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For Information Only – Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper, PA-MSC-0474

This letter transmits two (2) non-proprietary copies of PWROG document "Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper", developed by AREVA and Westinghouse under PWROG program PA-MSC-0474. This document is being submitted for information only. No safety evaluation (SE) is expected and therefore, no review fees should be incurred.

This white paper summarizes the recent occurrences of ODSCC of stainless steel piping identified at Callaway, Wolf Creek and SONGS. Available operating experience (OE) at units that have observed similar phenomena is summarized as well to give a better understanding of the issue. Each of the key factors that contribute to ODSCC was considered along with the reported operating experience to perform a preliminary assessment of areas that may be susceptible to ODSCC. Also a qualitative evaluation was performed to determine whether ODSCC of stainless steel piping represents an immediate safety concern.

This white paper is meant to address the issue of ODSCC of stainless steel systems for the near term. I&E guidelines are currently being developed through the PWROG to provide long term guidance.

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Sincerely yours,

Melvin L. Arey, Jr.

Melvin L. Arey, Jr., Chairman
PWROG Owners Group

MLA:JPM:las

Enclosures:

1. Two (2) non-proprietary copies of PWROG document "Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper"

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Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper

PA-MSC-0474
October 13, 2010

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ODSCC Revised Final White Paper

Prepared: Ryan Hosler (AREVA)

1.0 Purpose

The purpose of this white paper is to perform an evaluation of the recently observed occurrences of outside diameter initiated stress corrosion cracking (ODSCC) of stainless steel piping components in the PWR industry and to make a preliminary assessment of the issue.

2.0 Scope

This white paper summarizes the recent occurrences of ODSCC of stainless steel piping identified at Callaway, Wolf Creek and SONGS. Available operating experience (OE) at units that have observed similar phenomena is summarized as well to give a better understanding of the issue. Each of the key factors that contribute to ODSCC were considered along with the reported operating experience to perform a preliminary assessment of areas that may be susceptible to ODSCC. Also a qualitative evaluation was performed to determine whether ODSCC of stainless steel piping represents an immediate safety concern.

3.0 Operating Experience

3.1 Recent OE

Recent operating experience at Callaway, Wolf Creek and SONGS has shown ODSCC of austenitic stainless steel piping. These events are summarized below.

3.1.1 Callaway

During outage preparation work in the fall of 2008, Callaway discovered a small boric acid leak in the 2-inch diameter Schedule 160, Type 304 stainless steel pressurizer auxiliary spray line underneath a painted pipe support clamp. The leak was found to be less than five drops per minute. The affected piping had been in service for 24 years when the leak was discovered. Because auxiliary pressurizer spray is not a function required by technical specifications, a functionality determination was performed that concluded that the line was degraded but was still functional.

During the fall 2008 outage, Callaway removed additional insulation for cleaning and a second support clamp was found to be corroded. The amount of corrosion products present indicated that there could be another leak under the second pipe support clamp, although no active leaking was observed. The affected section of pipe was replaced and the cracked pipe was sent to a metallurgical lab for destructive testing to determine the crack initiator.

Metallography results showed branched transgranular cracks. Laboratory penetrant testing found through-wall cracks in the pipe under the first support, but not under the second support. Trace levels of chlorides were detected on the fracture surface by SEM/EDS analysis, which exhibited characteristics typical of stress corrosion cracking in stainless steel. Pitting corrosion was also observed on the surface of the pipe under both support clamps after the boric acid and corrosion products were removed. The pitting corrosion was also likely caused by the presence of chlorides. The cause of the leaks was concluded to be outside diameter initiated stress corrosion cracking induced by the presence of chlorides on the surface of the pipe.

The operating experience provided by Callaway did not identify the source of chlorides. Given that cracking occurred in the piping at the support clamp, it is possible that crevice conditions between the pipe and the clamp allowed the concentration of sufficient chlorides to cause cracking. Crevice conditions can allow trace contaminants, such as chlorides, on the pipe surface and in the air to concentrate in the crevice. This process is discussed further in section 4.1.2.

3.1.2 Wolf Creek

As a result of the cracking observed at Callaway, Wolf Creek inspected the Type 304 stainless steel pressurizer auxiliary spray line beneath the support clamps in the fall of 2009. Similar to the auxiliary spray line at Callaway, the line at Wolf Creek is insulated. Leakage in the form of boric acid deposits was observed. In 12 of the 14 locations inspected, dye penetrant testing revealed axial indications that were individually characterized as 1/32" to 3/8" in length. The affected piping had been in service for 24 years when the leak was discovered. Close grouping and alignment of the indications were also observed by non-destructive testing, which required that the indications be combined and considered as a single flaw when compared to the acceptance criteria. Destructive evaluation is still underway, but the indications are believed to be ODSCC that likely developed from chlorides that concentrated under the piping support clamps.

Visual inspections for leakage in the form of boric acid deposits were performed on seven other portions of piping in systems judged to be potentially susceptible to ODSCC (i.e., Chemical & Volume Control, Accumulator Safety Injection, and High Pressure Coolant Injection). The inspected piping did not have any boron crystal deposits, thus no leakage was noted.

Evaluation of this incident is still underway.

3.1.3 San Onofre Nuclear Generating Station (SONGS)

In response to the cracking observed at Callaway and Wolf Creek, SONGS Unit 2 performed visual inspections of the pressurizer auxiliary spray line. No boric acid deposits were found.

Boric acid deposits were identified in the fall of 2009 during a walk down of the emergency core cooling system (ECCS) stainless steel suction piping and the stainless steel piping from the refueling water storage tanks to the charging pumps at both SONGS Units 2 and 3. An additional leak was identified on the common train ECCS mini-flow return line to the refueling water tank. The affected piping was not insulated nor were crevice conditions present at the observed indications. The leaks were not immediately consequential because the leak rates were too small to quantify, and the flaws were stable and acceptable based on Code Case N-513-2. The affected piping was in service for 25 years and was exposed to the outside marine environment. All observed cracking was located in the weld heat affected zone (HAZ) of Type 304 stainless steel with a carbon content in excess of 0.03 wt%. General surface pitting corrosion was observed with a higher concentration of pitting observed in the weld HAZ. The HAZs of the Schedule 10 stainless steel piping were sensitized. Destructive evaluation is still underway, but the cause of leakage is believed to be due to a combination of both outside and inside diameter initiated SCC.

3.2 Historical OE

Given the recent occurrences of ODSCC in stainless steel pipe at Callaway, Wolf Creek and SONGS, it is prudent to take a look at other units that have experienced similar phenomena. The key elements of each these ODSCC occurrences are summarized in Table 1. This list is not comprehensive, but it provides a reasonable cross section of the historical data.

