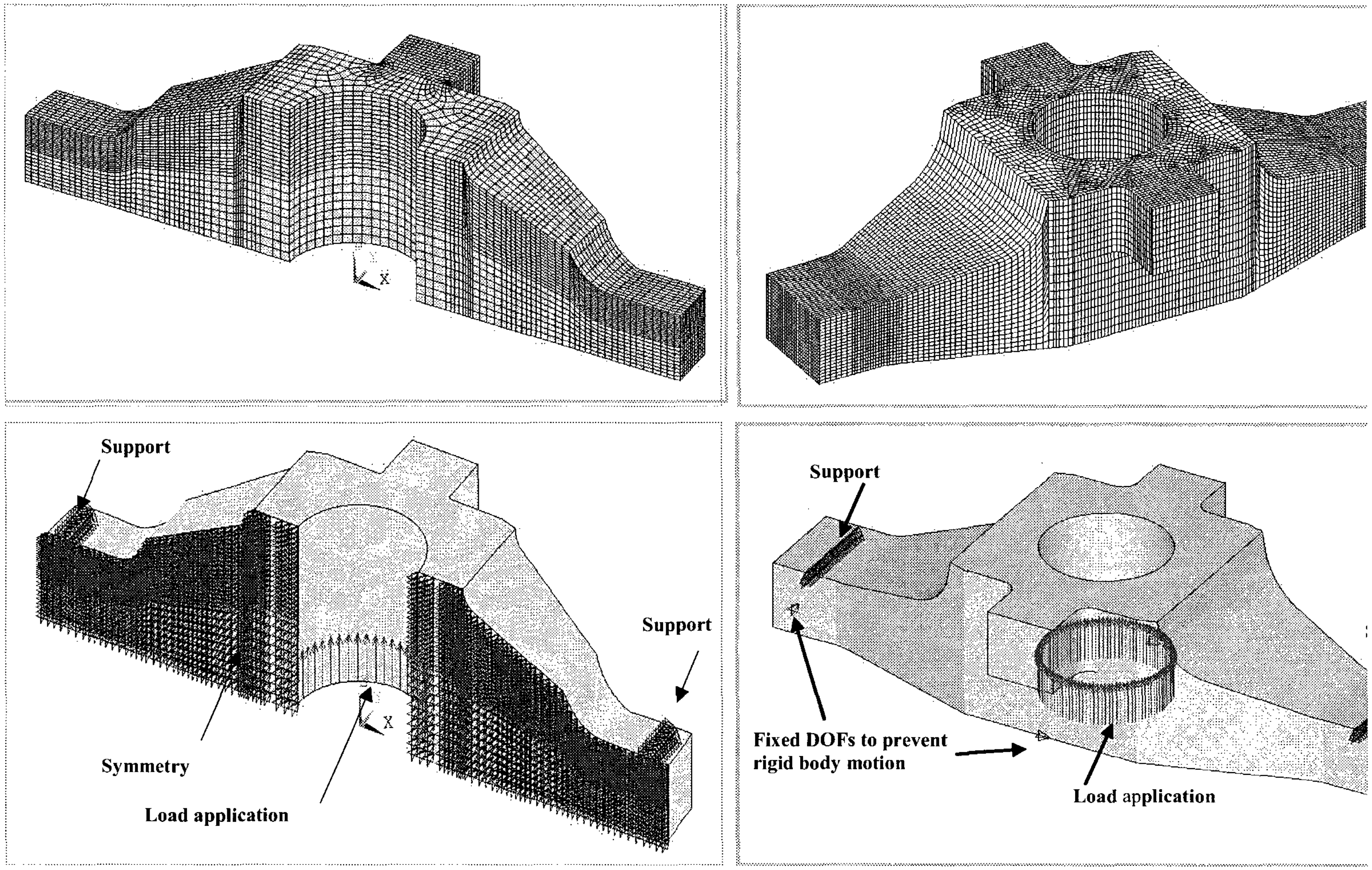

Figure 6-1
Finite Element Mesh and Boundary Conditions for the Group 2 (Left) and Group 3 (Right) Jet Pump Beam Designs

6.2 Postulated Crack Planes

Nine initial crack planes, A through I, were selected for analysis of the Group 2 jet pump beam. These planes were distributed throughout the length of the beam and placed in all three inspection regions: BB-1, BB-2 and BB-3. The results of the LEFM analysis of these initial crack planes as well as review of the stress analysis were used to add additional crack planes for evaluation, A1, C1, and IR, to ensure that the behavior of the jet pump beam was adequately investigated and the critical flaw locations were considered.

