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BWRVIP-183NP: BWR Vessel and Internals Project

Top Guide Grid Beam Inspection and Flaw Evaluation Guidelines

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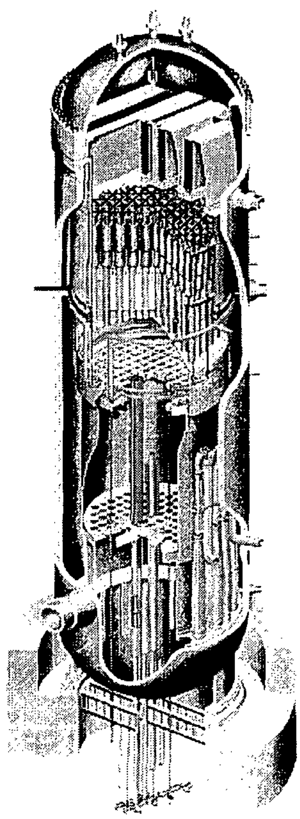

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Top Guide Grid Beam Inspection and Flaw Evaluation Guidelines

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Final Report, December 2007

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REPORT SUMMARY

This report presents results of an evaluation of the flaw tolerance of top guide grid beams.

Background

In 1996, the Boiling Water Reactor Vessel and Internals Project (BWRVIP) published inspection and flaw evaluation guidelines (BWRVIP-26) that recommended inspections for top guides in boiling water reactors (BWRs). The Nuclear Regulatory Commission (NRC) has subsequently expressed concern that cracking of grid beams might present a safety concern, particularly later in plant life and during the license renewal period. The primary concern is that sufficient cracking could develop in top guide grid beams (in particular, cracking in multiple beams) to prevent the top guide from maintaining core configuration during dynamic events.

Objectives

To evaluate flaw tolerance of the top guide grid beam structure and determine what, if any, periodic inspections of top guide grid beams are needed.

Approach

The project team evaluated design and susceptibility of top guide construction and materials. Inspection experience and results were compiled. Finite element and fracture mechanics analyses were performed to evaluate consequences of the as-found indications in two plants. Lastly, concerns such as severed beams, multiple cracks, and loose parts that could affect operation and safety were evaluated.

Results

The evaluations performed show that cracking of top guide grid beams does not result in unacceptable safety consequences. Safe reactor operation will not be compromised with the presence of postulated top guide loose parts in the reactor vessel. The study also shows that crack growth experienced at one plant cannot be explained solely based on the postulated applied stress using the irradiated BWRVIP crack growth model. Other crack initiation and growth mechanisms most likely exist, such as effects of irradiation, cold work, crevice corrosion, oxide wedging, local water chemistry, weld repairs, and plant-specific stress conditions that are not fully understood and are difficult to quantify as a whole. Therefore, guidelines for periodic inspection of top guide grid beams were developed.

EPRI Perspective

Component inspections provide a means to effectively manage material degradation. This report provides a common basis for BWRVIP members to plan and implement inspections of top guide grid beams in a manner consistent with the BWRVIP inspection and evaluation guidelines for other reactor internals.

Keywords

Boiling water reactor
Top guide
Vessel and internals
Inspection strategy
Flaw evaluation

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1
INTRODUCTION

1.1 Background

During the period 1991-1995, GE issued RICSIL 059 [1], SIL 544 [2] and SIL 588, Rev. 1 [3] to report cracking in BWR top guides. The first plant in the U.S to identify top guide cracking was

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In 1996, the BWRVIP published top guide inspection and flaw evaluation guidelines (BWRVIP-26), which was subsequently republished as BWRVIP-26-A [4] in 2004 and technically equivalent to the earlier version, that recommended inspections for top guides in BWRs. Based on safety considerations, the guidelines concluded that only certain top guide components required inspection in order to ensure that the top guide would continue to maintain its safety functions. The components requiring periodic inspection include the aligner assemblies, hold down assemblies, and the rim weld on certain types of BWRs. It was determined that the other components of the top guide, including the grid beam assembly, had sufficient flaw tolerance such that no inspections were required for the life of the plant.