Table 1: ODSCC of Stainless Steel Piping*

Unit	Component	Nominal Size	Temperature	Contaminant	Stress Source	Service Life/ Year Found	Source
Callaway (W)	PZR Aux Spray Line	2" Sch. 160	550°F in use and 80-110°F not in use	Chlorides (source unknown)	2250 psi pressurized pipe	24 years /2008	CAR 200809 886
Wolf Creek (W)	PZR Aux Spray Line	2" Sch. 160	550°F in use and 80-110°F not in use	Chlorides (source unknown)	2250 psi pressurized pipe	24 years /2008	OE 30001
San Onofre Unit 2 & 3 (CE)	ECCS suction piping	24" Sch. 10	Outside ambient	Chlorides (marine environment)	Residual stress in weld HAZ	25 years /2009	OE 30296
San Onofre Units 2 & 3 (CE)	Alternate boration gravity feed to charging line	6" Sch. 10	Outside ambient	Chlorides (marine environment)	Residual stress in weld HAZ	25 years /2009	OE 30296
San Onofre Units 3 (CE)	ECCS mini flow return to RWST	Not available	Outside ambient	Chlorides (marine environment)	Residual stress in weld HAZ	25 years /2009	OE 30296

Seabrook (W)	Inlet piping to residual heat removal pump suction relief valve	Not available	Not available	Chlorides (non standard insulation)	Residual stress in weld HAZ	7 years /1997	INPO event # 443-971205-1
Ikata (Mitsubishi)	CVCS standby charging pipe	Not available	120-212°F Maintained during start up	Chlorides (Vinyl chloride tape)	Pressure not available	23 years /2000	OE 12516
Sequoyah Units 1&2 (W)	CVCS BA transfer line	1” Sch. 40	175-185°F Normal operation	Chlorides (source unknown)	Not available	3 years /1986	OE 1845
Turkey Point Unit 3 (W)	CVCS BA transfer line	¾”-3” Sch. 40	180°F (1st 19 years) and 130°F (4 years)	Chlorides (source unknown)	Residual stress in weld HAZ	23 years /1995	OE 7201
St. Lucie Unit 2 (CE)	ECCS suction piping	24” Sch. 10	Outside ambient	Chlorides (marine environment)	Residual stress in field weld HAZ	16 years /1993	OE 10050
Salem Unit 1 (W)	RCS instrument tubing	3/8” tubing	Not available	Chlorides (historic spills or service water leaks)	Residual stress in weld HAZ	29 years /2006	OE 22672
River Bend (GE BWR)	CRD hydraulic system piping	Not available	125°F	Chlorides (historical spill)	1200-1300 psi pressurized pipe	8 years /1994	LER # 94-027-00
Fukushima Daiichi Unit 3 (Toshiba BWR)	CRD hydraulic system piping	Not available	125°F	Chlorides (leaking seawater pipe)	1200-1300 psi pressurized pipe	26 years /2002	OE 15325
North Anna Unit 1 (W)	Lower head safety injection piping in the valve pit	10” Sch. 40S	Not available	Chlorides (leaking ground water)	Residual stress in weld HAZ	27 years /2005	Root Cause N-2005-5034

*Affected materials are Type 304 stainless steel with carbon content likely greater than 0.03 wt%. Seabrook and Ikata OE did not specify stainless steel grade.

3.2.1 German OE

An overview of 30 years of German operating experience with ODSCC of stainless steel is presented in Reference 1. The information from this source was not included in Table 1 because the document summarizes and draws conclusions from the events, but does not provide specific information about each event. However, it is worth considering this reference to support understanding of the phenomena.

Of all the occurrences of TGSCC of stainless steel components in units located in Germany (11 PWRs and 6 BWRs), about 12% initiated on the outside surface of the pipe. The observed ODSCC had three consistent features: 1) any size pipe or component may be affected with similar probability, 2) cracking was mostly discovered before it led to leakage because it is identifiable from the outside and 3) the chloride source could be identified in most cases. Some examples of chloride sources were vinyl chloride tape, overhead dripping water pipe and chloride containing adhesives, much like what was seen in the U.S. and Japan. Most cracking was observed at locations that operated at higher temperature, but in some cases cracking was found below 120°F.

The example given by Reference 1 for ODSCC occurring at relatively low temperatures is Koeberg Nuclear Station, which is located in South Africa. Widespread ODSCC of stainless steel piping that operated below 120°F was observed at Koeberg. Chlorides were present on the affected piping in ample quantities due to the marine environment. Testing has shown that sensitization plays a strong role in the SCC susceptibility of austenitic stainless steel in a coastal environment [2], but it is unknown whether this material was sensitized. The piping concerned was manufactured from cold rolled plate having one continuous seam weld that was not annealed to remove the imposed residual stress [3]. These high residual stresses may have contributed to the observed ODSCC.

4.0 ODSCC Factors

There are two types of SCC: intergranular and transgranular. Intergranular stress corrosion cracking (IGSCC) propagates along the crystalline grain boundaries and is common among sensitized austenitic stainless steels. Transgranular stress corrosion cracking (TGSCC) grows through the crystalline grains and typically involves chloride contamination. Crack propagation was transgranular in all of the ODSCC events considered in this paper except North Anna, which was intergranular. Outside diameter initiated IGSCC is discussed in section 4.3.1.

ODSCC of stainless steel will not occur unless three synergistic elements of SCC are present: 1) aggressive environment, 2) sustained tensile stress and 3) susceptible material. The rate of crack growth will depend on the severity of these three elements.

The three synergistic elements discussed below are known to contribute to ODSCC susceptibility. However, the magnitude of each element required for crack initiation and growth is not known. Nor is it fully understood how interactions between these elements drive ODSCC. The EPRI MRP are currently performing research activities to better understand these unknowns as part of the "SCC of Austenitic Stainless Steel in PWRs Environments Strategic Plan," which is maintained by the "SCC of Stainless Steel" core team in the PWROG. These efforts focus on inside diameter initiated SCC of stainless steel lines, but many of the same principles apply to ODSCC as well.

The following sections state the current understanding of the factors affecting the three synergistic elements of SCC.

4.1 Environment

An aggressive environment is one of the three required elements for SCC initiation and growth. The key environmental parameters promoting ODSCC in austenitic stainless steels are temperature and halogens.

4.1.1 Temperature

The minimum temperature required for ODSCC is limited by the required driving force for SCC. Reference 4 refers to a general rule of thumb for the onset of SCC in water of 140°F. It is emphasized that this temperature applies only to austenitic stainless steels that are not sensitized and are in near-neutral pH waters of moderate to low chloride content (moderate to low was not defined). Low pH, concentrated chlorides, sensitization or high tensile stresses could lead to failures at temperatures below 140°F. For piping indoors in a controlled environment, the minimum temperature for the occurrences of ODSCC may be as low as 120°F based on operating experience. For piping outside in a marine environment, ODSCC is possible at ambient temperature.

In the case of ODSCC, the maximum temperature that cracking can occur is limited by the ability for moisture to accumulate on the piping outer surface. At atmospheric pressure moisture will typically not remain on the piping outer surface above 212°F unless there is a constant replacement, as by active drops or sprays. It is possible for moisture to exist above 212°F in a crevice where the dew point can be altered. All ODSCC occurrences considered in this white paper were on piping operating below 212°F.

4.1.2 Halogens

Halogens, such as chlorides, are known to be a key contributor to ODSCC in stainless steel [5].

For components exposed to the outdoors, levels of chlorides high enough to cause cracking are typically due to a marine environment. For units on the coast, salt water in the air provides ample chlorides and moisture. For non-coastal units, the sources of chlorides are expected to be similar to those for indoor piping, as discussed below.

Indoors in a controlled environment, levels of chlorides high enough to cause cracking are typically due to 1) a contamination event or 2) a mechanism that concentrates trace chlorides over time. Possible chloride contamination events include use of vinyl chloride tape, spills of high chloride containing substances, use of high chloride containing non-standard insulation and exposure to leaking water containing chlorides. Components that have crevices, heat tracing or are alternately wetted/dried can concentrate trace chlorides on the surface over time.

Crevice conditions most frequently occur in joints and connections, or points of contact between metals, such as pipe hangers and clamps. Contaminants and corrosion products tend to concentrate in crevices [5]. Alternate wetting/drying can lead to concentration of atmospheric pollutants and contaminants.

Heat tracing is sometimes used to provide heat to a stainless steel line. For example, heat tracing insulation has been used on the CVCS boric acid transfer line prior to boron concentration reduction modifications. Due to alternate wetting/drying, heat tracing can concentrate water soluble contaminants (e.g., chlorides) present on the outer surface of the piping [5].

