ELECTRIC POWER RESEARCH INSTITUTE

Materials Reliability Program: Review of Stress Corrosion Cracking of Alloys 182 and 82 in PWR Primary Water Service (MRP-220)

1015427

Materials Reliability Program: Review of Stress Corrosion Cracking of Alloys 182 and 82 in PWR Primary Water Service (MRP-220)

1015427

Technical Update, October 2007

EPRI Project Managers

K. Ahluwalia

C. King

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1395 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

AREVA NP

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This document was prepared by

AREVA NP
Tour AREVA
92084 Paris La Défense
France

Principal Investigators
P. Scott
M.-C. Meunier

This document describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Materials Reliability Program: Review of Stress Corrosion Cracking of Alloys 182 and 82 in PWR Primary Water Service (MRP-220). EPRI, Palo Alto, CA: 2007. 1015427.

REPORT SUMMARY

Since 1999, there have been several incidences involving primary water stress corrosion cracking (PWSCC) of Alloy 182/82 butt welds in pressurized water reactor (PWR) plants in the United States and abroad. These events resulted in unplanned or extended outages with associated economic costs. This report summarizes the available information on PWSCC of Alloy 182 and 82 weld metals observed in PWR primary circuit components up to the end of 2006. Relevant data from laboratory stress corrosion testing are also collated.

Background

EPRI Report 1009549 (MRP-113) describes the safety assessment carried out for U.S. PWR plant designs. Ongoing inspections of penetration nozzles in PWR vessel closure heads have also revealed PWSCC, not only in the Alloy 600 nozzles themselves but also in their butt welds and J-groove attachment welds (made of Alloy 182). The Materials Reliability Program is actively managing these issues and investigating a range of mitigation possibilities.

Objective

To examine in-service experience and laboratory test results on PWSCC of Alloy 182 and 82 weld metals in order to identify the critical factors that render nickel weld metals susceptible to PWSCC in PWR primary water service.

Approach

The project team drew upon its in-house experience as a designer of PWR plants and fabricator of primary system components, as well as its wide range of international experience. One of the principal investigators has also been a major contributor to both the engineering and scientific knowledge base on PWSCC of nickel-base alloys for nearly 30 years. In preparing this report, the project team analyzed the root causes of in-service failures of Alloy 182/82 welds due to PWSCC and examined consistencies or inconsistencies in laboratory data, leading to recommendations for future actions.

Results

Alloy 182 (13-17% Cr) welds are significantly more susceptible to PWSCC in service than Alloy 82 (18-22% Cr) welds. This is consistent with a factor of six improvement in times to detectable cracking of Alloy 82 relative to Alloy 182 in laboratory tests. Compositional variables other than chromium in Alloys 182 and 82 have been observed in laboratory work to have a relatively small or no impact on PWSCC initiation and growth. No further compositional effects have been identified from investigations of in-service failures.

Common and structurally acceptable weld defects—such as small slag inclusions, porosity, and minor subsurface hot cracks or lack-of-fusion defects—seem to have had only marginal, or no influence on cracking behavior, both in service and in laboratory testing.

The effect of temperature in PWSCC field experience is not as marked as would be anticipated from laboratory testing. It is argued that another dispersed variable, probably residual surface stress, is masking a stronger effect of temperature. This report identifies factors that give rise to high surface residual stresses as well as those that significantly ameliorate such stresses. Stress relief heat treatments given to adjacent low-alloy steel components are particularly beneficial.

EPRI Perspective

One of the most important aspects of the MRP program on PWSCC of thick-walled nickel-base alloy components has been to collate service experience and analyze it in the context of the huge database of laboratory experiments on Alloy 600, most of which was generated from experiments on thin-walled steam generator tubing. An earlier EPRI report (1007832, MRP-87) described such an effort up to mid 2002, but much has happened since then. The present report, although restricted deliberately to Alloy 182/82 weld metals, benefits both from being up-to-date and from a more international perspective on the issue. It provides an important resource for utility management of Alloy 600 PWSCC, as required in MRP-126 (EPRI report 1009561), and should also be read in conjunction with two other EPRI reports, MRP 106 (1009378) and MRP-114 (1009559). Both reports deal with more specific aspects of the problem addressed here, including residual and operating stresses/effects of weld repairs.

