Attachment 3

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ABWR Dryer Operating Experience for STP Units 3 and 4

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WCAP-17369-NP
Revision 1

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1 EXECUTIVE SUMMARY

The first Advanced Boiling Water Reactor (ABWR) Kashiwazaki-Kariwa Unit No. 6 (K-6) commenced commercial operation in 1996, followed by Unit No. 7 the following year which are both operated by Tokyo Electric Power Company (TEPCO). A third ABWR, Hamaoka Unit No. 5 (H-5), operated by Chubu Electric Company, commenced commercial operation in January 2005. The ABWR is an evolutionary design that builds on operating Boiling Water Reactor (BWR) experience and includes significant design improvements such as the reactor internal pump (RIP) and fine motion control rod drives (FMCRD) as well as material advances, which have led to outstanding operating history in all operating ABWRs.

This report describes the evolution of dryer design from BWR/2 to ABWR, the operating experience[1] with steam dryers in both BWR and ABWR plants, [ ][a,c], and the design improvement and vibration assessment plans for STP Units 3&4 ABWR. Based upon the discussion above, this report provides an assessment of the expected performance of STP dryer.

The field experience is separated into three parts:

1. Operating BWRs at original licensed thermal power (OLTP) where some cracking was observed but no significant structural issues were seen.

   Cracking was observed in several locations in BWR dryers (e.g. drain channel welds, dryer hoods, dryer support rings, tie rods). The cracking in these cases was not considered to be structurally significant and was addressed by routine repairs such as stop-hole drilling at the crack tip, larger welds or component stiffening with thicker panels.

2. Field experience at Quad Cities and the extensive cracking observed in the dryer when the plant was operating at Extended Power Uprate (EPU) at 117% of OLTP.

   Evaluation of the loading conditions indicated that the Electromatic Relief Valve (ERV) standpipe configuration resulted in acoustic resonance. The plant modified the stand pipe configuration by installing an acoustic side branch to eliminate the acoustic resonance at high power. Following the implementation of this modification, both Quad Cities units have been operating successfully under EPU conditions with no damage to the steam dryer.

[ ][a,c]

[1] Operating experience and field experience are essentially the same in this report.

[ ]a,c

As part of the Regulatory Guide 1.20 Rev. 3 (Reference 1) program for a prototype reactor, the STP Unit 3 dryer will be instrumented with pressure transducers, strain gages and accelerometers in the pre-operational and initial startup power testing. In particular, as part of initial plant startup, STP Unit 3 will be subject to a power ascension program similar to that used in operating BWRs prior to EPU implementation. Starting at approximately a 60% power plateau, data from the instrumentation will be analyzed to verify that the dryer stresses are within acceptable limits. The analysis will be performed by comparison with limit curves. The analysis will be performed at approximately 10% increments up to 100% power and will assure that the stresses remain within acceptable limits.

In summary it can be stated that:

1. ABWR design is an evolutionary design that has incorporated design changes and improvements based upon operational experience of previous generations of BWR designs.

[ ]a,c

6. The STP Unit 3 dryer will undergo a comprehensive vibration assessment program (CVAP) that would involve a power ascension plan to hold the power level at 60% to collect [ ]a,c, to allow development of limit curves that would be utilized to go up to 100 % power level in discrete steps.

This report concludes that based upon discussion above, the STP Unit 3&4 dryers would meet the cyclic stress requirements and perform without degradation during power operation.

2 INTRODUCTION AND BACKGROUND

The main function of the steam dryer in a BWR is to remove moisture from the steam in order to minimize erosion of piping and the turbine. The dryer is not safety-related and is not an ASME Code component. Although there have been some differences in the design configuration of the steam dryer with evolution of BWR types (BWR/2-6) and the ABWR, the basic features of the dryer have remained the same.

The steam dryer assembly is mounted in the reactor vessel above the separator assembly and forms the top and sides of the wet steam plenum. During refueling operations, the dryer is removed to allow access to the reactor core. Vertical guide rods on the inside of the vessel provide alignment for the dryer assembly during re-installation. The dryer assembly is supported by brackets extending inward from the vessel wall and is held down in position during operation by the vessel head hold down brackets. Steam from the separators flows upward and outward through the dryer's drying vanes. These vanes are attached to a top and bottom supporting member forming a rigid integral unit. Moisture is removed and carried by a system of troughs and drains to the pool surrounding the separators and then into the recirculation downcomer annulus between the core shroud and reactor vessel wall.