The Group 3 jet pump beam evaluation was performed subsequent to the Group 2 jet pump beam evaluation; therefore, the results of the Group 2 evaluation were used to reduce the number of crack planes required for evaluation. Five crack planes were considered for the analysis of the Group 3 jet pump beam. Four were placed at the limiting locations determined from the Group 2 jet pump beam evaluation and one was placed in the BB-3 region in order to illustrate the effect of the reduced material height in this region of the Group 3 design.

Tables 6-1 and 6-2 identify the locations, along the longitudinal axis of the jet pump beam, of each crack plane considered for the Group 2 and Group 3 designs with respect to the center of the bolt hole, respectively. Figures 6-2 and 6-3 show the location of all crack planes on sketches of the Group 2 and Group 3 jet pump beams, respectively.

Table 6-1
Location of Crack Planes Considered in Group 2 LEFM Analysis

Crack Plane ID	Jet Pump Beam Region	Location[1], in	Note
A1	N/A	5.033	Outboard of hold-down location
A	BB-2	4.548	Adjacent to hold-down location
B	BB-2	4.160	At bottom of fillet radius
C1	BB-2	3.930	At peak stress location on fillet radius
C	BB-2	3.817	At middle of fillet radius
D	BB-2	3.475	At top of fillet radius
E	BB-3	3.010	Approximately 1/3 of the distance between Section D and G
F	BB-3	2.380	Approximately 2/3 of the distance between Section D and G
G	BB-3	1.913	At bottom of fillet radius at the inboard edge of the transition region
H	BB-1	1.480	At intersection between taper and full width section of jet pump beam
I	BB-1	0.000	At peak stress location of beam bolt hole
IR	BB-1	0.000	At peak stress location of beam bolt hole proceeding to peak stress location at corner between lifting lug and beam body

Note: 1. Dimension with respect to jet pump beam bolt hole centerline.

Table 6-2
Location of Crack Planes Considered in Group 3 LEFM Analysis

Crack Plane ID	Jet Pump Beam Region	Location[1], in	Note
B	BB-2	4.160	At bottom of fillet radius between regions BB-2 and BB-3.
C1	BB-2	3.975	At peak stress location on fillet radius between regions BB-2 and BB-3.
D	BB-2	3.884	At top of fillet radius between regions BB-2 and BB-3.
E	BB-3	2.957	In transition region between BB-1 and BB-2.
IR	BB-1	N/A	At peak stress location of beam bolt hole proceeding to peak stress location at corner between lifting lug and beam body (region BB-1).

Note 1. Dimension with respect to jet pump beam bolt hole centerline.

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Figure 6-2
Crack Planes Considered for LEFM Analysis of Group 2 Jet Pump Beam Design

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Figure 6-3
Crack Planes Considered for LEFM Analysis of Group 3 Jet Pump Beam Design

6.3 Allowable Flaw Size Calculations

The jet pump beam is fabricated from Alloy X-750. Field experience and failure analysis of this material support the use of plastic collapse in shear as the failure method for the jet pump beam. The allowable flaw size is determined by solving for the un-cracked ligament required to react the shear load applied to the jet pump beam. Noting that the average shear stress in a rectangular section is given by,

$$\tau = SF\frac{F}{td}$$ **Equation 6-1**

Where, SF is the applied safety factor on load
F is the applied load, lbs
d is the ligament thickness, in
t is the section width, in

The allowable flaw size is then determined by setting the applied stress equal to the shear flow stress of the material and solving for the ligament thickness, d, required to prevent plastic collapse:

$$d = SF\frac{F}{t\tau_f}$$ **Equation 6-2**

Where, τ_f is the shear flow stress of the material, psi

At collapse, the displacement controlled bolt preload will have been entirely relieved and the resulting load acting on the beam will be the hydraulic load contributed by the reactor coolant inside the jet pump. For this evaluation, the normal/upset hydraulic loads are considered; therefore, the applicable safety factor, SF, is 3.0. A SF=3.0 rather than 2.77 is used for a rectangular cross section and is consistent with the ASME Code intent. Tables 6-3 and 6-4 summarize the allowable flaw sizes for the crack planes evaluated in the Group 2 and Group 3 jet pump beam designs.

