SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

BOILING WATER REACTOR (BWR) VESSEL AND INTERNALS PROJECT (BWRVIP)

TOPICAL REPORT (TR) "BWRVIP-139: BWR VESSEL AND INTERNALS PROJECT,

STEAM DRYER INSPECTION AND FLAW EVALUATION GUIDELINES"

BWRVIP

PROJECT NO. 704

1.0 INTRODUCTION

1.1 History

By letter dated May 11, 2005 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML051380174), the BWRVIP submitted TR "BWRVIP-139: BWR Vessel and Internals Project, Steam Dryer Inspection and Flaw Evaluation Guidelines," to the U.S. Nuclear Regulatory Commission (NRC) staff for review. The purpose of TR BWRVIP-139 is to define baseline visual inspection requirements for BWR steam dryer assemblies, current steam dryer configurations, areas of known fatigue cracking and intergranular stress corrosion cracking (IGSCC) susceptibility, locations of relatively high stress, flaw evaluation methods to be used if cracking is discovered, steam line moisture carryover measurement techniques, and limited flaw repair guidance.

By letter dated June 30, 2005 (ADAMS Accession No. ML051860129), the NRC staff provided its acceptance review to the BWRVIP. By letter dated September 28, 2005 (ADAMS Accession No. ML052760159), the BWRVIP submitted an errata to TR BWRVIP-139 with revised Table 5.1, indicating that for square hood steam dryer designs, interior as well as exterior inspections of the outer bank hoods, hood end plates, and cover plates, are recommended.

By letter dated April 13, 2006 (ADAMS Accession No. ML061140069), the NRC staff sent a request for additional information (RAI) to the BWRVIP. By letter dated August 9, 2007 (ADAMS Accession No. ML072250216), the BWRVIP stated that the response to the RAI would be sent to the NRC staff by November 30, 2007. The response to the RAI was received by the NRC staff in letter dated November 30, 2007 (ADAMS Accession No. ML073381267). In addition, by letter dated April 23, 2008 (ADAMS Accession No. ML081190085), the BWRVIP submitted supplemental information related to the NRC staff RAI including a list of summary of revisions to be made by the BWRVIP to TR BWRVIP-139.

1.2 Purpose and Applicability

TR BWRVIP-139 is intended to provide utility engineers with guidelines in planning for comprehensive baseline visual inspections of steam dryer assemblies. The results of the baseline inspections define a starting point that can be compared to subsequent inspection results to assess the potential effects of time and/or power increases on dryer condition. In addition to providing methods for evaluating flaws and defining repair approaches, TR BWRVIP-139 provides guidelines for inspecting critical locations in the steam dryer based on configurations and relative stresses due to operating fluctuating loads to minimize the risk of loose parts.

TR BWRVIP-139 applies to the BWR steam dryers that use commercially available modules of dryer vanes enclosed in a housing designed by General Electric (GE) making up the steam dryer assembly. TR BWRVIP-139 indicates that the guidance given for inspection locations is generic to the category of dryers, and it is affected by plant specific differences, repairs, or modifications.

1.3 Summary

TR BWRVIP-139 addresses the following items: (1) steam dryer configurations for various BWR plants, (2) a summary of dryer cracking incidents, (3) dryer regions prone to fatigue and IGSCC cracking, (4) failure modes and effects of cracking in steam dryer components, (5) an overview of the relative stresses in the different steam dryer components, (6) detailed inspection recommendations for the different dryer designs, (7) examples of evaluation approaches used to justify continued operation with IGSCC cracking or cracking in non-structural components that will not result in risk of loose parts generation, (8) operational guidance for monitoring moisture carryover, and (9) repair and flaw mitigation guidance.

TR BWRVIP-139 provides inspection and flaw evaluation guidelines for various steam dryers pertaining to operating BWRs to proactively address potential degradation of steam dryers. Steam dryers use commercially available modules of dryer vanes that are enclosed in a housing designed by GE to make up the steam dryer assembly. The modules or subassemblies of dryer vanes, called dryer units, are arranged in parallel rows called banks. Four to six banks are used depending on the vessel size. Dryer banks are attached to an upper support ring, which is supported by four to six steam dryer support brackets that are welded attachments to the reactor pressure vessel (RPV). The steam dryer assembly does not physically connect to the shroud head and steam separator assembly and it has no direct connection with the core support or shroud. A cylindrical skirt attaches to the upper support ring and projects downward forming a water seal around the array of steam separators. Normal operating water level is approximately mid-height on the dryer skirt.