This report is noteworthy for 1) its clear attempt to establish the truly important factors in PWSCC service behavior of nickel-base alloy welds, and 2) its conclusion that a satisfactory approach to the prediction of field failures (one using Weibull analysis) will remain elusive unless the statistical basis for determination of failure probability can be improved. In particular, this would involve taking proper account of reliable field inspections that have not revealed reportable indications in component welds.

Keywords

Pressurized Water Reactor
Primary Water Stress Corrosion Cracking (PWSCC)
Service Experience
Nickel-Base Alloy Welds
Alloy 182
Alloy 82

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Intergranular stress corrosion cracking (IGSCC) of the wrought nickel base Alloy 600 in the primary coolant of Pressurized Water Reactors (PWR), commonly known as PWSCC, has been widespread but until the last few years the associated weld metals, Alloys 182 and 82, had not been significantly affected. PWSCC of Alloy 600 has been typically associated with areas of high stress and heavy cold work. Occasionally cracks that initiated in Alloy 600 were observed to propagate into Alloy 182 weld metal but until 1994 cracking had not been seen to initiate in nickel-base weld metal. On the other hand, laboratory testing revealed that Alloy 182 is essentially as susceptible to PWSCC as Alloy 600 although Alloy 82 is significantly less susceptible.

The first observations of PWSCC initiating in nickel alloy welds of PWR primary coolant circuits were reported in 1994/1995 and initially concerned only Pressurizer nozzle dissimilar metal butt welds. However, towards the end of the year 2000, three separate PWRs experienced cracking attributed to PWSCC of major primary circuit welds made from Alloy 182 and/or 82. These events concerned dissimilar metal butt welds between the main austenitic stainless steel primary circuit piping and the Reactor Pressure Vessel (RPV) outlet nozzles of Ringhals 4 and V. C. Summer and some J-groove welds of RPV closure head Control Rod Drive Mechanism (CRDM) nozzles at Oconee 1.

Since 2000, a significant number of additional incidents (cracks detected non-destructively or leaks) of primary circuit Alloy 182 and/or 82 welds apparently caused by PWSCC have been reported, although this may in part be related to an increase in the number of inspections in addition to the increase in operating time. However, the extent of cracking observed in service so far has been much less than in the case of wrought Alloy 600. Nevertheless, cracking of Alloy 182/82 has extended to Bottom Mounted Instrumentation (BMI) nozzle J-groove welds, Steam Generator (SG) drain line J-groove welds and SG tube sheet cladding. In fact, since 1994 until the end of 2006, a total of more than 300 nickel base Alloy 182 or 82 welds in over 30 PWR plants, have been identified with PWSCC after operating times between 53,400 and 180,000 EFPH (Effective Full Power Hours). The main types of welds that have been affected are:

- J-groove welds of CRDM, BMI, SG drain lines, Pressurizer instrument nozzles and hot leg instrument nozzles
- Butt welds (full penetration dissimilar metal welds) of RPV and Pressurizer nozzles
- SG tube sheet cladding

Alloy 182 weld metal is used in the form of coated electrodes for shielded-metal arc welding (SMAW) whereas Alloy 82 weld metal is used as uncoated wire for manual or machine gas tungsten arc welding (GTAW) with an inert cover gas. The main difference in chemical composition between these two materials is that Alloy 82 has 18 – 22% chromium whereas Alloy 182 has 13 – 17% chromium (which is similar to Alloy 600). A modified form of Alloy 182 known as Alloy 132, which has the same chromium content, has been used in Japan with apparently similar observations of susceptibility to PWSCC. The specified chemical compositions of these weld metals are shown in Table 1-1 and compared with Alloy 600 and the more modern replacement materials Alloys 690, 152 and 52.

Table 1-1
Nickel Base Weld Metals used in PWRs (wt%) Compared with Alloy 600 and Alloy 690