4.2 Stress

Tensile stress is the second element required for SCC initiation and growth. There does not appear to be a minimum level of stress for SCC incidence, the stress level merely dictates the time to failure [5]. The two types of stresses that promote ODSCC in austenitic stainless steels are operational and residual.

4.2.1 Operational

Operational stresses tend to be applied on the entire component when in service and are relaxed when the component is not in use. In the case of piping, the main operational stresses are due to pressurization and thermal expansion, which create a tensile stress on the outer surface of the pipe.

4.2.2 Residual

Residual stresses are stresses that remain after the original cause of the stresses (e.g., operational pressure, thermal gradients, cold work, etc.) has been removed. In the case of annealed austenitic stainless steel piping, the most common cause of residual stresses is welding. These residual stresses create tensile stresses on the outside surface of the pipe adjacent to the weld and typically in the weld HAZ. Residual stresses can also be caused by cold work, such as pipe fabricated from cold-rolled plate. However this is considered to be an extreme case since cold rolled stainless steel has a higher susceptibility to SCC compared to the annealed stainless steel that is typically used in the U.S. fleet.

4.3 Material

Material susceptibility is the third required element for SCC initiation and growth. Austenitic stainless steel can be most susceptible to ODSCC when it is sensitized or when conditions permit pitting corrosion to occur. Sensitization or pitting is not required for ODSCC, but they do increase material susceptibility.

4.3.1 Sensitization

The straight grades of austenitic stainless steels with medium carbon levels ($0.03<C<0.08$ wt%) can become sensitized in the weld HAZ. During the welding process, the base metal surrounding the weld reaches temperatures (800-1500°F [7]) high enough to cause chromium to diffuse towards the grain boundaries and form chromium carbides. This reduces the material's local chromium content surrounding the grain boundaries, and effectively decreases the material's resistance to ODSCC. Sensitization can be minimized or prevented by using the low-carbon (<0.03%) or stabilized grades of stainless steels.

Experimental testing has shown that austenitic stainless steels exposed to a marine atmospheric environment have an increased susceptibility to ODSCC when the material is sensitized [2]. Based on destructive examination, cracking appears to have initiated as IGSCC due to the carbon depletion surrounding the grain boundaries and then propagated as TGSCC due to the chloride present in the coastal air.

The cracking observed at North Anna Unit 1 was found to be OD-initiated IGSCC with heavy sensitization acting as a main contributing factor [8]. The Type 304 stainless steel pipe had the maximum allowable carbon content of 0.08 wt%. Since the original construction welding procedures did not specify the maximum heat input, it was assumed that the heat input was likely high. The combination of high carbon and high welding temperature caused the weld HAZ to become heavily sensitized. The other contributing factors were exposure to leaking ground water and residual stresses from the welding process. The chloride content of the ground water around the containment and auxiliary buildings ranged from 1.9 to 28 ppm.

4.3.2 Pitting

Pitting is a corrosion mechanism that is more common with passive materials such as austenitic stainless steels. Most pitting is the result of halide contamination (e.g., chlorides) [6]. Any continuously wetted or alternately wetted/dried surfaces tend to concentrate aggressive species such as chlorides and are prone to pitting. Type 316 is more resistant than Type 304 to pitting due to its molybdenum content [9].

Pits commonly act as initiation sites for ODSCC because the pits further concentrate chlorides and they provide a point of stress concentration [10]. In cases where only trace amounts of chlorides are present, ODSCC will likely not initiate until pitting corrosion has occurred.

5.0 Areas Potentially Susceptible to ODSCC

This section will identify areas of austenitic stainless steel piping that are potentially susceptible to ODSCC using current knowledge of the ODSCC phenomena discussed in section 4.0 and the operating experience considered in section 3.0. This assessment is limited to the near term and may be modified as a result of the future work described in section 10.0.

Indoors in a controlled environment, potentially susceptible areas of austenitic stainless steel piping are those that have all three of the following conditions: 1) extended amount of time between 120 and 212°F, 2) sustained tensile stress and 3) sufficient chloride contamination to cause measurable cracking. Based on the OE considered in this white paper, it typically takes several years for small cracks to develop. In the case of stainless steel piping, tensile stress is due to pressurization or residual stress from the weld thermal cycle, grinding or some other form of cold-work. Levels of chlorides high enough to cause measurable cracking are typically due to either a contamination event (e.g., vinyl chloride tape, spills, non-standard insulation or leaking raw water) or a mechanism that concentrates trace chlorides over time (e.g., crevice or alternate wetting/drying, such as heat tracing).

Austenitic stainless steel indoors in a controlled environment could be susceptible to ODSCC when the pipe temperature is greater than 212°F if cool raw water was leaking on to the pipe. This could locally cool the pipe and the alternate wetting/drying would concentrate chlorides from the raw water.

For austenitic stainless steel outside in a marine environment, testing has shown that heavy sensitization increases susceptibility to SCC [2]. Heavily sensitized samples with high tensile stress cracked in less than five years while heavily sensitized samples with moderate stress did not crack. There does not appear to be a minimum level of stress for SCC incidence, the stress level merely dictates the time to failure [5]. Austenitic stainless steel can become sensitized in the weld HAZ when it has a high carbon content (>0.03 wt%). The welding process can create high residual stresses adjacent to the weld (typically in the weld HAZ). High tensile stresses can also be caused by grinding or other cold-work imposed on the pipe surface. Piping fabricated from cold-rolled plate has high residual stresses, but this is not common practice in the U.S. fleet.

Austenitic stainless steel piping outside that is not exposed to a high chloride containing environment is considered to be significantly less susceptible to ODSCC because relatively high concentrations of chlorides are required to drive cracking at ambient temperature.

6.0 Existing Inspection Requirements

Under existing inspection requirements, stainless steel piping undergoes visual, surface and volumetric inspections for cracks, active leaking of coolant and boric acid deposits. Inspections are performed indirectly by each unit's boric acid corrosion control (BACC) program and directly by ASME B&PV Code Section XI or a Risk Informed In-service Inspection (RI-ISI) program.

6.1 BACC Program

U.S. NRC Generic Letter 88-05 [11] requires all PWR utilities to implement a BACC program that consists of systematic measures to ensure that there is an extremely low probability of abnormal leakage, rapidly propagating failure, or gross rupture of the reactor coolant pressure boundary due to boric acid corrosion. Generic Letter 88-05 only requires inspection of carbon steel and low-alloy steel piping, since stainless steel is not susceptible to boric acid corrosion.

Since the industry response to Generic Letter 88-05 varied significantly from unit to unit, WCAP-15988 was created to provide generic guidance to serve as a basis for developing consistent and satisfactory BACC programs [12]. This guidance has two NEI 03-08 requirements: 1) each utility must have a BACC program (mandatory) and 2) each program shall contain the attributes laid out in WCAP-15988 (needed).

The BACC programs created by the PWR utilities require visual walk down inspections of carbon steel and low-alloy steel piping during each refueling outage. During these walk down inspections of carbon steel and low-alloy steel piping, boric acid deposits may also be observed on the surrounding stainless steel piping. PWR utilities are required to consider stainless steel piping leaking borated water onto carbon steel and low-alloy steel piping in their BACC programs [12].

6.2 ASME Section XI

Section XI of the ASME B&PV Code requires all Class 1, 2 and 3 piping to be visually (VT-2) inspected during pressure tests. According to Table IWB-2500-1, Class 1 piping is VT-2 inspected each refueling outage. Based on Tables IWC-2500-1 and IWD-2500-1, Class 2 and 3 piping is VT-2 inspected each period (40 months). The time that VT-2 inspections are performed on Class 2 and 3 piping is different for each unit. Since the 69 PWRs in the U.S. inspect specific Class 2 and 3 systems at different times, most if not all piping systems will be visually inspected each refueling outage (across the fleet, not at a single unit).