Historically, there have been instances of minor cracking in BWR steam dryers, with the exception of the more significant Quad Cities EPU-related dryer cracking (discussed later). A variety of options, (e.g. hole drilling to stop crack growth, increasing weld size and replacement of plates with thicker plates), have been implemented successfully as design fixes. Cracking in the dryer would have to be very significant to cause structural integrity concerns. Because dryers are visually inspected after removal in outages, significant cracking and associated loose parts due to cracking during the subsequent cycle are unlikely (the experience at the two Quad Cities units was an exception because of the Electromatic Relief Valve (ERV) stand pipe configuration which caused acoustic resonance and subsequent dryer cracks when EPU conditions were applied). When cracking has occurred as a result of plant operation, design fixes were implemented successfully [

]^{a,c}.

Section 3 of this report describes the evolution of the BWR dryer designs and describes how the ABWR dryers incorporate the improvements in dryer design.

Section 4 of the report describes the field experience in operating BWR plants at original licensed thermal power (OLTP) operation. Specifically, it addresses the most historically common locations of cracking – drain channel and skirt cracking, hood and tie rod cracking and intergranular stress corrosion cracking (IGSCC) of the steam dryer support ring. The driving force and mechanism of cracking and the design fixes are discussed. It also describes how the ABWR dryer design features address the cracking mechanism.

Section 5 describes the field experience at the Quad Cities Station and the extensive cracking observed in the dryer when the plant was operating at extended power uprate (EPU) conditions (117% of OLTP). Evaluation of the source of the loading conditions indicated that the ERV standpipe configuration resulted in acoustic resonance. The plant modified the stand pipe configuration (by installing an acoustic side branch to 'detune' the system) to address acoustic resonance. With the implementation of this modification, both Quad Cities units have been operating successfully under EPU conditions with no reported damage to the steam dryer.

Section 6 describes the ABWR operating experience, in particular, the operating history of various ABWRs in Japan. It also provides [ ]^{a,c} as well as the inspection results. In addition, it describes the results of [ ]^{a,c}.

Section 7 describes [ ]^{a,c}.

Section 8 discusses the expected performance of the STP dryers and describes why cracking of the type experienced in other dryers is not expected to occur at STP 3&4. It describes how the lessons learned from previous dryer cracking have been incorporated in the STP dryer design. It also describes the elements of the Regulatory Guide 1.20 Rev. 3 program that will be implemented for STP Unit 3, specifically, the STP Unit 3 instrumentation plans and the power ascension measurement and analysis plan (starting at approximately 60% power and subsequent incremental increases in power) to further assure the structural integrity of the STP 3&4 dryers.

Section 9 summarizes the technical basis for the conclusion that the STP dryers will perform their design function without degradation and in accordance to design requirements during power operation.

Appendix A provides the procedures and summary of results [ ]^{a,c}.

3 EVOLUTION OF THE STEAM DRYER DESIGN (FROM BWR/2 TO ABWR)

BWRVIP-139-A (Reference 2) describes the evolution of BWR steam dryers from BWR/2 to BWR/6 designs. GE BWR steam dryer technology has evolved over many years and several product lines. BWRVIP-139-A Figure 2-4 shows the evolution of the steam dryer designs, which started as square hoods, then slanted hoods with perforated plates, to the current curved hoods with perforated plates.

Some BWR/2 GE steam dryers inclined the dryer units 20° from vertical (see BWRVIP-139-A Figure 2-6); however, later GE BWR steam dryers installed the units vertically. Earlier BWR/2 and BWR/3 dryers (see BWRVIP-139-A Figure 2-9) used square hoods and the typical active height of the dryer vanes was 48 inches. BWR 2/3 dryers did not use perforated plates.

In BWR 4/5 steam dryers the active vane height was increased to 72 inches. Perforated plates were included on the inlet and outlet sides of the vanes in order to more effectively utilize the increased vane height. The addition of perforated plates results in a more uniform velocity over the height of the vanes. BWRVIP-139-A Figure 2-21B shows dryers with slanted hoods for earlier BWR/4 plants and BWRVIP-139-A Figure 2-23 shows a detail of the slanted hood design. BWRVIP-139-A Figure 2-37 shows the curved hood design used in late model BWR/4 and all BWR/5 and BWR/6 plants.