	Alloy 600	Alloy 182	Alloy 132	Alloy 82	Alloy 690	Alloy 152	Alloy 52
Nickel	>72.0	≥59	≥68	≥67	>58.0	Bal.	Bal.
Chromium	14-17	13-17	13-17	18-22	28-31	28-31.5	28-31.5
Iron	6-10	≤10.0	<11	<10	7-11	8-12	8-12
Titanium		≤1.0		≤0.75		≤0.50	≤1.0
Aluminum							≤1.10
Niobium plus Tantalum		1.0-2.5	1.5-4.0	2.0-3.0		1.2-2.2	≤0.10
Molybdenum						≤0.50	≤0.05
Carbon	≤0.05	≤0.10	<0.08	≤0.10	≤0.04	≤0.045	≤0.040
Manganese	≤1.0	5.0-9.5	2.0-3.5	2.5-3.5	≤0.50	≤5.0	≤1.0
Sulfur	≤0.015	≤0.015	<0.015	≤0.015	≤0.015	≤0.008	≤0.008
Phosphorus		≤0.030	<0.015	≤0.030		≤0.020	≤0.020
Silicon	≤0.5	≤1.0	<0.5	≤0.50	≤0.50	≤0.65	≤0.50
Copper	≤0.5	≤0.50	<0.5	≤0.50	≤0.5	≤0.50	≤0.30
Cobalt	≤0.10	≤0.12		≤0.10	≤0.10	≤0.020	≤0.020

In the case of dissimilar metal butt welds, Alloy 182 buttering was typically applied to the low-alloy steel part, which then received a post weld heat treatment (PWHT) with the primary objective of stress relieving the low-alloy steel component. The final Alloy 82 or 182 butt weld was then made to complete the joint with the stainless steel part. This design eliminated the need to stress-relieve the low alloy or carbon steel part after welding and avoided exposing the stainless steel material to PWHT temperatures where it could become sensitized. There were some variations of this basic configuration, especially for the case of reactor vessel nozzle to pipe welds in Westinghouse plants [1]. In some cases, the weld between the low alloy steel RPV nozzle and the stainless steel safe end were stress relieved with the vessels, the carbon content of the selected stainless steel being sufficiently low to avoid sensitization. (There are, of course, also a significant number of dissimilar metal butt welds with stainless steel filler metals in PWR service).

The root passes of butt welds and then two or three additional weld beads were typically applied using manual or machine GTAW with Alloy 82 filler metal. The welds were then completed using the manual SMAW process with Alloy 182 filler metal in earlier plants or by GTAW using Alloy 82 filler metal in some later plants. Some degree of latitude appears to have existed for the vendors regarding which filler material and welding process was used so that the composition is not always known. Consequently, the convention use in this document will be to label all such butt welds as Alloy 182/82 unless more precise information is available.

Concerning J-groove welding, manual SMAW using Alloy 182 has normally been used. The final weld surface would normally be ground to the design profile although this has not always been the case, especially in the early years of PWR construction.

This report summarizes the published information relating to the Alloy 182 and 82 weld metal cracking observed since 1994. Relevant data from laboratory stress corrosion testing are also summarized. The apparent lack of consistency between operating experience and laboratory testing of Alloy 182 in PWR primary water is examined and possible reasons discussed. Nevertheless, the apparent upsurge in PWSCC of nickel-base weld metals in PWRs has confirmed the potential risk revealed by laboratory testing. These data are examined in order to try and identify the critical factors that render nickel weld metals susceptible to PWSCC in PWR primary water service.

2
SUMMARY OF OPERATING EXPERIENCE OF PWSCC OF ALLOYS 182 AND 82

Most incidents of PWSCC in nickel-base weld metals have, until relatively recently, been detected by visual observation, typically revealed by the presence of a white boric acid deposit from primary water leaks. Dye penetrant testing, ultrasonic testing and eddy current were then used to characterize defects after detection. More recently, following the implementation of the EPRI inspection guidelines for dissimilar metal butt welds in MRP 139 [1], defects have been detected by ultrasonic inspection before leakage and usually inferred as PWSCC from the proximity of the indications to the internal primary water wetted surface. Only in relatively few cases have samples been removed for destructive examination to confirm that the indications were in fact PWSCC.

Table 2-1 gives details of known cracking events in nickel-base alloy welds in chronological order. The information in this table has been collected from many sources including technical journals, conference proceedings, NRC publications, and Owners' Groups. It has been cross-checked with a similar compilation by AREVA NP Inc in Lynchburg. In some cases, no citable reference has been located and the information has then been checked with the appropriate utility representatives, as indicated in Table 2-1.