Section XI also requires surface and volumetric examinations of pressure retaining welds in Class 1 and 2 piping. For Class 1 piping, 25% of all the welds are examined each 10 year inspection interval. For Class 2 piping, the sampling criteria is reduced to 7.5% and only applied if the nominal pipe size (NPS) is greater than four inches. Of the welds requiring examination, inspections are evenly distributed over the 10 year interval. The extent of examination is 100% of each weld requiring inspection. The time that these inspections are performed on Class 1 and 2 piping is different for each unit. Since the 69 PWRs in the U.S. inspect specific Class 1 and 2 systems at different times, most of Class 1 and 2 piping systems will be inspected each refueling outage (across the fleet, not at a single unit).

Section XI requires a sample of welded attachments to Class 1, 2 and 3 piping to be periodically inspected. Welded attachments to Class 1 and 2 piping are surface examined and attachments to Class 3 piping are visually (VT-1) examined.

6.3 RI-ISI Program

Many U.S. PWR units have implemented an approved RI-ISI program, which replaces the ASME Section XI examination requirements for piping. The program is sometimes applied to Class 1 piping only or to all Class 1, 2 and 3 piping. The RI-ISI program is similar to the ASME Section XI examination requirement with some modifications. In general, application of the RI-ISI methodology tends to increase the number of inspection locations in higher risk pipe segments and decrease the number of inspections in lower risk pipe segments. Risk in this case is based on the safety significance of an individual pipe segment. The safety significance is determined by the consequences of failure and the likelihood of failure. The likelihood of failure was based on several potential degradation mechanisms including SCC, but OD-initiated SCC was not considered. Since a RI-ISI program will increase inspections at pipe locations with high consequences of failure, its effectiveness in detecting OD-initiated SCC in safety significant locations is considered similar to inspections performed per ASME Section XI.

7.0 Safety Concern Evaluation

The key factors that contribute to ODSCC are considered to qualitatively evaluate whether ODSCC of stainless steel piping represents an immediate safety concern. The focus of this assessment is on piping temperature, stress and material.

7.1 Temperature

The growth rate of ODSCC in stainless steel piping is limited by the pipe surface temperature. It is generally accepted that the rate of SCC crack growth increases with increasing temperature. Since SCC typically occurs on the pipe surface at temperatures below 212°F, the rate of crack growth is significantly less than what is seen at higher temperatures.

7.2 Stress

The stress component of ODSCC is from operational stresses and residual stresses. In the case of austenitic stainless steel piping, pressurization and thermal expansion account for the operational stresses and residual stresses are typically in the HAZ due to the welding that is performed to join the piping together. The surface tensile stresses in the weld HAZ are higher than the base metal because the stress magnitude is a combination of both operational and weld residual stresses. The welding sequence creates residual stresses in the weld HAZ, which create high tensile stress at the outside surface, but at some point through the wall thickness the residual stresses become compressive. This variability in stress field affects the driving force for cracking and can cause crack growth to slow.

In cases where pitting corrosion is present, such as under support clamps, the stress component of ODSCC is likely due to stress concentration points in corrosion pits coupled with the stresses due to pressurization and thermal expansion. As discussed in section 7.3, in some cases ODSCC initiates in pits. Since it takes time for pits to develop, ODSCC that initiates in a pit may take many years to develop.

7.3 Material

Austenitic stainless steel piping is not prone to brittle fracture due to the inherent ductility at all relevant temperatures of the material. The annealed austenitic stainless steel used for piping applications has a high resistance to brittle fracture and this resistance does not diminish over time since in piping applications, the material is not embrittled as the result of neutron radiation nor are the wrought forms of austenitic stainless steels susceptible to thermal embrittlement since they have low (<1 percent) delta ferrite. For these reasons, catastrophic failure of austenitic stainless steel pipe due to SCC is rare. None of the occurrences of ODSCC discussed in this paper resulted in significant leakage or catastrophic failure.

Austenitic stainless steels have a passive surface layer that makes them resistant to general corrosion, but susceptible to pitting corrosion when chlorides and moisture are present. Pits commonly act as initiation sites for ODSCC because the local chemistry in a pit is conducive to cracking and the pit can act as a point of stress concentration. In cases where only trace amounts of chlorides are present, ODSCC will likely not initiate until pitting corrosion has occurred. When chloride concentrations are low the pitting process can take an extended period of time. Since it takes time for pits to develop, ODSCC that initiates in a pit may take many years to develop.

7.4 Crack Tightness

The tight nature of SCC makes it difficult to visually identify. If cracking becomes through-wall, leakage can be visually identified by the presence of boric acid deposits in borated water systems. SCC allows a minimal amount of leakage, which is commonly too small to measure. The ability to locate through-wall cracks in borated systems by visual means while they are small and tight gives sufficient time to react before leakage and crack size become significant. Leakage from small tight cracks is visually identifiable in the form of boric acid deposits regardless of whether the piping is insulated. For example, the leakage at Callaway was observed while insulation was in place. Callaway's evaluation of the flaw size found that the piping was structurally sound.

In non-borated systems, leakage is more difficult to visually identify due to the absence of boric acid deposits. The auxiliary feedwater system is the key safety related system that contains non-borated water. This system is not insulated so identifying leaks during a periodic pressure test will be possible even though boric acid deposits will not be present.

7.5 Safety Concern Determination

The ODSCC phenomena observed in austenitic stainless steel piping is not a safety concern in the near term because crack growth is generally slow, the piping material has a high resistance to brittle fracture and the ability to identify through-wall cracks in borated systems while they are small and tight allows sufficient time to react before crack size becomes structurally significant. The auxiliary feedwater system is the key safety related system that contains non-borated water. This system is not insulated so identifying leaks during a periodic pressure test will be possible even though boric acid deposits will not be present.

8.0 Summary

ODSCC of stainless steel piping will not occur unless the three synergistic elements of SCC are present: 1) aggressive environment, 2) sustained tensile stress and 3) susceptible material. However, the magnitude of each element required for crack initiation and growth is not known. Nor is it fully understood how interactions between these elements drive ODSCC. The EPRI MRP is currently performing research activities to better understand these unknowns as part of the "SCC of Austenitic Stainless Steel in PWRs Environments Strategic Plan," which is maintained by the "SCC of Stainless Steel" core team in the PWROG. These efforts focus on inside diameter initiated SCC of stainless steel lines, but many of the same principles apply to ODSCC as well.

Under existing inspection requirements, stainless steel piping undergoes visual, surface and volumetric inspections for cracks, active leaking of coolant and boric acid deposits. Inspections are performed indirectly by each unit's BACC program and directly by ASME B&PV Code Section XI or a RI-ISI program.

The ODSCC phenomena observed in austenitic stainless steel piping is not a safety concern in the near term because crack growth is generally slow, the piping material has a high resistance to fracture and the ability of required inspections to identify through-wall cracks in borated water systems while they are small and tight allows sufficient time to react before crack size becomes structurally significant.

9.0 Conclusions

Experience has demonstrated that BACC programs, RI-ISI and ASME Section XI inspections, along with other plant activities, to be effective in identifying OD-initiated cracks or associated leaks long before the crack is of structural significance. Therefore the existing inspection requirements are adequate for addressing the ODSCC of stainless steel in the near term because the current requirements provide a reasonable cross section of the data and the phenomenon is not an immediate safety concern.

10.0 Future Plans

The PWROG MSC "SCC of Stainless Steel" strategic plan will be updated to account for this recent OE in our long-term plans. This will include a thorough extent of condition assessment and development of long term inspection and mitigation recommendations.