Following the publication of BWRVIP-26-A, the NRC expressed concern that cracking of grid beams might present a safety concern, particularly later in plant life and during the license renewal period. In their evaluation of BWRVIP-26 [4, Appendix E], they state that "...accumulated neutron fluence is a [time limited ageing analysis] TLAA issue and must be identified and evaluated by individual applicants considering license renewal." The primary concern is that sufficient cracking could develop in the top guide grid beams (in particular, cracking in multiple beams) to prevent the top guide from maintaining core configuration during dynamic events.

1.2 Objectives and Scope

The purpose of this project is to evaluate the flaw tolerance of the top guide grid beam structure and determine what, if any, periodic inspection of the top guide grid beams should be required.

1.3 Implementation Requirements

In accordance with the implementation requirements of Nuclear Energy Institute (NEI) 03-08, Guideline for the Management of Materials Issues, Sections 4 and 8 are "needed" and the remaining sections are for information only.

2 DESIGN AND SUSCEPTIBILITY

2.1 Top Guide Grid Beam Design

The top guides reviewed in this study are:

- BWR/2: Nine Mile Point 1
- BWR/2: Oyster Creek
- BWR/3: Pilgrim
- BWR/3: Quad Cities 1 & 2
- BWR/4: Hope Creek
- BWR/4: Limerick 1 & 2
- BWR/4: Peach Bottom 2 & 3
- BWR/4: Susquehanna 1 & 2
- BWR/4: Kernkraftwerk Mühleberg
- BWR/5: LaSalle 1 & 2
- BWR/5: Nine Mile Point 2
- BWR/6: Perry

The following evaluations are based on the information contained in BWRVIP-26-A.

The top guide on BWR/2-5 plants (Figure 2-1) consists of a grid of beams forming square holes, which maintains the alignment of control rods and fuel bundles during normal operation, pressure transients and dynamic events. The grid beam intersections are accomplished by interlocking vertical slots in each beam (Figure 2-2), which create crevices above or below the slot at each intersection. The grid beams attach to a rim on the periphery of the top guide by means of, in most cases, reinforcement blocks and pins which attach to the bottom plate and cover plate, if any.

The top guide on BWR/6 plants (Figure 2-3) consists of a solid plate which has machined out square holes for each fuel cell, and is bolted in place along with the upper shroud. It is machined from a solid piece of Type 304L stainless steel, typically fabricated by welding two or three plates together. Solution annealing was not required, and was typically not performed due to the size of the final assembly. In this configuration, cracking along the fabrication welds does not impact top guide function, since, in the worst case, the plate pieces would be adequately supported by the perimeter bolting.