Table 2-2 shows the same information classified by generic component class. With the exception of the earliest cases of cracking in pressurizers that occurred rather quickly after plant start-up, the shortest operating time before detection of cracking is 13 years (97,297 EFPH) in the case of confirmed non-stress relieved welds with documented repairs (CRDM Weld of the OHI 3 RPV) and 12 years (77,000 EFPH) in the case of a steam generator tube sheet impacted by a loose part. The first appearance of indications attributed to PWSCC for each type of weld is as follows:

- Buttering : CRDM (in 1994 after an operating time of 90,304 hours)
- J-groove welds : CRDM (in 2000 after an operating time of 169,000 hours)
- Butt welds: RPV nozzles/safe end welds (in 2000 after an operating time of 116,139 hours).
- Cladding: (Tube sheet of a steam generator impacted by a loose part - only one known case in 1995 after an operating time of 77,000 hours).

The service temperatures of welds with indications attributed to PWSCC range from 290°C (RPV BMI nozzle weld, CRDM nozzle welds of OHI3) to ~345°C in the Pressurizer. It is noted that some of the shorter operating times to defect detection, again with the exception of the earliest cases of cracking in Pressurizers that occurred quickly after plant start-up, have been associated with those components that operated at the lower service temperatures of ~290°C (RPV BMI nozzle weld of South Texas Project Unit 1, and CRDM J-groove weld of OHI 3). This suggests that another dominant variable, probably residual stress, is swamping the expected strong effect of temperature (based on laboratory data – see Chapter 3).

Table 2-1
PWSCC Experience in Ni-Base Welds of Commercial PWRs

Units	Welds (Type Of Filer Metal)	Date [Ref]	Visual Detection	Operating Time (Years)	Operating Time (EFPH*)	N° Of Affected Welds	Temp. (°C)	Cracks Orient.	Observations
ST LUCIE 2 [2,3]	Pressurizer Instrumentation Nozzles Weld-Steam (182)	Mar-94	Leakage	1	7500	3	345		Welding Defects Present
SAN ONOFRE 3 [2, 3]	Pressurizer Instrumentation Nozzles Weld - Steam (182) [HAZ]	Aug-95	Boric Acid Deposit	10	75000	2	345		Repaired
ST LAURENT B1 [4]	Tube Sheet Plate Cladding (82)	Sep-95		13	77000	1	323		Impacted By Loose Part
CALVERT CLIFFS 2 [2, 3]	Pressurizer Instrumentation Nozzles Weld - Steam (182)	Jul-98	Vapor Leakage	9	53400	1	345		Repaired
ARKANSAS 1 [3]	Hot Leg Nozzle Welds (182)	Feb-00	Boric Acid Deposit	13	147618	7	317		
RINGHALS 4 [1, 5]	RPV Outlet Nozzle Weld (182)	Aug-00		17	116139	1	321	Axial	Repairs
RINGHALS 3 [1, 5]	RPV Outlet Nozzle Weld (182)	Sep-00		19	118143	1	321		No Documented Repairs
VC SUMMER [1, 6]	RPV Outlet Nozzle Weld + Buttering (82/182)	Oct-00	Boric Acid Deposit	16	112449	1	319	Axial + Circumf.	Repairs Welds Ground
FT CALHOUN [3]	Pressurizer Instrumentation Nozzles Weld-Primary Water (82/182)	Oct-00	Leakage	27	167033	1	340		
OCONEE 1 [2, 3]	CRDM And Thermocouple Welds (182)	Nov-00	Boric Acid Deposit	27	169000	1+ 5	317	Axial	Small Pin Holes Detected
OCONEE 2 [2, 3]	CRDM Welds (182)	Apr-01	Boric Acid Deposit	26	179206	4	317		
CATAWBA 2[†]	SG Lower Head Drain Nozzle Weld (182)	Sept-01	Boric Acid Deposit	14	104533	1	286 To 320	Axial	Partial Penetration Weld Of Half Coupling
CRYSTAL RIVER 3 [2, 3]	CRDM Welds (182)	Oct-01	Boric Acid Deposit	24	127146	1	317		
TMI-1 [1, 2]	CRDM Welds (182)	Oct-01	Boric Acid Deposit	27	141831	4	317	Axial + Circumf	Welds Smooth Ground