11.0 References

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Subject: PWR Owners Group
For Information Only – Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper, PA-MSC-0474

This letter transmits two (2) non-proprietary copies of PWROG document "Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper", developed by AREVA and Westinghouse under PWROG program PA-MSC-0474. This document is being submitted for information only. No safety evaluation (SE) is expected and therefore, no review fees should be incurred.

This white paper summarizes the recent occurrences of ODSCC of stainless steel piping identified at Callaway, Wolf Creek and SONGS. Available operating experience (OE) at units that have observed similar phenomena is summarized as well to give a better understanding of the issue. Each of the key factors that contribute to ODSCC was considered along with the reported operating experience to perform a preliminary assessment of areas that may be susceptible to ODSCC. Also a qualitative evaluation was performed to determine whether ODSCC of stainless steel piping represents an immediate safety concern.

This white paper is meant to address the issue of ODSCC of stainless steel systems for the near term. I&E guidelines are currently being developed through the PWROG to provide long term guidance.

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Sincerely yours,

Melvin L. Arey, Jr.

Melvin L. Arey, Jr., Chairman
PWROG Owners Group

MLA:JPM:las

Enclosures:

1. Two (2) non-proprietary copies of PWROG document "Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper"

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Outside Diameter Initiated Stress Corrosion Cracking Revised Final White Paper

PA-MSC-0474
October 13, 2010

Prepared: Ryan Hosler (AREVA)
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ODSCC Revised Final White Paper

Prepared: Ryan Hosler (AREVA)

1.0 Purpose

The purpose of this white paper is to perform an evaluation of the recently observed occurrences of outside diameter initiated stress corrosion cracking (ODSCC) of stainless steel piping components in the PWR industry and to make a preliminary assessment of the issue.

2.0 Scope

This white paper summarizes the recent occurrences of ODSCC of stainless steel piping identified at Callaway, Wolf Creek and SONGS. Available operating experience (OE) at units that have observed similar phenomena is summarized as well to give a better understanding of the issue. Each of the key factors that contribute to ODSCC were considered along with the reported operating experience to perform a preliminary assessment of areas that may be susceptible to ODSCC. Also a qualitative evaluation was performed to determine whether ODSCC of stainless steel piping represents an immediate safety concern.

3.0 Operating Experience

3.1 Recent OE

Recent operating experience at Callaway, Wolf Creek and SONGS has shown ODSCC of austenitic stainless steel piping. These events are summarized below.

3.1.1 Callaway

During outage preparation work in the fall of 2008, Callaway discovered a small boric acid leak in the 2-inch diameter Schedule 160, Type 304 stainless steel pressurizer auxiliary spray line underneath a painted pipe support clamp. The leak was found to be less than five drops per minute. The affected piping had been in service for 24 years when the leak was discovered. Because auxiliary pressurizer spray is not a function required by technical specifications, a functionality determination was performed that concluded that the line was degraded but was still functional.

During the fall 2008 outage, Callaway removed additional insulation for cleaning and a second support clamp was found to be corroded. The amount of corrosion products present indicated that there could be another leak under the second pipe support clamp, although no active leaking was observed. The affected section of pipe was replaced and the cracked pipe was sent to a metallurgical lab for destructive testing to determine the crack initiator.

Metallography results showed branched transgranular cracks. Laboratory penetrant testing found through-wall cracks in the pipe under the first support, but not under the second support. Trace levels of chlorides were detected on the fracture surface by SEM/EDS analysis, which exhibited characteristics typical of stress corrosion cracking in stainless steel. Pitting corrosion was also observed on the surface of the pipe under both support clamps after the boric acid and corrosion products were removed. The pitting corrosion was also likely caused by the presence of chlorides. The cause of the leaks was concluded to be outside diameter initiated stress corrosion cracking induced by the presence of chlorides on the surface of the pipe.

The operating experience provided by Callaway did not identify the source of chlorides. Given that cracking occurred in the piping at the support clamp, it is possible that crevice conditions between the pipe and the clamp allowed the concentration of sufficient chlorides to cause cracking. Crevice conditions can allow trace contaminants, such as chlorides, on the pipe surface and in the air to concentrate in the crevice. This process is discussed further in section 4.1.2.

3.1.2 Wolf Creek

As a result of the cracking observed at Callaway, Wolf Creek inspected the Type 304 stainless steel pressurizer auxiliary spray line beneath the support clamps in the fall of 2009. Similar to the auxiliary spray line at Callaway, the line at Wolf Creek is insulated. Leakage in the form of boric acid deposits was observed. In 12 of the 14 locations inspected, dye penetrant testing revealed axial indications that were individually characterized as 1/32" to 3/8" in length. The affected piping had been in service for 24 years when the leak was discovered. Close grouping and alignment of the indications were also observed by non-destructive testing, which required that the indications be combined and considered as a single flaw when compared to the acceptance criteria. Destructive evaluation is still underway, but the indications are believed to be ODSCC that likely developed from chlorides that concentrated under the piping support clamps.

Visual inspections for leakage in the form of boric acid deposits were performed on seven other portions of piping in systems judged to be potentially susceptible to ODSCC (i.e., Chemical & Volume Control, Accumulator Safety Injection, and High Pressure Coolant Injection). The inspected piping did not have any boron crystal deposits, thus no leakage was noted.

Evaluation of this incident is still underway.

3.1.3 San Onofre Nuclear Generating Station (SONGS)

In response to the cracking observed at Callaway and Wolf Creek, SONGS Unit 2 performed visual inspections of the pressurizer auxiliary spray line. No boric acid deposits were found.

Boric acid deposits were identified in the fall of 2009 during a walk down of the emergency core cooling system (ECCS) stainless steel suction piping and the stainless steel piping from the refueling water storage tanks to the charging pumps at both SONGS Units 2 and 3. An additional leak was identified on the common train ECCS mini-flow return line to the refueling water tank. The affected piping was not insulated nor were crevice conditions present at the observed indications. The leaks were not immediately consequential because the leak rates were too small to quantify, and the flaws were stable and acceptable based on Code Case N-513-2. The affected piping was in service for 25 years and was exposed to the outside marine environment. All observed cracking was located in the weld heat affected zone (HAZ) of Type 304 stainless steel with a carbon content in excess of 0.03 wt%. General surface pitting corrosion was observed with a higher concentration of pitting observed in the weld HAZ. The HAZs of the Schedule 10 stainless steel piping were sensitized. Destructive evaluation is still underway, but the cause of leakage is believed to be due to a combination of both outside and inside diameter initiated SCC.

3.2 Historical OE

Given the recent occurrences of ODSCC in stainless steel pipe at Callaway, Wolf Creek and SONGS, it is prudent to take a look at other units that have experienced similar phenomena. The key elements of each these ODSCC occurrences are summarized in Table 1. This list is not comprehensive, but it provides a reasonable cross section of the historical data.