During refueling, the steam dryer is supported from the floor of the equipment pool by the lower support ring that is located at the bottom edge of the skirt. Wet steam flows upward from the steam separators into an inlet header, horizontally through the perforated plates (if applicable) and dryer vanes, vertically in an outlet header and into the RPV dome. Steam then exits the RPV through steam outlet nozzles. Moisture is separated from the steam by the vane surface and the hooks attached to the vanes. The captured moisture flows downward by gravity to a collection trough that carries the liquid flow to drain pipes and vertical drain channels. The liquid flows by gravity through the vertical drain channels to the lower end of the skirt where the flow exits below normal water level. GE BWR steam dryer technology has evolved over many years and several product lines. The addition of perforated plates in certain designs results in a more uniform velocity over the height of the vanes. TR BWRVIP-139 describes 14 BWR steam dryer designs.

BWR 2/3/4/5/6 steam dryers are welded assemblies constructed with stainless steel type 304 with **[ ]**. Material in the weld heat affected zone is likely to be sensitized. Many dryer assembly welds have crevice areas at the weld root, which were not sealed from the reactor environment. Cold formed 304 stainless steel dryer parts were generally not solution annealed after forming and welding. Therefore, steam dryers are susceptible to IGSCC. Most of the steam dryer is located in the steam space, but the lower half of the skirt is below normal water level. These environments are highly oxidizing. The average steam flow velocity through the dryer vanes at rated conditions is relatively small (i.e., **[ ]**). However, local regions, near the steam outlet nozzles may be continuously exposed to steam flows in excess of **[ ]** with a concern for flow-induced vibration.

In order to capture the operating history of steam dryer degradation over the course of BWR plant operation, TR BWRVIP-139 summarized the BWR plant survey results from 21 plants characterizing the inspection methods, inspection frequency, and locations and extent of cracking associated with steam dryers. The plant survey data results in conjunction with component degradation information from GE Nuclear Energy were utilized by BWRVIP to develop a history of steam dryer cracking. Although there are specific issues related to certain dryer types, many of the cracking incidences associated with IGSCC of type 304 high carbon stainless steel in the as welded condition are common to the entire population of dryers. The characteristics of IGSCC crack growth are well known and provide the ability to manage and predict the future behavior of the existing IGSCC cracks. Some incidents of fatigue cracking are also found. The inspection and evaluation recommendations are based on information from the plant surveys and GE's internal data bases.

TR BWRVIP-139 included a brief discussion of the cracking in steam dryers based on the operating experience. The cover plate cracking associated with Quad Cities Nuclear Power Station (Quad Cities), Unit 2 became the focus of repair at several plants where the plate thickness and weld size provide the potential for cracking. Outer hood cracking in square hood dryer inner banks of BWR/2s and other types of dryers including BWR/4s was attributed to high cycle fatigue. Cracking detected in the end plates of dryer banks has been attributed to IGSCC and was followed over several operating cycles with the conclusion that it is stable when operating conditions or power levels are not changed. Drain channel cracking found in all types of BWRs was primarily attributed to fatigue and was also determined to be IGSCC due to type

304 stainless steel material sensitized by welding process and prone to crack initiation in the presence of cold work. High cycle fatigue caused crack initiation in the drain channel welds at the bottom of the drain channel, where there is maximum stress. These cracks were through the throat of vertical welds attaching the side of the drain channel to the exterior of the **[ ]** thick dryer skirt. Support ring cracking observed in many BWRs is identified as IGSCC caused by cold working during fabrication, and does not present any structural or loose part risk. Skirt cracking and drain channel cracking could be due to IGSCC or fatigue due to imposed local loads on steam dryer. Tie bar cracking is related to inadequate cross section of the tie bars to withstand the imposed displacements and stresses. The cracking in tack welds and lateral brackets of lifting rods was attributed to fatigue. Cracking was also observed in level screws, leveling screw welds, seismic blocks, dryer bank end plates and internal attachment welds, vertical internal hood angle brackets, and bottom plates.