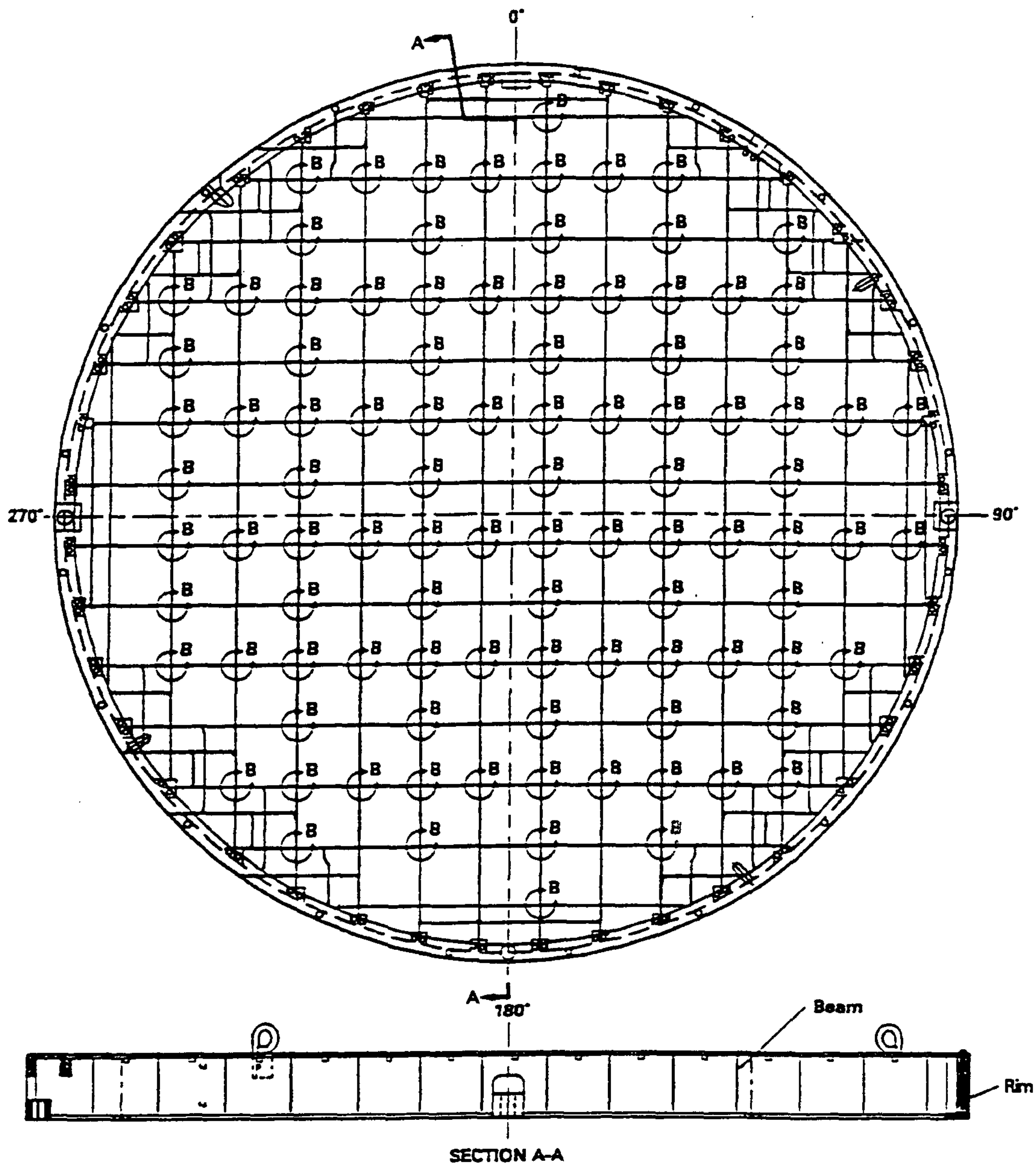

Figure 2-1
Typical BWR/2-5 Top Guide Assembly

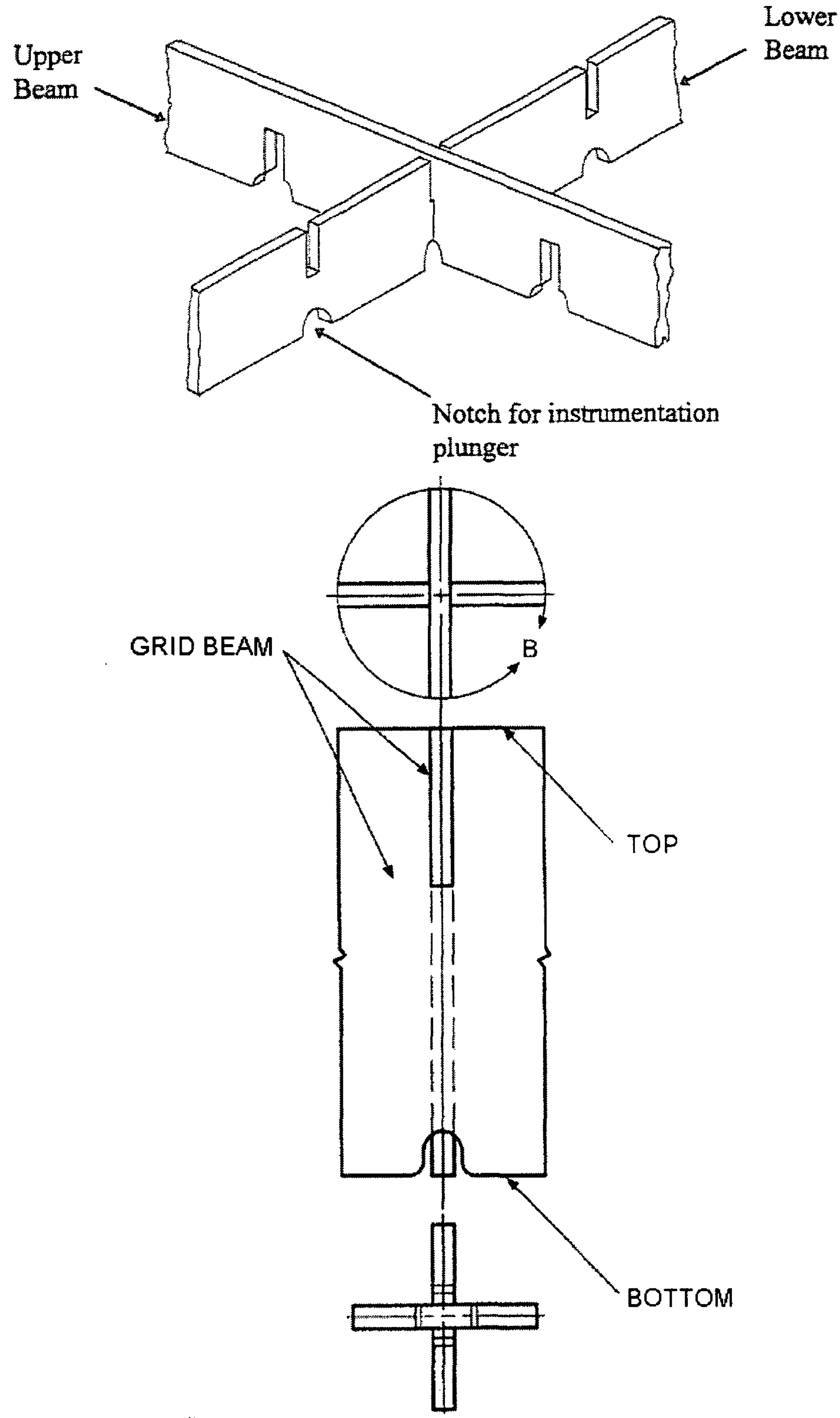

Figure 2-2
BWR/2-5 Top Guide Grid Beam and Beam-to-Beam Slot

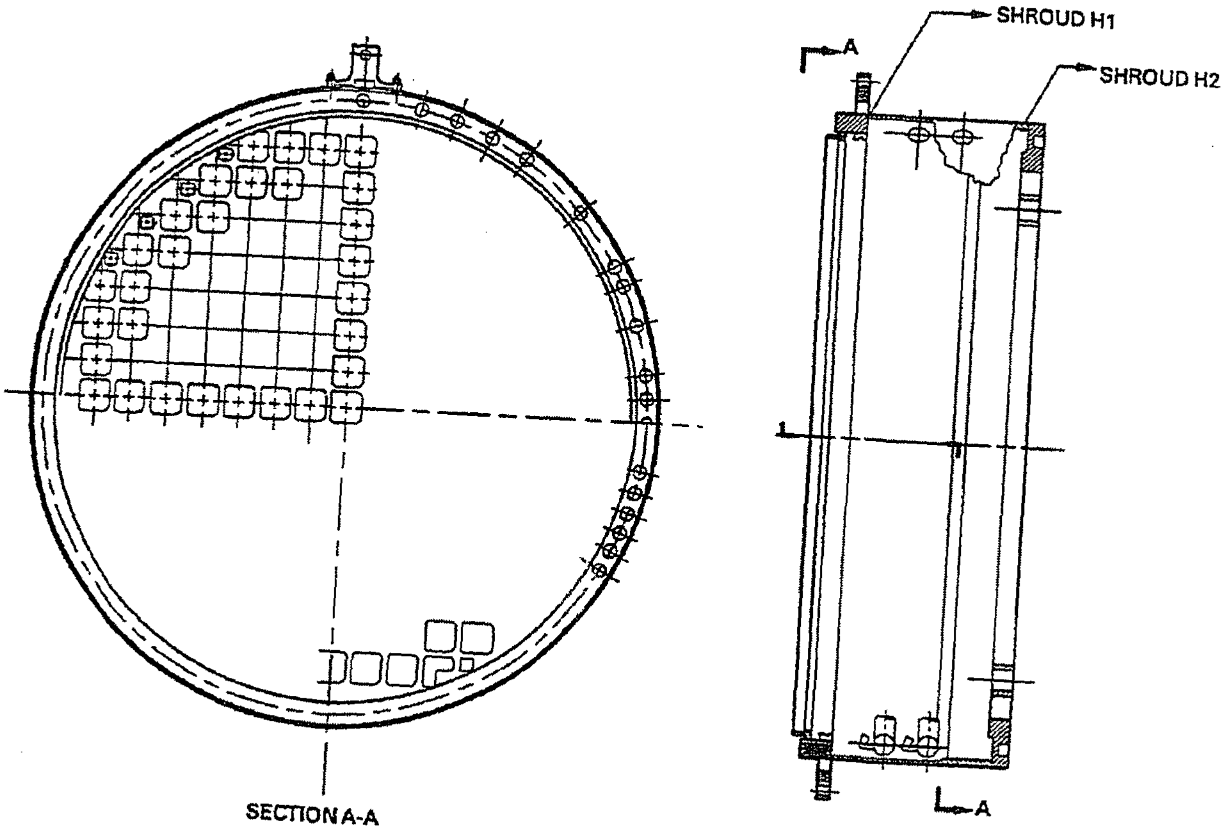

Figure 2-3
Typical BWR/6 Top Guide Assembly

2.2 Susceptibility Factors

The occurrence of intergranular stress corrosion cracking (IGSCC) or irradiation assisted stress corrosion cracking (IASCC) requires the combined presence of an aggressive environment, a susceptible material, and tensile stress. These specific factors are discussed for the top guide assembly in more detail below.

Another important consideration in evaluating stress corrosion cracking (SCC) susceptibility, because of the variability of the phenomenon, is the cracking history. A discussion of cracking history is contained in Section 3 as part of the background discussion on inspection.

2.2.1 Environment

The environment at the top guide assembly location is highly oxidizing in all BWRs because the most oxidizing reactor water is that exiting the core and occupying the upper shroud regions. Radiolysis model