Table 1: ODSCC of Stainless Steel Piping*

Unit	Component	Nominal Size	Temperature	Contaminant	Stress Source	Service Life/ Year Found	Source
Callaway (W)	PZR Aux Spray Line	2" Sch. 160	550°F in use and 80-110°F not in use	Chlorides (source unknown)	2250 psi pressurized pipe	24 years /2008	CAR 200809886
Wolf Creek (W)	PZR Aux Spray Line	2" Sch. 160	550°F in use and 80-110°F not in use	Chlorides (source unknown)	2250 psi pressurized pipe	24 years /2008	OE 30001
San Onofre Unit 2 & 3 (CE)	ECCS suction piping	24" Sch. 10	Outside ambient	Chlorides (marine environment)	Residual stress in weld HAZ	25 years /2009	OE 30296
San Onofre Units 2 & 3 (CE)	Alternate boration gravity feed to charging line	6" Sch. 10	Outside ambient	Chlorides (marine environment)	Residual stress in weld HAZ	25 years /2009	OE 30296
San Onofre Units 3 (CE)	ECCS mini flow return to RWST	Not available	Outside ambient	Chlorides (marine environment)	Residual stress in weld HAZ	25 years /2009	OE 30296

Seabrook (W)	Inlet piping to residual heat removal pump suction relief valve	Not available	Not available	Chlorides (non standard insulation)	Residual stress in weld HAZ	7 years /1997	INPO event # 443-971205-1
Ikata (Mitsubishi)	CVCS standby charging pipe	Not available	120-212°F Maintained during start up	Chlorides (Vinyl chloride tape)	Pressure not available	23 years /2000	OE 12516
Sequoyah Units 1&2 (W)	CVCS BA transfer line	1” Sch. 40	175-185°F Normal operation	Chlorides (source unknown)	Not available	3 years /1986	OE 1845
Turkey Point Unit 3 (W)	CVCS BA transfer line	¾”-3” Sch. 40	180°F (1st 19 years) and 130°F (4 years)	Chlorides (source unknown)	Residual stress in weld HAZ	23 years /1995	OE 7201
St. Lucie Unit 2 (CE)	ECCS suction piping	24” Sch. 10	Outside ambient	Chlorides (marine environment)	Residual stress in field weld HAZ	16 years /1993	OE 10050
Salem Unit 1 (W)	RCS instrument tubing	3/8” tubing	Not available	Chlorides (historic spills or service water leaks)	Residual stress in weld HAZ	29 years /2006	OE 22672
River Bend (GE BWR)	CRD hydraulic system piping	Not available	125°F	Chlorides (historical spill)	1200-1300 psi pressurized pipe	8 years /1994	LER # 94-027-00
Fukushima Daiichi Unit 3 (Toshiba BWR)	CRD hydraulic system piping	Not available	125°F	Chlorides (leaking seawater pipe)	1200-1300 psi pressurized pipe	26 years /2002	OE 15325
North Anna Unit 1 (W)	Lower head safety injection piping in the valve pit	10” Sch. 40S	Not available	Chlorides (leaking ground water)	Residual stress in weld HAZ	27 years /2005	Root Cause N-2005-5034

*Affected materials are Type 304 stainless steel with carbon content likely greater than 0.03 wt%. Seabrook and Ikata OE did not specify stainless steel grade.

3.2.1 German OE

An overview of 30 years of German operating experience with ODSCC of stainless steel is presented in Reference 1. The information from this source was not included in Table 1 because the document summarizes and draws conclusions from the events, but does not provide specific information about each event. However, it is worth considering this reference to support understanding of the phenomena.

Of all the occurrences of TGSCC of stainless steel components in units located in Germany (11 PWRs and 6 BWRs), about 12% initiated on the outside surface of the pipe. The observed ODSCC had three consistent features: 1) any size pipe or component may be affected with similar probability, 2) cracking was mostly discovered before it led to leakage because it is identifiable from the outside and 3) the chloride source could be identified in most cases. Some examples of chloride sources were vinyl chloride tape, overhead dripping water pipe and chloride containing adhesives, much like what was seen in the U.S. and Japan. Most cracking was observed at locations that operated at higher temperature, but in some cases cracking was found below 120°F.

The example given by Reference 1 for ODSCC occurring at relatively low temperatures is Koeberg Nuclear Station, which is located in South Africa. Widespread ODSCC of stainless steel piping that operated below 120°F was observed at Koeberg. Chlorides were present on the affected piping in ample quantities due to the marine environment. Testing has shown that sensitization plays a strong role in the SCC susceptibility of austenitic stainless steel in a coastal environment [2], but it is unknown whether this material was sensitized. The piping concerned was manufactured from cold rolled plate having one continuous seam weld that was not annealed to remove the imposed residual stress [3]. These high residual stresses may have contributed to the observed ODSCC.

4.0 ODSCC Factors

There are two types of SCC: intergranular and transgranular. Intergranular stress corrosion cracking (IGSCC) propagates along the crystalline grain boundaries and is common among sensitized austenitic stainless steels. Transgranular stress corrosion cracking (TGSCC) grows through the crystalline grains and typically involves chloride contamination. Crack propagation was transgranular in all of the ODSCC events considered in this paper except North Anna, which was intergranular. Outside diameter initiated IGSCC is discussed in section 4.3.1.

ODSCC of stainless steel will not occur unless three synergistic elements of SCC are present: 1) aggressive environment, 2) sustained tensile stress and 3) susceptible material. The rate of crack growth will depend on the severity of these three elements.

The three synergistic elements discussed below are known to contribute to ODSCC susceptibility. However, the magnitude of each element required for crack initiation and growth is not known. Nor is it fully understood how interactions between these elements drive ODSCC. The EPRI MRP are currently performing research activities to better understand these unknowns as part of the "SCC of Austenitic Stainless Steel in PWRs Environments Strategic Plan," which is maintained by the "SCC of Stainless Steel" core team in the PWROG. These efforts focus on inside diameter initiated SCC of stainless steel lines, but many of the same principles apply to ODSCC as well.

The following sections state the current understanding of the factors affecting the three synergistic elements of SCC.

4.1 Environment

An aggressive environment is one of the three required elements for SCC initiation and growth. The key environmental parameters promoting ODSCC in austenitic stainless steels are temperature and halogens.

4.1.1 Temperature

The minimum temperature required for ODSCC is limited by the required driving force for SCC. Reference 4 refers to a general rule of thumb for the onset of SCC in water of 140°F. It is emphasized that this temperature applies only to austenitic stainless steels that are not sensitized and are in near-neutral pH waters of moderate to low chloride content (moderate to low was not defined). Low pH, concentrated chlorides, sensitization or high tensile stresses could lead to failures at temperatures below 140°F. For piping indoors in a controlled environment, the minimum temperature for the occurrences of ODSCC may be as low as 120°F based on operating experience. For piping outside in a marine environment, ODSCC is possible at ambient temperature.

In the case of ODSCC, the maximum temperature that cracking can occur is limited by the ability for moisture to accumulate on the piping outer surface. At atmospheric pressure moisture will typically not remain on the piping outer surface above 212°F unless there is a constant replacement, as by active drops or sprays. It is possible for moisture to exist above 212°F in a crevice where the dew point can be altered. All ODSCC occurrences considered in this white paper were on piping operating below 212°F.

4.1.2 Halogens

Halogens, such as chlorides, are known to be a key contributor to ODSCC in stainless steel [5].

For components exposed to the outdoors, levels of chlorides high enough to cause cracking are typically due to a marine environment. For units on the coast, salt water in the air provides ample chlorides and moisture. For non-coastal units, the sources of chlorides are expected to be similar to those for indoor piping, as discussed below.

Indoors in a controlled environment, levels of chlorides high enough to cause cracking are typically due to 1) a contamination event or 2) a mechanism that concentrates trace chlorides over time. Possible chloride contamination events include use of vinyl chloride tape, spills of high chloride containing substances, use of high chloride containing non-standard insulation and exposure to leaking water containing chlorides. Components that have crevices, heat tracing or are alternately wetted/dried can concentrate trace chlorides on the surface over time.

Crevice conditions most frequently occur in joints and connections, or points of contact between metals, such as pipe hangers and clamps. Contaminants and corrosion products tend to concentrate in crevices [5]. Alternate wetting/drying can lead to concentration of atmospheric pollutants and contaminants.

Heat tracing is sometimes used to provide heat to a stainless steel line. For example, heat tracing insulation has been used on the CVCS boric acid transfer line prior to boron concentration reduction modifications. Due to alternate wetting/drying, heat tracing can concentrate water soluble contaminants (e.g., chlorides) present on the outer surface of the piping [5].