The TR included a discussion on susceptibility considerations for cracking based on materials of construction and previous cracking experiences. The report indicates that locations with high local stresses due to stress concentration are susceptible to fatigue cracking. These high local stress locations when subjected to fluctuating loads can produce cracking, and further crack propagation may be driven with increasing rates by these loads as the cracks get longer. Areas of classic weld heat affected zones (HAZ) are locations where IGSCC can occur. IGSCC cracks are manageable as the growth rate is stable and the crack growth is predictable. Some components such as dryer vanes, which are cold bent and tack welded though susceptible for IGSCC, are not critical from structural or loose parts concern based on the location and overall geometry.

Section 4 of the TR addresses steam dryer loads and structural analysis in order to assess the relative stress levels at various locations of the dryer to identify areas for increased inspection based on their vulnerability to flow induced vibrations. Steam dryers fall into three categories, square hood, slanted hood, and curved hood, and within these categories the major difference is primarily dryer assembly diameter based on the plant size. The TR states that results of the finite element structural analysis (FEA) of the dryer subjected to plant data based reference pressure spectrum load were utilized to assess the vulnerability of the dryer to fluctuating stresses that can lead to fatigue damage, and to provide inspection recommendations. The evaluation based on ANSYS finite element code is used to identify the components of the dryer most susceptible to low and high frequency excitation. The input data for the fluctuating loads were derived from reference plants that had previously instrumented steam dryers. The reference plant enveloping pressure spectrum is adjusted based on plant specific steam line velocity to the reference plant steam line velocity and was broadened to account for the uncertainty in frequency. The inspection recommendations for the upper section of the dryer in the steam dome are based on ANSYS FEA. The inspection recommendations for the skirt and drain channel regions are based on experience as opposed to stress predictions.

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Section 5 of the TR provides inspection guidelines by classifying steam dryers to four different design types, namely BWR/2 design, square hood design, slanted hood design, and curved hood design. [

] TR BWRVIP-139 states that BWR owners may opt to follow the re-inspection guidance contained in SIL 644, Revision 1.

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Moisture carryover may be impacted by reactor power level, core flow and power distributions, core inlet sub-cooling, and reactor water level. As an operational guidance, the BWRVIP recommends to initiate a plant shutdown if the evaluation of the plant data confirms that a significant steam dryer damage has occurred.

Section 8 of the TR provides general guidance for mitigating or repairing postulated cracks in steam dryer components. [

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2.0 STAFF EVALUATION

2.1 Nondestructive Examination (NDE) Aspects

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The examination is to ensure steam dryer functionality and efficiencies by detecting detrimental cracks that could lead to parts breaking loose from the steam dryer. According to BWRVIP-139, the recommended **[ ]** examinations have successfully detected steam dryer cracks. The crack susceptible areas are in and around welds which are described for the different steam dryer designs. The **[ ]** field of direct vision on the outside surfaces normally encompasses the entire weld of interest while the field of vision for remote techniques normally performed on inside surfaces occasionally encounter obstructions that limit viewing. Where limited viewing exists, the licensees are performing best effort **[ ]** examinations.

The success of the BWRVIP approach to detect cracks is predicated on the crack tolerant aspects of the steam dryer. The **[ ]** examination can miss small cracks and not compromise the steam dryer's functionality and efficiencies. Large cracks are easily detected with a **[ ]** examination because they have wide crack opening dimensions that extend over a long crack length. Once a crack is detected, the licensee determines the cracking mechanism as either intergranular stress corrosion or fatigue. The cracking mechanism determination is based on crack surface appearance and crack proximity to the weld. To help in the determination process, the licensees may augment the **[ ]** by using magnification or alternative NDE methods, such as ultrasonic or eddy current testing.

Since the issuance of BWRVIP-139 and the additional NDE criteria in BWRVIP-03, original version, the NRC has published NUREG/CR-6860, "An Assessment of Visual Testing," dated November 2004, and NUREG/CR-6943, "A Study of Remote Visual Methods to Detect Cracking in Reactor Components," dated October 2007. These NUREGs have identified essential variables that are pertinent to successful visual examinations. The BWRVIP is evaluating the applicability of these NUREGs and will consider making changes in future revisions of BWRVIP-139, if appropriate.