Table 6-3
Limit Load Allowable Flaw Sizes for the Group 2 Jet Pump Beam Crack Planes Considered

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Table 6-4
Limit Load Allowable Flaw Sizes for the Group 3 Jet Pump Beam Crack Planes Considered

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6.4 Compliance Evaluation

As mentioned above, the true normal operational loading on the jet pump beam is a displacement controlled load. Therefore, it is possible that as a crack grows deep into the jet pump beam cross-section the applied load would decrease. This would result from the increased compliance of the cracked structure. If this occurs then the driving force for a flaw would diminish and the resulting stress intensity factor and IGSCC crack growth rate would also decrease. This results in an increase in the time to failure of the component.

To investigate this effect, multiple crack cases were run with a 3-D FEM of the Group 2 jet pump beam. Corner crack, center crack and edge crack cases at each of the selected crack planes were evaluated for multiple crack depths. Because the output of this evaluation is a trend of component stiffness versus crack depth, crack tip elements are not required. The stress field local to the crack tip is not relevant to this evaluation; therefore, a simplified approach can be used. Each crack plane was meshed with coincident nodes; the nodes were left unmerged to model the crack and the nodes were merged to model the remaining ligament. In effect, the compliance of the beam was investigated by inserting notches into the beam to simulate the presence of cracks.

The results of these evaluations could be used to reduce the stress gradients obtained from the un-cracked analysis at flaw depths for which a significant increase in compliance was observed. As discussed in Section 7.4 of Appendix A, the compliance evaluation did not show significant load relaxation until the flaws became very deep; therefore, no credit was taken for increased compliance in the LEFM evaluations for the Group 2 or Group 3 jet pump beams.

6.5 Linear Elastic Fracture Mechanics Evaluation

The GE proprietary code PROPLIFE was used for all locations in the Group 2 and Group 3 jet pump beams except for the failure plane assumed at the bolt hole location in region BB-1. The GE proprietary code 3DFAS was used to evaluate the more complex bolt hole location in the jet pump beam at the BB-1 region. Each method is addressed separately; however, both methods consider crack growth in the following manner:

1. Assume an initial flaw size, typically 0.01" x 0.01"
2. Calculate the mode I stress intensity factor, K_I, at the width, c, and depth, a, of the flaw
3. Calculate the incremental crack growth in the width, Δc, and depth, Δa, direction using the K_I values from step 2 and the normal water chemistry (NWC) & hydrogen water chemistry (HWC) crack growth relationships presented in Section 5.
4. Increment the crack size by the Δa and Δc calculated in step 3.
5. Iterate steps 2 through 4 until the crack reaches the allowable flaw size determined using the method described in Section 6.3.

Crack growth is determined using the IGSCC crack growth relationships for NWC and HWC presented in Section 5. These relationships use the mode I stress intensity factor to determine the incremental crack growth rate (CGR) and have a plateau CGR at K_I=50 ksi-in$^{0.5}$. The plateau K_I=50 ksi-in$^{0.5}$ is used for crack dimensions which result in a K_I>50 ksi-in$^{0.5}$. The time increment used in the crack growth calculations was 500 hours. Review of the crack growth calculations shows that there was less than 1% change in the K values between successive 500-hour increments. This confirms adequacy of the time increment.

The crack dimension versus operating time curves at each crack location, determined using the process above, can be used to identify critical locations in the jet pump beam and desired inspection frequencies. The critical locations are those regions with the least life for a chosen initial flaw size.