calculations, validated by electrochemical corrosion potential (ECP) measurements at several internal locations, predict that the environment in contact with the top guide assembly has relatively high levels of peroxide (H_2O_2) which leads to high ECP values. High ECP is considered one of the key factors in promoting SCC in austenitic stainless steel components when present in combination with adverse material microstructures and tensile stress (residual, applied, and/or fit-up).

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In summary, all locations on the top guide meet the first requirement for IGSCC (aggressive environment). All locations are within a region of high ECP. In addition, the environment at locations like the beam-to-beam intersections in BWR/2-5 plants is aggravated due to the creviced configuration. The BWR/6 design has welds and plate surfaces that are potentially susceptible to cracking. Finally, certain locations on the top guide are susceptible to IASCC due to the high fluence.

2.2.2 Material

The top guide assembly is constructed of either Type 304 or Type 304L austenitic stainless steel. GE required all austenitic stainless steel plates to be supplied in the solution heat treated condition. However, those fabrication welds which were made following delivery of the material as part of the top guide assembly process contain an as-welded heat affected zone (HAZ) that is a susceptible location for IGSCC. These weld locations might require inspection, depending on the role a particular component has with regard to top guide function.

In terms of IGSCC susceptibility, higher strength (or higher hardness) materials are in general more susceptible than the same materials with lower strength (or lower hardness). The GE purchase specifications established maximum hardness requirements after annealing of R_B 90 for Type 304 and Type 304L plate. This maximum value was selected because it provides sufficient structural margin for the material while limiting excessive hardening. The specifications also restricted bending to a minimum radius of 20 times the plate thickness (limiting the strain to less than 2.5%). This specification limits the local work hardening allowed in a component.