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], the NRC staff believes that any deleterious cracks will be detected before they result in significant loose steam dryer parts.

2.2 <u>Mechanical and Structural Aspects</u>

The NRC staff has reviewed TR BWRVIP-139 dealing with steam dryer inspection and flaw evaluation guidelines. The NRC staff finds the inspection recommendations provided in the TR for steam dryer components reasonable as they are based on an extensive survey of operating experience data of BWR plants as well as structural evaluation of the dryer. The inspection recommendations for the upper section of the dryer in the steam dome are based on ANSYS FEA. The inspection recommendations for the skirt and drain channel regions are based on historic experience of steam dryer's performance in operating reactors. The NRC staff finds these inspection recommendations reasonable. The NRC staff reviewed the discussion on susceptibility considerations for cracking and concurs with the conclusion to consider areas with high local stresses or displacements as potential fatigue cracking locations and weld HAZ as potential IGSCC locations.

The NRC staff agrees that for structural evaluation of the steam dryer, analysis based on a three dimensional (3-D) finite element structural model using actual steam dryer configuration as stated in the TR is appropriate due to the complexity of the dryer structure and variations in design such as square hood, slanted hood, or curved hood models from plant to plant. The NRC staff reviewed and finds, the steam dryer structural analysis approach utilized by the BWRVIP to identify the locations of maximum relative stress for inspection purposes, reasonable as it is based on a detailed FEA of square hood, slanted hood, and curved hood type dryer configurations. The NRC staff also finds the reference fluctuating load inputs used in structural analysis acceptable as they are enveloping type loads from available in-plant pressure measurements on previously instrumented dryers from three different plants.

In response to NRC staff's request, the BWRVIP agreed to revise and expand Section 2.2 of the "A" version of TR BWRVIP-139 regarding the steam flow velocities as follows. Average steam flow velocities through the dryer vanes at rated conditions are **[ ]**. The steam flow velocity over the outer hood is in the range of **[ ]**. The highest velocities on the outer hood are in the region of the steam outlet nozzles where the flow is converging and accelerating towards the steam line. The velocities in this region may be in excess of **[ ]**. The steam line flow velocities are much greater than the velocities on the outer hood. For the majority of plants, these velocities are in the **[ ]** range and can be as high as **[ ]** for a limited number of plants. The flow of the steam over the outer hood and through the steam lines can lead to flow turbulence and acoustic pressure loading on the steam dryer components. The NRC staff reviewed the revised portion and finds it acceptable as it contained the requested information on steam line flow velocities.

The NRC staff also requested the BWRVIP to address generic significance of steam dryer failures in addition to Quad Cities dryer failures. In response, the BWRVIP provided updated Section 1 which includes an enhanced discussion on Quad Cities dryer failures and modifications including the acoustic load mitigation devices installed in safety relief valve stand pipes. These devices eliminated the high amplitude high frequency pressure loading on the dryer. The updated section also addressed cracking found in fillet welds of upper support ring and cover plate in the Dresden Nuclear Power Station (Dresden) units. General features of Dresden and Quad Cities replacement dryers were also included. The updated section is acceptable to the NRC staff.

As a response to the NRC staff's request regarding plant specific aspects of steam dryer loading, the BWRVIP stated that steam dryer fluctuating pressure loading is very plant specific and is dependent on steam dryer design, the steam velocity, plant-specific geometry of local standoff piping at relief valves, and flow past the dryer outer hood and into the nozzles. The industry is pursuing to develop plant specific load definition methodologies based on testing and analysis. TR BWRVIP-139 recommends applying the guidance given in TR BWRVIP-182 upon approval by the NRC staff for plants considering a power uprate to demonstrate steam dryer integrity. The NRC staff considers the information regarding plant-specific steam dryer loading reasonable.