6.5.1 PROPLIFE LEFM Methodology

The GE PROPLIFE computer program is a linear elastic fracture mechanics code that can use 1-D and 2-D stress gradients as input into published LEFM solutions for various common geometries. Further, this code calculates the K_I at the width, c, and depth, a, of a crack, and then determines the incremental crack growth, Δa and Δc, at the extents of the flaw using a user defined crack growth relationship. The program iteratively determines a K_I and incremental crack growth until the flaw reaches a user defined failure criterion. The significant strengths of this code are:

- Accepts complex stress distributions from a FEA
- Iteratively determines the K_I at the length and depth of the crack and calculates incremental growth using user defined crack growth relationships
- Can change the flaw aspect ratio as the iterative calculation progresses to accommodate changes in flaw shape caused by non-uniform stress distributions
- Includes a crack transition capability to transition from a corner crack to an edge crack or a center crack to an edge crack

The corner crack solution in PROPLIFE uses a 2-D stress gradient. The edge crack solution and center crack solution use a 1-D stress gradient. The 2-D stress gradients used for this evaluation are taken directly from the ANSYS output. The 1-D stress gradient was determined by selecting the maximum stress across the width of the beam at each elevation through the thickness of the beam. This approach forms a bounding 1-D gradient at each crack plane. This method is very conservative for some crack planes that show a highly non-uniform stress distribution. For the surface crack geometries such as the corner and center cracks, crack growth calculations at the surface and the deepest point were conducted. It is then assumed that the resulting crack shape is semi-elliptical with the newly calculated length and depth.

The LEFM solutions used by PROPLIFE are all published in the open literature and are referenced in the PROPLIFE User's manual. When a crack front nears the surface of the component, PROPLIFE automatically changes the crack geometry to an edge crack. This transition occurs when the crack is within one plastic zone size of the edge of the component. The method for transitioning a corner crack to an edge crack or a center crack to an edge crack used for this analysis is to define the edge crack depth equal to the deepest part of the corner or center crack at the time that the crack broke through to the sides of the component. This conservative approach does not take credit for the time it takes for the edges of the flaw to grow in depth to a truly rectangular shape assumed for the edge crack. The stress intensity solutions in PROPLIFE are all load-controlled solutions.

6.5.2 3DFAS LEFM Methodology

GE has developed a 3-D finite element LEFM code called 3DFAS for complex geometries where handbook solutions are not readily available in the literature. 3DFAS is essentially a sophisticated pre-processor and meshing algorithm that enables a user to embed complex flaws into existing finite element meshes then export the cracked mesh into the ANSYS environment. The un-cracked mesh is extracted in the region adjacent to the crack and remeshed with degenerate quadratic solid elements with the mid-side nodes moved to the quarter point location local to the crack and tetrahedral elements away from the crack. The nodes on the boundary of the original mesh and the inserted cracked mesh are coincident; therefore, continuity of the field variables is enforced. Moving the mid-side nodes of a quadratic element to the ¼ point location at the crack tip is a common method to capture the stress and displacement field local to the crack tip and is discussed extensively in the literature. The ANSYS solution environment is used to solve for the displacement field. The stress intensities for all three crack modes are extracted from the ANSYS solution.

3DFAS was used to embed cracks at the crack plane I location in the BB-1 region and determine the K_I along the crack front. For crack growth, the length dimension was controlled by the K_I at the edge of the crack and the depth dimension was controlled by the average K_I along the crack front. The crack growth relationship in Section 5 was used to determine the incremental CGR.

The 3DFAS analyses are performed with a displacement boundary condition at the jet pump beam bolt hole. This is an accurate representation of the load condition for the beam and inherently models any increase in compliance, as a crack grows deeper into the cross-section. Unlike for the static stress analysis of the other crack planes in the Group 2 design, a full model of the jet pump beam was used for these analyses. This was done in order to model a single crack emanating from the bolt hole in the BB-1 region; a half symmetric model would have effectively considered two cracks diametrically opposed at the bolt hole.

7 FLAW ACCEPTANCE AND REINSPECTION CRITERIA

7.1 Crack Growth Predictions

Using the fracture mechanics methodology described in Section 6 and presented in detail in Appendices A and B, the flaw tolerance of the Group 2 and Group 3 jet pump beam designs considering reasonable incipient cracking and 99th percentile loads has been established. Detailed results for each jet pump beam design are contained in Appendices A and B. Results for each crack plane considered include the postulated crack location along the length of the beam, stress state normal to the crack plane, residual life prediction, and Mode I stress intensity results at the width and depth of the crack for center and corner cracks. The results are presented for NWC conditions. Note that the crack growth rate for HWC conditions assumes a factor of improvement of 2; therefore, the HWC residual life predictions for any crack location presented in Appendices A and B can be obtained by multiplying the NWC results by 2. The stress and stress intensity results presented are independent of water chemistry; therefore, they are applicable for both NWC and HWC water chemistry.