4.2 Stress

Tensile stress is the second element required for SCC initiation and growth. There does not appear to be a minimum level of stress for SCC incidence, the stress level merely dictates the time to failure [5]. The two types of stresses that promote ODSCC in austenitic stainless steels are operational and residual.

4.2.1 Operational

Operational stresses tend to be applied on the entire component when in service and are relaxed when the component is not in use. In the case of piping, the main operational stresses are due to pressurization and thermal expansion, which create a tensile stress on the outer surface of the pipe.

4.2.2 Residual

Residual stresses are stresses that remain after the original cause of the stresses (e.g., operational pressure, thermal gradients, cold work, etc.) has been removed. In the case of annealed austenitic stainless steel piping, the most common cause of residual stresses is welding. These residual stresses create tensile stresses on the outside surface of the pipe adjacent to the weld and typically in the weld HAZ. Residual stresses can also be caused by cold work, such as pipe fabricated from cold-rolled plate. However this is considered to be an extreme case since cold rolled stainless steel has a higher susceptibility to SCC compared to the annealed stainless steel that is typically used in the U.S. fleet.

4.3 Material

Material susceptibility is the third required element for SCC initiation and growth. Austenitic stainless steel can be most susceptible to ODSCC when it is sensitized or when conditions permit pitting corrosion to occur. Sensitization or pitting is not required for ODSCC, but they do increase material susceptibility.

4.3.1 Sensitization

The straight grades of austenitic stainless steels with medium carbon levels ($0.03<C<0.08$ wt%) can become sensitized in the weld HAZ. During the welding process, the base metal surrounding the weld reaches temperatures (800-1500°F [7]) high enough to cause chromium to diffuse towards the grain boundaries and form chromium carbides. This reduces the material's local chromium content surrounding the grain boundaries, and effectively decreases the material's resistance to ODSCC. Sensitization can be minimized or prevented by using the low-carbon (<0.03%) or stabilized grades of stainless steels.

Experimental testing has shown that austenitic stainless steels exposed to a marine atmospheric environment have an increased susceptibility to ODSCC when the material is sensitized [2]. Based on destructive examination, cracking appears to have initiated as IGSCC due to the carbon depletion surrounding the grain boundaries and then propagated as TGSCC due to the chloride present in the coastal air.

The cracking observed at North Anna Unit 1 was found to be OD-initiated IGSCC with heavy sensitization acting as a main contributing factor [8]. The Type 304 stainless steel pipe had the maximum allowable carbon content of 0.08 wt%. Since the original construction welding procedures did not specify the maximum heat input, it was assumed that the heat input was likely high. The combination of high carbon and high welding temperature caused the weld HAZ to become heavily sensitized. The other contributing factors were exposure to leaking ground water and residual stresses from the welding process. The chloride content of the ground water around the containment and auxiliary buildings ranged from 1.9 to 28 ppm.

4.3.2 Pitting

Pitting is a corrosion mechanism that is more common with passive materials such as austenitic stainless steels. Most pitting is the result of halide contamination (e.g., chlorides) [6]. Any continuously wetted or alternately wetted/dried surfaces tend to concentrate aggressive species such as chlorides and are prone to pitting. Type 316 is more resistant than Type 304 to pitting due to its molybdenum content [9].

Pits commonly act as initiation sites for ODSCC because the pits further concentrate chlorides and they provide a point of stress concentration [10]. In cases where only trace amounts of chlorides are present, ODSCC will likely not initiate until pitting corrosion has occurred.

5.0 Areas Potentially Susceptible to ODSCC

This section will identify areas of austenitic stainless steel piping that are potentially susceptible to ODSCC using current knowledge of the ODSCC phenomena discussed in section 4.0 and the operating experience considered in section 3.0. This assessment is limited to the near term and may be modified as a result of the future work described in section 10.0.

Indoors in a controlled environment, potentially susceptible areas of austenitic stainless steel piping are those that have all three of the following conditions: 1) extended amount of time between 120 and 212°F, 2) sustained tensile stress and 3) sufficient chloride contamination to cause measurable cracking. Based on the OE considered in this white paper, it typically takes several years for small cracks to develop. In the case of stainless steel piping, tensile stress is due to pressurization or residual stress from the weld thermal cycle, grinding or some other form of cold-work. Levels of chlorides high enough to cause measurable cracking are typically due to either a contamination event (e.g., vinyl chloride tape, spills, non-standard insulation or leaking raw water) or a mechanism that concentrates trace chlorides over time (e.g., crevice or alternate wetting/drying, such as heat tracing).

Austenitic stainless steel indoors in a controlled environment could be susceptible to ODSCC when the pipe temperature is greater than 212°F if cool raw water was leaking on to the pipe. This could locally cool the pipe and the alternate wetting/drying would concentrate chlorides from the raw water.

For austenitic stainless steel outside in a marine environment, testing has shown that heavy sensitization increases susceptibility to SCC [2]. Heavily sensitized samples with high tensile stress cracked in less than five years while heavily sensitized samples with moderate stress did not crack. There does not appear to be a minimum level of stress for SCC incidence, the stress level merely dictates the time to failure [5]. Austenitic stainless steel can become sensitized in the weld HAZ when it has a high carbon content (>0.03 wt%). The welding process can create high residual stresses adjacent to the weld (typically in the weld HAZ). High tensile stresses can also be caused by grinding or other cold-work imposed on the pipe surface. Piping fabricated from cold-rolled plate has high residual stresses, but this is not common practice in the U.S. fleet.

Austenitic stainless steel piping outside that is not exposed to a high chloride containing environment is considered to be significantly less susceptible to ODSCC because relatively high concentrations of chlorides are required to drive cracking at ambient temperature.

6.0 Existing Inspection Requirements

Under existing inspection requirements, stainless steel piping undergoes visual, surface and volumetric inspections for cracks, active leaking of coolant and boric acid deposits. Inspections are performed indirectly by each unit's boric acid corrosion control (BACC) program and directly by ASME B&PV Code Section XI or a Risk Informed In-service Inspection (RI-ISI) program.

6.1 BACC Program

U.S. NRC Generic Letter 88-05 [11] requires all PWR utilities to implement a BACC program that consists of systematic measures to ensure that there is an extremely low probability of abnormal leakage, rapidly propagating failure, or gross rupture of the reactor coolant pressure boundary due to boric acid corrosion. Generic Letter 88-05 only requires inspection of carbon steel and low-alloy steel piping, since stainless steel is not susceptible to boric acid corrosion.

Since the industry response to Generic Letter 88-05 varied significantly from unit to unit, WCAP-15988 was created to provide generic guidance to serve as a basis for developing consistent and satisfactory BACC programs [12]. This guidance has two NEI 03-08 requirements: 1) each utility must have a BACC program (mandatory) and 2) each program shall contain the attributes laid out in WCAP-15988 (needed).

The BACC programs created by the PWR utilities require visual walk down inspections of carbon steel and low-alloy steel piping during each refueling outage. During these walk down inspections of carbon steel and low-alloy steel piping, boric acid deposits may also be observed on the surrounding stainless steel piping. PWR utilities are required to consider stainless steel piping leaking borated water onto carbon steel and low-alloy steel piping in their BACC programs [12].

6.2 ASME Section XI

Section XI of the ASME B&PV Code requires all Class 1, 2 and 3 piping to be visually (VT-2) inspected during pressure tests. According to Table IWB-2500-1, Class 1 piping is VT-2 inspected each refueling outage. Based on Tables IWC-2500-1 and IWD-2500-1, Class 2 and 3 piping is VT-2 inspected each period (40 months). The time that VT-2 inspections are performed on Class 2 and 3 piping is different for each unit. Since the 69 PWRs in the U.S. inspect specific Class 2 and 3 systems at different times, most if not all piping systems will be visually inspected each refueling outage (across the fleet, not at a single unit).