During installation of the top guide assembly there might have been installation steps which introduced localized regions of susceptibility. Along the curved surfaces such as the rim, there might also be localized regions that received more cold work from bending. If cracking were to initiate at such localized regions, it is not certain that through-thickness cracks would result. Regardless, such cracks would be limited to the length of the cold-worked region.

Therefore, top guide materials can be susceptible to IGSCC at locations where a heat affected zone or excessive cold work exists.

2.2.3 Stress State

During normal operation, no components of the top guide are highly stressed; however, residual stresses due to welding and fit-up can be significant. All weld locations which were not solution annealed have residual stresses associated with them. In general, the welds in the top guide assembly are similar enough that the residual stresses would not provide a means to differentiate by location or plant type.

The welding process introduces residual stress in the material. The level of this residual stress and the location of the tensile component vary with geometry and the welding process used. Experience and analysis verifies the presence of residual stress in all welds that are not subjected to annealing. The practice of annealing welds was not required during assembly of the top guide. During sub-assembly steps, the required dimensional stabilizing heat treatments were performed at temperatures between 550-750°F (288-399°C), but these heat treatments would not provide the benefits of solution heat treatments typically performed between 1,900-2,000°F (1038-1093°C).

Consequently, significant tensile stresses, the third requirement for IGSCC, might exist at weld locations in the top guide. Moreover, significant tensile stresses due to cold work, fit-up, and/or weld repair might also exist on the top guide, and these sources are difficult to quantify.

2.3 Conclusion

In summary, even though a low stress state during operating conditions is expected in the top guide grid beams, the highly oxidizing environment, high fluence level, and possibility of tensile stresses from other sources that are difficult to measure could lead to crack initiation. Therefore, based on the above evaluations, the top guide material is considered susceptible to stress corrosion cracking.

3
TOP GUIDE GRID BEAM CRACKING HISTORY

3.1 Top Guide Inspection History

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3.2 Top Guide Grid Beam Cracking History

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Table 3-1
General Top Guide Inspection Results

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Table 3-1 (continued)
General Top Guide Inspection Results

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Table 3-2
Oyster Creek Top Guide Grid Beam Inspection History

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Table 3-2 (continued)
Oyster Creek Top Guide Grid Beam Inspection History

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Table 3-3
Nine Mile Point, Unit 1 Top Guide Grid Beam Inspection History

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Table 3-3 (continued)
Nine Mile Point, Unit 1 Top Guide Grid Beam Inspection History

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Table 3-3 (continued)
Nine Mile Point, Unit 1 Top Guide Grid Beam Inspection History

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4 TOP GUIDE LOADINGS AND EVALUATIONS

Plant specific flaw acceptance evaluations were performed for the Oyster Creek and Nine Mile Point, Unit 1 top guides, with the results for one plant reported herein. The conclusions reached from these analyses are expected to bound all GE BWR/2-5 top guide designs under the assumption that they are all subject to similar loading conditions. No analysis is required for the GE BWR/6 top guides because its perforated plate design, with no crevices, precludes crevice cracking susceptibility. In addition, SIL No. 588R1 [3] recommends no inspection for BWR/6 top guides.

The analyses for BWR/2-5 top guides consist of finite element stress analyses of applicable loads and load combinations on the top guide, and fracture mechanics crack growth and flaw acceptance evaluations of grid beam flaws.

4.1 Loads and Load Combinations

The first step of the evaluation described herein is to obtain stresses from applicable loads and load combinations. The loads evaluated for the top guide grid beam structure are dead weight, pressure differentials due to fluid drag through the grid beam structure (both normal operating and faulted conditions), thermal loads (both normal operating and faulted conditions), and dynamic loads (both normal operating and faulted conditions).

Finite element analyses are performed for the prescribed load cases, and stress results from the analyses are combined to create appropriate loading scenarios that the top guide experiences.