The changes in the design such as the change to a curved hood dryer (greater structural capability), taller dryer banks (to accommodate increased active vane height) and the use of perforated plates (more uniform steam velocity) provided greater structural capability and better performance (see BWRVIP-139-A Figure 2-38 for details of the curved hood design). These features were incorporated in the BWR/5 and BWR/6 dryers. The ABWR dryer design is similar to the BWR/6 design configuration but incorporated the following additional design changes:

- Dimensional changes, e.g. thicker plates, larger weld sizes, wraparound welds on the edges of plates, to increase structural and fatigue margins.
- Material changes, e.g. change from Type 304 stainless steel to L grade stainless steel (Type 316 L or 304L), to eliminate sensitization and mitigate intergranular stress corrosion cracking (IGSCC).
- Elimination of as many creviced welds as possible.
- Controls on fabrication procedures, e.g. restrictions on grinding and cold work, to improve IGSCC resistance.

4 FIELD EXPERIENCE WITH BWR DRYERS (PRE-QUAD CITIES DRYER CRACKING)

There have been instances of minor cracking in BWR dryers over the last 30 years. Routine repairs were applied in these cases and the dryers were returned to service. Because the steam dryer is not a safety-related component, the service-induced cracking in the dryers did not result in any safety concerns. In all these cases, the observed cracking occurred under power levels at or slightly above OLTP. The cracking in the Quad Cities Unit 2 steam dryer under EPU conditions was much more extensive. Subsequent analysis concluded that the root cause of the damage at Quad Cities Unit 2 under EPU was different from the early dryer cracking (at the OLTP). Because of the significant differences in the dryer cracking (extent of cracking and root cause), the following field experience discussion is separated into two parts: 1) pre-Quad Cities cracking in plants operating at or slightly higher than OLTP, and 2) post- Quad Cities cracking in plants operating under EPU conditions. This section describes the pre-Quad Cities field experience.

Figure 4-1 shows the different locations where cracking has occurred in BWR steam dryers. BWRVIP-139-A Figure 2-51 (Reference 2) shows the number of U.S. BWR plants with steam dryer cracking (by location). It is seen that the support ring and the drain channel welds are the most likely locations for cracking. The details of the cracking, cause and design fixes or repairs are discussed below:

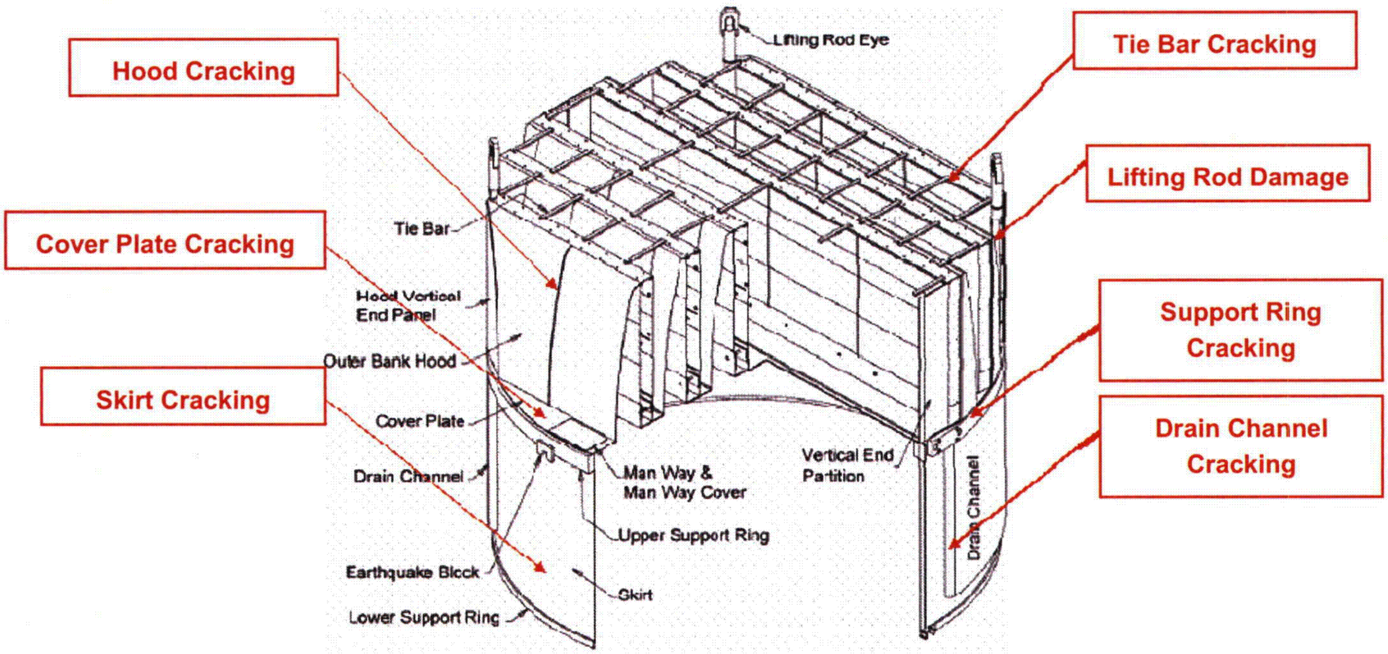

Figure 4-1 Field Cracking in BWR Steam Dryers

Drain Channel Cracking

Drain channel cracking has occurred in many U.S. BWR dryers and is attributed to high cycle fatigue and IGSCC. In Type 304 stainless steel dryers, welded regions are subject to weld sensitization and the weld heat affected zone (HAZ) can experience IGSCC. However, even when crack initiation is due to IGSCC, subsequent crack growth can occur due to fatigue. There have been many instances of fatigue cracking in the drain channel welds. The cracks were generally through the throat of vertical welds that attach the side of the drain channel to the exterior of the dryer skirt. The cracks are thought to have originated at the bottom of the drain channel where there is maximum stress in the welds. The high fatigue strength reduction factor at the fillet weld, weld residual stresses and flutter vibration of the relatively thin drain channel are believed to be the contributors to the cracking. The design fixes for the cracking include stop-hole drilling at the crack tip (short term) and increasing the weld size. The weld was also modified to wrap around the bottom of the attachment (where the drain channel is open at the end) to eliminate the sharp notch.

[ ] a,b,c

Support Ring Cracking

Support ring cracking has been found in many U.S. BWRs (at least 19 plants). The accepted cause of cracking has been IGSCC with potential contributors being weld sensitization and cold working during the fabrication process. Unlike fatigue crack growth, IGSCC crack growth rates decrease as the crack driving force from the residual stress attenuates. Most plants with support ring cracking have chosen to monitor the cracks and no repairs are planned.

[ ] a,b,c

Tie Bar Cracking

Tie bar fatigue cracking has been reported in several U.S. BWR plants. The tie bars connect different dryer banks and increase the overall stiffness of the dryer. Fatigue cracking has been observed in plants with slender tie bars made of angle iron. The fact that plants with stiffer tie bars have not experienced fatigue cracking suggests that the potential for cracking is related to the size of the cross section of the tie bar itself.

[ ] a,b,c

Dryer Hood Cracking

Outer hood cracking has occurred in 11 U.S. BWR plants, more often so in square hood design dryers. These hood cracks were attributed to high cycle fatigue. The curved hood provides higher structural capability when compared to the square hood designs. The fix for the hood cracking has been to increase the weld size and in some cases, increase the thickness of the hood plate.

[ ]a,b,c

Skirt Cracking

Skirt cracking has been associated with drain channel cracking (i.e., the location of skirt cracking is near the drain channel welds). The cracking is believed to be due to a combination of IGSCC and fatigue.

[ ]a,b,c

Lifting Rod Cracking

Lifting rod cracking has been due to a combination of weld HAZ IGSCC and fatigue cracking in tack welds and bracket attachments. They have been fixed by removing the cracks and performing weld repair.

The ABWR field experience has been excellent, due mainly to the use of IGSCC resistant material and improved weld designs.

Cover Plate Cracking

Cover plate cracking is associated with Quad Cities Unit 2 as discussed in the next Section. It has been addressed by increasing the thickness of the plate and the associated welds.

Conclusion

The ABWR dryer design incorporates the lessons learned from the field experience in earlier BWRs and cracking has not been observed in ABWR dryers. The excellent field experience [ ]a,c.