The flaw tolerance results at the limiting locations for each beam design are presented in Figures 7-1 through 7-4. The lower left plots in these figures show the residual life of the jet pump beam along the abscissa for an initial flaw size read from the ordinate. Any assumed initial flaw size can be read from this plot and the corresponding lifetime of the beam can be identified. This analysis was performed by assuming a very small initial flaw size and then allowing that flaw to grow consistent with the stress distribution on the crack plane. This method allows the reader to investigate the residual life for many different initial flaw dimensions.

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Figure 7-1
NWC, 99th Percentile Load, Group 2 Jet Pump Beam, Corner Crack Evaluation, Crack Plane IR

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Figure 7-2
NWC, 99th Percentile Load, Group 2 Jet Pump Beam, Center Crack Evaluation, Crack Plane C

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Figure 7-3
NWC, 99th Percentile Load, Group 3 Jet Pump Beam, Corner Crack Evaluation, Crack Plane IR

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Figure 7-4
NWC, 99th Percentile Load, Group 3 Jet Pump Beam, Center Crack Evaluation, Crack Plane

7.2 Inspection Intervals

The inspection intervals are based on both initiation and crack growth analyses. The initiation data [3] was used to define the time of the initial inspection. The initial inspection under NWC conditions is consistent with the recommendations in BWRVIP-41, Revision 1 for _Group 2 beams. The reduced probability of initiation was factored in selecting initial inspection timing for Group 3 beams.

The re-inspection intervals are based on the time for an assumed flaw (smaller than the detection limit) to reach a critical size. The time for an assumed flaw to reach the critical size is dependent on the initial flaw depth, the location, and the operating environment.

7.2.1 Initial Inspection Criteria

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Tables 7-1 and 7-2 summarize the baseline inspection requirements for the Group 2 and Group 3 jet pump beams, respectively.

Table 7-1
Group 2 Beam Inspection Recommendations

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Table 7-2
Group 3 Beam Inspection Recommendations

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7.2.2 Re-Inspection Intervals

The results of the flaw tolerance evaluations performed for both the Group 2 and Group 3 jet pump beam designs show that both beam designs exhibit substantial tolerance to cracking. In other words, the beam designs can contain large flaws and still possess multiple years of residual life. The logic used to define inspection intervals for the Group 2 beam design is:

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A
GROUP 2 JET PUMP BEAM LEFM EVALUATION

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GROUP 3 JET PUMP BEAM LEFM EVALUATION

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C
RECORD OF REVISIONS (BWRVIP-138, REV. 1)

BWRVIP-138, Rev. 1	Information from the following documents were used in preparing the changes included in this revision of the report: *BWRVIP-138: BWR Vessel and Internals Project, Updated Jet Pump Beam Inspection and Evaluation Guidelines,* EPRI, Palo Alto, CA: 2004. 1008213. *Technical Basis for the Inspection Frequency of a BWR Group 2 Jet Pump Beam,* 0000-0069-0773-01, Rev. 0, GE Hitachi Nuclear Energy *Technical Basis for the Inspection Frequency of a BWR Group 3 Jet Pump Beam,* 0000-0082-8669-01, Rev. 0, GE Hitachi Nuclear Energy Details of the revisions can be found in Table C-1.

Table C-1
Revision Details

Required Revision	Source of Requirement for Revision	Description of Revision Implementation
Update Section 1, "Introduction & Background"	Technical Revision	Added Section 1.3, "Implementation Requirements"
Update Section 4, "Inspection Regions"	Utility Input	Updated inspection definitions and techniques.
Separate Crack Growth discussion into separate section	Technical Revision	Section 6.1 (X-750 Crack Growth Rate) of BWRVIP-138 revised to be Section 5 of BWRVIP-138 Rev. 1. Subsequent sections renumbered accordingly.
Report results of updated fracture mechanics evaluation	Technical Revision	Section 6 revised
Update Reinspection Intervals	Technical Revision	Tables 7-1 and 7-2 Added
Add GEH Group 2 JPB Fracture Mechanics Report	Technical Revision	Report added as Appendix A Note: Revision Bars not used
Add GEH Group 3 JPB Fracture Mechanics Report	Technical Revision	Report added as Appendix B Note: Revision Bars not used

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