4.2 Fracture Mechanics Evaluation

The flaw evaluation utilizes the linear elastic fracture mechanics (LEFM) techniques presented in Appendix B of BWRVIP-26-A. Fluence is time dependent and varies significantly across the height of the grid beams. Per BWRVIP-100-A [5], fluence affects the fracture toughness of the grid beam material. In addition, per BWRVIP-99 [6], fluence affects the crack growth rate (CGR) used to evaluate indications in the top guide grid beams.

Therefore, the scope of this project is to evaluate the reported indications considering the effects of varying fluence on CGR and fracture toughness. As a result, an analytical methodology was developed that accounts for the variations in fracture toughness and CGR.

Instead of using a constant CGR and fracture toughness (K_{Ic}) to perform the flaw evaluations at the end of the evaluation period, the approach will be time-dependent and use the appropriate CGR and fracture toughness based on the fluence at the crack tip location.

4.2.1 Flaw Acceptance Evaluation

Based on the methodology presented in Appendix B of BWRVIP-26-A, the stresses from the load combinations are curve-fit into a third order polynomial to calculate the resulting stress intensity factors (K_I and K_{III}), based on the grid beam geometry and crack size, and imported to a fracture mechanics program to perform crack growth and flaw acceptance evaluations.

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4.2.2 Fluence Dependent Fracture Toughness

For irradiated stainless steel material, BWRVIP-100-A addresses the variation in fracture toughness (K_{Ic}) in terms of fluence, as summarized in Table 4-1.

Table 4-1
Analysis Methods and Fracture Toughness

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4.2.3 Fluence Dependent Crack Growth Rate

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Table 4-2
Crack Growth Rates for SCC

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The use and impact of the parameters above are summarized in the flowchart shown in Figure 4-1. It shows that the evaluations are iterative and can be best performed using a computer code. As a result, a computer program, PolyCrack, was developed to perform real time crack growth and flaw acceptance evaluations.

A detailed evaluation of the Nine Mile Point, Unit 1 top guide grid beam flaws is presented in Appendix A, as an example analysis.

4.3 Conclusion

The results of the analyses presented in Appendix A conclude that normal operating loads do not create sufficient stresses in the grid beams to promote any significant growth due to IGSCC or IASCC.

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Figure 4-1
Flowchart for Fracture Mechanics Evaluation of Each Grid Beam Flaw

5
SEVERED BEAM EVALUATION

5.1 Introduction

One concern is the potential for a flaw to grow through the entire height of a grid beam, causing beam separation and excess beam deflection during a dynamic event, such that control rod blade insertion could be affected.

5.2 Seismic Analysis

A finite element analysis was performed on the Oyster Creek top guide, with the grid beam section at indications 5 and VT-6 severed (see Figure B-3 for the flaw locations). The lateral seismic force that will deflect the severed beams is the force perpendicular to the grid beam surface.

Such a seismic event will cause the fuel bundles to impact onto the grid beam surface. Appropriate pressure loading on the impact surfaces of the grid beams is applied to simulate the seismic event. The pressure load incorporates the added effect of fuel and associated water.

5.3 Results and Conclusion

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Figure 5-1
Maximum Deflection at Indication No. 5 of the Oyster Creek Top Guide

(Deformation shown is exaggerated for clarity. Undeformed shape is outlined.)

6
MULTIPLE CRACKS IN ONE BEAM

6.1 Introduction

Another concern is that multiple cracks could exist within a grid beam in one cell (see Figure 6-1), and that this could invalidate the fracture mechanics methodology based on a single edge cracked plate model that is used in BWRVIP-26-A.

6.2 Handbook Solutions

According to Tada, et al [8], for a semi-infinite space with an infinite number of parallel edge cracks (Figure 6-2), the applied stress intensity factor at the crack tips is smaller than that for a single edge cracked plate (Figure 6-3). Therefore, multiple cracks in the top guide grid beams can be conservatively evaluated as many single, independent cracks. As a result, the fracture mechanics methodology in BWRVIP-26-A is a valid and conservative approach.