5 FIELD EXPERIENCE WITH DRYERS UNDER EPU (POST-QUAD CITIES CRACKING)

This section (taken largely from BRVIP-139-A) describes the field experience specific to the Quad Cities units under EPU conditions.

In March 2002, Quad Cities Unit 2 reached EPU power level of 117% OLTP after its planned refueling outage and began continuous operation at this power level. In June 2002, several anomalous readings related to pressure, water level, steam flow and moisture carry over were detected and it was determined that the steam dryer was operating in a degraded condition. The plant was subsequently shut down to perform a visual inspection of the steam dryer. The inspection revealed that one cover plate adjacent to one of the outer bank inlet hoods was missing. The root cause was identified at that time as high cycle fatigue caused by low frequency pressure loading. Quad Cities Unit 2 replaced the 1/4 inch cover plates with new 1/2 inch cover plates and ½ inch fillet welds and the plant was returned to its EPU operating level of 117% OLTP.

In April 2003, Quad Cities Unit 2, while operating at 117% OLTP, experienced an inadvertent opening of a pilot operated relief valve (PORV). The plant was shut down and the PORV replaced. Following return to EPU conditions, a significant increase in moisture content was observed and the plant elected to shut down the unit in June 2003 for steam dryer inspections. Significant cracking including a through-wall crack approximately 90 inches long was observed in the top of the outer hood cover plate and the top of the vertical hood plate. There was also failure of the internal braces in the outer hood. After metallurgical and analytical evaluations, the cause of the second steam dryer failure was determined to be high cycle fatigue due to low frequency pressure loading. Following the second failure, steam dryer modifications included replacing the damaged ½ inch outer hood plates with 1 inch plates and adding gussets at the outer vertical hood plate and cover plate junction. The combined effect of these modifications was to increase the natural frequency of the outer hood and reduce the maximum stress. Following the repairs, the unit was returned to service in June 2003.

During the Quad Cities Unit 2 dryer inspection in the spring 2004 refueling outage, cracking was observed in some of the previous repairs and modifications. After the third repair (some to address cracking in the prior repairs) the unit was returned to service at the completion of the outage. It was clear, however, that the extent of the loading on the dryer was not fully understood and that the local stress concentration factors may have contributed to the cracking.

Similar cracking was also observed in Quad Cities Unit 1 under EPU operation, in October 2003. Detailed inspection of the steam dryer during the outage revealed significant damage to the outer hood similar to that observed on Unit 2 in June 2003. Following the steam dryer modifications similar to that used in Unit 2, EPU operation was resumed by Unit 1.

The steam dryers in both Quad Cities units were replaced with new dryers incorporating a series of improvements (e.g., thicker hood plates, stronger welds, use of full penetration welds where possible and IGSCC resistant materials). Installation of the new dryer also gave the opportunity to instrument the Unit 2 dryer with pressure transducers, strain gages and accelerometers. Tests were conducted at incremental power levels up to EPU power levels. Contrary to the earlier belief that the damage may have been caused by low frequency pressure loading, it was evident that the damage was caused by high frequency pressure loading based on the instrumented steam dryer test data at Quad Cities 2. This high frequency pressure loading resulted from a coupling of the vortex shedding frequency at the inlets of the relief valves and the ¼ standing wave acoustic frequencies of the valve stand pipes. The acoustic resonance not only caused dryer cracking, but also resulted in damage to several ERV actuators in the Quad Cities units.

Since the damage was due to acoustic resonance, one way to eliminate the severe loading was to 'detune' the system by increasing the effective length of the relief valve standpipes. The licensee decided to add an 'acoustic side branch' (ASB), which increases the effective length and decreases the frequency of the acoustic standing wave. Since the vortex shedding frequency remains the same at a given power level, reducing the acoustic standing wave frequency eliminates the potential for resonance (i.e., coupling of the acoustic and vortex shedding frequency) at the EPU flow velocities. This also means that resonance can occur at a lower steam velocity, but the loading will also be lower. Installation of the ASBs has eliminated the high amplitude, high frequency pressure loading on the steam dryer. The Quad Cities steam dryers have since been operating under EPU conditions with ASBs and there has been no reported degradation.