Section XI also requires surface and volumetric examinations of pressure retaining welds in Class 1 and 2 piping. For Class 1 piping, 25% of all the welds are examined each 10 year inspection interval. For Class 2 piping, the sampling criteria is reduced to 7.5% and only applied if the nominal pipe size (NPS) is greater than four inches. Of the welds requiring examination, inspections are evenly distributed over the 10 year interval. The extent of examination is 100% of each weld requiring inspection. The time that these inspections are performed on Class 1 and 2 piping is different for each unit. Since the 69 PWRs in the U.S. inspect specific Class 1 and 2 systems at different times, most of Class 1 and 2 piping systems will be inspected each refueling outage (across the fleet, not at a single unit).

Section XI requires a sample of welded attachments to Class 1, 2 and 3 piping to be periodically inspected. Welded attachments to Class 1 and 2 piping are surface examined and attachments to Class 3 piping are visually (VT-1) examined.

6.3 RI-ISI Program

Many U.S. PWR units have implemented an approved RI-ISI program, which replaces the ASME Section XI examination requirements for piping. The program is sometimes applied to Class 1 piping only or to all Class 1, 2 and 3 piping. The RI-ISI program is similar to the ASME Section XI examination requirement with some modifications. In general, application of the RI-ISI methodology tends to increase the number of inspection locations in higher risk pipe segments and decrease the number of inspections in lower risk pipe segments. Risk in this case is based on the safety significance of an individual pipe segment. The safety significance is determined by the consequences of failure and the likelihood of failure. The likelihood of failure was based on several potential degradation mechanisms including SCC, but OD-initiated SCC was not considered. Since a RI-ISI program will increase inspections at pipe locations with high consequences of failure, its effectiveness in detecting OD-initiated SCC in safety significant locations is considered similar to inspections performed per ASME Section XI.

7.0 Safety Concern Evaluation

The key factors that contribute to ODSCC are considered to qualitatively evaluate whether ODSCC of stainless steel piping represents an immediate safety concern. The focus of this assessment is on piping temperature, stress and material.

7.1 Temperature

The growth rate of ODSCC in stainless steel piping is limited by the pipe surface temperature. It is generally accepted that the rate of SCC crack growth increases with increasing temperature. Since SCC typically occurs on the pipe surface at temperatures below 212°F, the rate of crack growth is significantly less than what is seen at higher temperatures.

7.2 Stress

The stress component of ODSCC is from operational stresses and residual stresses. In the case of austenitic stainless steel piping, pressurization and thermal expansion account for the operational stresses and residual stresses are typically in the HAZ due to the welding that is performed to join the piping together. The surface tensile stresses in the weld HAZ are higher than the base metal because the stress magnitude is a combination of both operational and weld residual stresses. The welding sequence creates residual stresses in the weld HAZ, which create high tensile stress at the outside surface, but at some point through the wall thickness the residual stresses become compressive. This variability in stress field affects the driving force for cracking and can cause crack growth to slow.

In cases where pitting corrosion is present, such as under support clamps, the stress component of ODSCC is likely due to stress concentration points in corrosion pits coupled with the stresses due to pressurization and thermal expansion. As discussed in section 7.3, in some cases ODSCC initiates in pits. Since it takes time for pits to develop, ODSCC that initiates in a pit may take many years to develop.

7.3 Material

Austenitic stainless steel piping is not prone to brittle fracture due to the inherent ductility at all relevant temperatures of the material. The annealed austenitic stainless steel used for piping applications has a high resistance to brittle fracture and this resistance does not diminish over time since in piping applications, the material is not embrittled as the result of neutron radiation nor are the wrought forms of austenitic stainless steels susceptible to thermal embrittlement since they have low (<1 percent) delta ferrite. For these reasons, catastrophic failure of austenitic stainless steel pipe due to SCC is rare. None of the occurrences of ODSCC discussed in this paper resulted in significant leakage or catastrophic failure.

Austenitic stainless steels have a passive surface layer that makes them resistant to general corrosion, but susceptible to pitting corrosion when chlorides and moisture are present. Pits commonly act as initiation sites for ODSCC because the local chemistry in a pit is conducive to cracking and the pit can act as a point of stress concentration. In cases where only trace amounts of chlorides are present, ODSCC will likely not initiate until pitting corrosion has occurred. When chloride concentrations are low the pitting process can take an extended period of time. Since it takes time for pits to develop, ODSCC that initiates in a pit may take many years to develop.

7.4 Crack Tightness

The tight nature of SCC makes it difficult to visually identify. If cracking becomes through-wall, leakage can be visually identified by the presence of boric acid deposits in borated water systems. SCC allows a minimal amount of leakage, which is commonly too small to measure. The ability to locate through-wall cracks in borated systems by visual means while they are small and tight gives sufficient time to react before leakage and crack size become significant. Leakage from small tight cracks is visually identifiable in the form of boric acid deposits regardless of whether the piping is insulated. For example, the leakage at Callaway was observed while insulation was in place. Callaway's evaluation of the flaw size found that the piping was structurally sound.

In non-borated systems, leakage is more difficult to visually identify due to the absence of boric acid deposits. The auxiliary feedwater system is the key safety related system that contains non-borated water. This system is not insulated so identifying leaks during a periodic pressure test will be possible even though boric acid deposits will not be present.

7.5 Safety Concern Determination

The ODSCC phenomena observed in austenitic stainless steel piping is not a safety concern in the near term because crack growth is generally slow, the piping material has a high resistance to brittle fracture and the ability to identify through-wall cracks in borated systems while they are small and tight allows sufficient time to react before crack size becomes structurally significant. The auxiliary feedwater system is the key safety related system that contains non-borated water. This system is not insulated so identifying leaks during a periodic pressure test will be possible even though boric acid deposits will not be present.

8.0 Summary

ODSCC of stainless steel piping will not occur unless the three synergistic elements of SCC are present: 1) aggressive environment, 2) sustained tensile stress and 3) susceptible material. However, the magnitude of each element required for crack initiation and growth is not known. Nor is it fully understood how interactions between these elements drive ODSCC. The EPRI MRP is currently performing research activities to better understand these unknowns as part of the "SCC of Austenitic Stainless Steel in PWRs Environments Strategic Plan," which is maintained by the "SCC of Stainless Steel" core team in the PWROG. These efforts focus on inside diameter initiated SCC of stainless steel lines, but many of the same principles apply to ODSCC as well.

Under existing inspection requirements, stainless steel piping undergoes visual, surface and volumetric inspections for cracks, active leaking of coolant and boric acid deposits. Inspections are performed indirectly by each unit's BACC program and directly by ASME B&PV Code Section XI or a RI-ISI program.

The ODSCC phenomena observed in austenitic stainless steel piping is not a safety concern in the near term because crack growth is generally slow, the piping material has a high resistance to fracture and the ability of required inspections to identify through-wall cracks in borated water systems while they are small and tight allows sufficient time to react before crack size becomes structurally significant.

9.0 Conclusions

Experience has demonstrated that BACC programs, RI-ISI and ASME Section XI inspections, along with other plant activities, to be effective in identifying OD-initiated cracks or associated leaks long before the crack is of structural significance. Therefore the existing inspection requirements are adequate for addressing the ODSCC of stainless steel in the near term because the current requirements provide a reasonable cross section of the data and the phenomenon is not an immediate safety concern.

10.0 Future Plans

The PWROG MSC "SCC of Stainless Steel" strategic plan will be updated to account for this recent OE in our long-term plans. This will include a thorough extent of condition assessment and development of long term inspection and mitigation recommendations.

11.0 References

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