In Section 5.3 of TR BWRVIP-139 dated April 2005 (ADAMS Accession No. ML051380174), the BWRVIP stated that it would provide steam dryer re-inspection provisions following review of baseline inspection results and corresponding plant operational parameters. In the interim, TR BWRVIP-139 indicated that BWR owners may opt to follow the steam dryer re-inspection provisions contained in GE Service Information Letter (SIL) 644, Revision 1, “BWR Steam Dryer Integrity.” In RAI 139-9, the NRC staff requested the BWRVIP to discuss the steam dryer re-inspection guidance for BWR licensees while its steam dryer re-inspection provisions were being developed.

By letter dated November 30, 2007 (ADAMS Accession No. ML073381267), the BWRVIP stated that the BWR Owners Group does not make specific recommendations regarding the performance of periodic steam dryer inspections. The BWRVIP noted that SILs, such as SIL-644, Revision 1, are issued directly by GE to BWR customers. The BWRVIP stated that sufficient baseline inspections have been conducted by the BWR plants to include re-inspection guidance in a revision to TR BWRVIP-139. **[**

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In response to RAI 139-8, the BWRVIP provided the results of the steam dryer baseline inspections for BWR plants that were used to support the planned steam dryer re-inspection provisions. The **[ ]** approach to steam dryer re-inspections in the planned revision to BWRVIP-139 differs from the specific re-inspection schedule provided in GE SIL-644. Each BWR licensee will determine the appropriate re-inspection approach according to GE SIL-644 or BWRVIP-139 in consideration of the steam dryer performance at its plant.

Based on the results of the steam dryer baseline inspections to date, the NRC staff considers a **[ ]** approach for steam dryer re-inspections to be acceptable where the licensee justifies extension of the re-inspection interval on an incremental refueling outage basis by an evaluation of the steam dryer inspection results to support the extended re-inspection interval. Similarly, unanticipated steam dryer inspection results would constitute a basis for reduction of the steam dryer re-inspection intervals. License conditions associated with steam dryer monitoring programs in power uprate license amendments take precedence over the steam dryer re-inspection provisions in GE SIL-644 or BWRVIP-139. The licensee will justify any adjustments to its steam dryer re-inspection program where commitments exist to implement the re-inspection provisions in GE SIL-644 in support of a power uprate license amendment or other activities. The licensee is expected to inform the NRC staff of significant changes to its steam dryer re-inspection program where the staff relied on the program in a regulatory decision.

3.0 CONCLUSION

Based on the above evaluation, the NRC staff considers the guidance provided in TR BWRVIP-139 for NDEs capable of detecting cracks before they create loose steam dryer parts.

In addition, the NRC staff agrees with the two bases utilized by TR BWRVIP-139 to provide susceptible steam dryer locations recommended for inspection as they are based on (1) prior extensive operating history experience data on cracking and (2) steam dryer structural evaluation using 3-D FEA analysis to identify maximum relative stress locations. The NRC staff also finds the structural evaluation approach utilized by the BWRVIP reasonable as it is based on detailed 3-D FEA analyses of squared hood, slanted hood, and curved hood type steam dryer configurations. The NRC staff agrees with the statement in the TR that the size of the dryer or the dryer diameter affects the stiffness of the components and the magnitude of stresses and displacements, but will not affect the location of the highest relative stresses as the specific component differences such as the dryer hood type, presence of internal stiffening structures, or dryer inner bank thickness are more critical for locations of high relative stresses. The NRC staff finds the BWRVIP-139 TR, supplemented by updated information, acceptable as it is based on a proactive approach to address potential degradation of steam dryers by providing recommended locations of steam dryer components for inspection. As discussed throughout this SE, the modifications that are stated in response to the NRC staff's RAIs must be incorporated in the "A" version of BWRVIP-139.

For re-inspection, the guidelines below must be followed:

- Each BWR licensee will determine the appropriate re-inspection approach according to GE SIL-644 or BWRVIP-139 in consideration of the steam dryer performance at its plant.

- License conditions associated with steam dryer monitoring programs in power uprate license amendments take precedence over the steam dryer re-inspection provisions in GE SIL-644 or BWRVIP-139.

- The licensee will justify any adjustments to its steam dryer re-inspection program where commitments exist to implement the re-inspection provisions in GE SIL-644 to support a power uprate license amendment or other activities.

- The licensee is expected to inform the NRC staff of significant changes to its steam dryer re-inspection program where the staff relied on the program in a regulatory decision.

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