It is interesting to note that there is a power level (or, alternatively, steam flow velocity) at which there is coupling of the acoustic and vortex shedding frequencies (resonance) and loading on the dryer is increased. However, if the coupling occurs at lower power level, even with the load amplification by the resonance, the magnitude of the load on the dryer is acceptable. [

]a,c.

6 ABWR OPERATING EXPERIENCE AND INSPECTION

This section describes the ABWR operating experience based upon [

]a,c.

a,c

a,b,c

a,b,c

a,c

7 [

]a,c

[

]a,c. Therefore, the STP steam dryer is expected to perform without degradation and in accordance with design requirements.

Table 7-1 [ ]^a,c

a,b,c

Table 7-2 [ ]a,c

a,b,c

8 EXPECTED PERFORMANCE OF STP DRYERS

The performance of the STP 3&4 ABWR dryers is expected to be better than that of previous BWR dryer designs for several reasons including design improvements when compared to BWRs and designing the system to avoid resonance at higher power levels. A comprehensive vibration assessment program (CVAP) including dryer instrumentation pre-operational testing, measurement and analysis will demonstrate compliance with the guidance of Regulatory Guide 1.20 Rev. 3 and a power ascension plan with limit curves will assure that the cyclic stresses are within stress limits specified in the STP 3&4 COLA. These reasons are discussed in more detail in the following subsections.

8.1 DESIGN IMPROVEMENTS

In addition to the design features in the BWR/6 dryer, the STP dryers incorporate additional design, materials and fabrication improvements that mitigate the potential for service induced cracking:

[ ]a,c

Table 8-1 Comparison of the STP Dryer with BWR/2-6 Dryers

a,b,c

Cracking Attribute	
Component	Support Ring
	Drain Channel
	Dryer Hood
	Tie Bar
	Skirt
	Lifting Rod
Cracking Mechanism	IGSCC
	Fatigue
	Crevice cracking
	Acoustic Resonance
Regulatory Codes	ASME
	BWRVIP

8.2 DESIGN TO AVOID ACOUSTIC RESONANCE

[ ]a,c

8.3 COMPREHENSIVE VIBRATION ASSESSMENT PROGRAM (CVAP)

STP Unit 3 will include a comprehensive vibration assessment program that meets the guidance of Regulatory Guide 1.20 Rev. 3. STP Unit 3 is conservatively designated as a 'prototype' per the definition in the regulatory guide, although there is a significant amount of vibration test data [ ]a,c. Consistent with the definition in Regulatory Guide 1.20 Rev. 3, STP Unit 4 is designated as 'Non-prototype, Category I' since it has the same arrangement, design, size, and operating conditions as STP Unit 3, which will have been tested as a prototype. The STP Unit 3 dryer will include instrumentation (e.g. pressure transducers, accelerometers and strain gages) to monitor the loading and structural response of the dryer. This will provide verification that the vibratory stresses are below the endurance limit. [ ]a,c add further confirmation of the adequacy of the STP 3&4 dryers.

8.4 POWER ASCENSION PLAN

The initial plant startup plan will include a power ascension program to monitor the dryer response at different power levels. The process will be similar to the power ascension plan used by BWR plants implementing EPU. [

]^{a,c}. Use of the power ascension plan with incremental power steps will assure that the vibratory stresses in the dryer are within acceptance limits as the plant goes to full power.

9 CONCLUSIONS

Based on [

]^{a,c} the plans for extensive instrumentation of the STP dryer and the preoperational and start-up power testing to confirm that the dryer stresses are within applicable stress limits, it can be concluded that the STP 3&4 dryers will meet the cyclic stress requirements and will perform without degradation during power operation.

10 REFERENCES

1. Regulatory Guide 1.20, Revision 3, "Comprehensive Vibration Assessment Program for Reactor Internals during Preoperational and Initial Startup Testing," U.S Nuclear Regulatory Commission, March 2007.

2. BWRVIP-139-A: BWR Vessel and Internals Project, *Steam Dryer Inspection and Flaw Evaluation Guidelines*," EPRI Technical Report 1018794, July 2009. (Proprietary)

3. BWR Vessel and Internals Project, *Guidelines for Selection and Use of Materials for Repairs to BWR Internal Components* (BWRVIP-84)," EPRI Technical Report 1000248, October 2000 (Proprietary)