6.3 Limitations

It should be noted that treating the multiple cracks individually as single edge cracks is only conservative in the fracture mechanics aspect of the flaw evaluation. It does not eliminate the other threats that multiple cracks in one beam could pose, such as the safety concern of potential loose parts when the cracks grow through-height.

The safety concern for potential loose parts is discussed in detail in the next section.

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Figure 6-1
Mulitple Cracks in One Grid Beam Cell

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**Figure 6-2
Parallel Edge Cracks in a Semi-Infinite Plate**

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Figure 6-3
Single Edge Notch Test Specimen

7
LOOSE PARTS EVALUATION

7.1 Introduction

If multiple cracks occurred within one grid beam cell and grew through the entire height of the grid beam, a loose beam fragment could potentially interfere with plant operations. Based on the information contained in BWRVIP-06-A [9], this evaluation addresses the safety and operational concerns during plant operation with a postulated loose part from the top guide.

The top guide structure, which is located in the upper core shroud region, is designed to maintain the lateral position of the fuel assemblies. Lateral support of the fuel assemblies is required to limit movement, thereby ensuring that insertion of control rods is possible at all times during normal and emergency conditions. Loose parts represent a safety concern if they result in the potential for fuel bundle flow blockage and consequent fuel damage, the potential for interference with control rod drive (CRD) operation, or the potential for corrosion or chemical reaction with other reactor materials. Only those loose parts which are not detectable and could impact safe plant operation and shutdown capability are generally considered to be of safety significance.

7.2 Loose Parts Description

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7.3 Safety and Operation Concerns

7.3.1 Potential for Fuel Bundle Flow Blockage and Consequent Fuel Damage

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7.3.2 Potential for Interference with CRD Operation

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7.3.3 Potential for Corrosion or Chemical Reaction with Reactor Materials

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7.3.4 Potential for Interference with RWCU or RHR Isolation Valves

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7.3.5 Potential for Interference with Main Steam Isolation Valves (MSIV)

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7.3.6 Potential for Damage to the Fuel Due to Fretting

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7.4 Conclusion

This evaluation concludes that safe reactor operation will not be compromised with the presence of postulated top guide loose parts in the reactor vessel. There is no safety concern for flow blockage to the fuel bundles, interference with the control rod scram function, corrosion or adverse chemical reaction with other reactor materials, or interference with MSIV, RWCU, or RHR isolation valves.

8
INSPECTION STRATEGY

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Therefore, based on the inspection experience, results of the analysis, and potential contribution from other crack initiation and growth mechanisms that have not been quantified, it is recommended that inspections of the top guide grid beams of all BWR plants be conducted.

8.1 Inspection Guidelines

All BWRs currently in operation shall perform inspections[1] of the top guide grid cells unless it can be demonstrated that the bottom portions have not exceeded the IASCC threshold fluence for stainless steel of 5.0×10^{20} n/cm^2.

8.1.1 BWR/2-5 Inspection Frequency

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[1] In some plants the top guide is included in the ISI program and receives a VT-3 examination. The examinations recommended by this guideline do not supersede the requirements of the ASME Code.

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Table 8-1
Quantity of Top Guide Cells Containing Control Rod Blades for Plants Reviewed in this Study

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Figure 8-1
Grid Beam Regions to be Inspected for BWR/2-5 Designs

8.1.2 BWR/6 Inspection Frequency

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8.2 Scope Expansion

Scope expansion shall be applied as follows.

8.2.1 BWR/2-5 Scope Expansion

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**Table 8-2
Flaw Length Determination**

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8.2.2 BWR/6 Scope Expansion

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8.3 Reinspection Guidelines

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8.4 Flaw Acceptance Criteria for Continued Operation

All flaws shall be evaluated for continued operation. The flaw acceptance evaluation shall be performed in accordance with Section 4. Refer to Appendix A for an example flaw evaluation.

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11. ASME Boiler and Pressure Vessel Code, Section II, Part D – Properties, 1998 Edition with Addenda through 2000.

A
TOP GUIDE GRID BEAM FLAW EVALUATION

Entire Appendix -
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B
FIT-UP STRESS EVALUATION

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