Table 2-1 (continued)
PWSCC Experience in Ni-Base Welds of Commercial PWRs

Units	Welds (Type of Filer Metal)	Date [Ref]	Visual Detection	Operating Time (Years)	Operating Time (EFPH*)	N° of Affected Welds	Temp. (°C)	Cracks Orient.	Observations
NORTH ANNA 2 [2, 3]	CRDM Welds (182)	Oct-01	Boric Acid Deposit	21	147235	3	317		Welds Not Ground
SURRY 1 [2, 3]	CRDM Welds (182)	Oct-01	?	29	170946	6	314		Welds Smooth Ground
OCONEE 3 [1, 3]	CRDM Welds (182)	Nov-01	Boric Acid Deposit	26	175651	5	317		Welds Ground
DAVIS BESSE [7]	CRDM Welds (182)	Feb-02	Boric Acid Deposit	23	137807	5	318		Repairs
OCONEE 1 [3]	CRDM Welds (182)	Feb-02	Boric Acid Deposit	28	181400	1	317		
NORTH ANNA 2 [3, 8]	CRDM And Thermocouple Welds (182)	Feb-02	Boric Acid Deposit	22	153330	49 + 6	310	Axial + Circumf.	Some Repairs
TIHANGE 2 ** [1, 9]	Prz Surge Nozzle To Safe-End Weld (182)	Oct-02	No	20	138000	1	343		
SOUTH TEXAS 1 [10]	Rpv Bmi Nozzle Weld (182)	Apr-03	Boric Acid Deposit	14	97350	2	293	Axial	
TIHANGE 2 ** [1]	Rpv Outlet Nozzle Weld (182)	May-03		20	145140	1			
TSURUGA 2 [11]	Pressurizer Safety And Relief Line Piping Nozzle Weld (132) + Buttering	Sep-03	Boric Acid Deposit	16	121375	2	345	Axial	Repairs
TMI-1 [12]	Surge Line Nozzle To- Safe End Dissimilar Metal Weld (82/182)	Oct-03	No	29	156330	1	317	Axial	Repairs
OHI 3 [13]	Crdm Weld	Apr-04	Boric Acid Deposit	13	97297	1	290 (?)	Axial	No Sign Of Surface Finishing
RINGHALS 2 [14]	Sg Manway Drain Nozzle Welds (Hot And Cold Legs) (82)	May-04	Boric Acid Deposit	14	~105000	2	290 325	Axial	Repairs – Weld Defects

Table 2-1 (continued)
PWSCC Experience in Ni-Base Welds of Commercial PWRs

Units	Welds (Type of Filer Metal)	Date [Ref]	Visual Detection	Operating Time (Years)	Operating Time (EFPH*)	N° of Affected Welds	Temp. (°C)	Cracks Orient.	Observations
CATAWBA 2 [15]	Sg Tube To Tubesheet Welds	Sept-04	No	18	129914	196	325	Axial + Circum.	Some Defects Due To Rolling
CATAWBA 2†	SG Lower Head Drain Nozzle Weld (182)	Sept-04	Boric Acid Deposit	17	128647	2	286 To320	Unknown	Partial Penetration Weld Of Half Coupling
DC COOK 2 [16]	CRDM Welds	Oct-04	No	26	136182	2	315		Repairs
PALISADES 1 [17]	CRDM Welds (182)	Oct-04	?	23	147806	2	318		Buttering
CALVERT CLIFFS 2 [18]	Piping Nozzle To Safe-End Weld For The Drain RCS Hot Leg (Dissimilar Weld Metal) (82/182)	Feb-05	?	28	130000	3	316	Axial	
	Piping Nozzle To Safe-End Weld For The Letdown/Drain Line RCS Cold Leg (82/182)	Feb-05	?	28	130000	1	285	Axial	
WOLF CREEK 1 [19]	Sg Lower Head Bowl Drain Line Weld (182)	Apr-05	Boric Acid Deposit	19	143700	2	325		
DC COOK 1 [9]	Prz Safety Nozzle (82/182)	Apr-05	No	29	164260	1	345	Axial	Repairs
MILLSTONE 3†	Prz Spray Nozzle (82/182)	Oct-05		19	116460	1	345	Axial	
ST. LUCIE 2†	Crdm Weld (182)	Jan-05		22	158600	1	313	Axial	

Table 2-1 (continued)
PWSCC Experience in Ni-Base Welds of Commercial PWRs

Units	Welds (Type of Filer Metal)	Date [Ref]	Visual Detection	Operating Time (Years)	Operating Time (EFPH*)	N° of Affected Welds	Temp. (°C)	Cracks Orient.	Observations
CALVERT CLIFFS 1 [20]	Hot Leg Surge Nozzle To Safe End Weld *** (82/182)	Mar-06	No	31	141535	1	325	Circ.	
	Hot Leg Drain Nozzle To Safe End Weld *** (82/182)	Mar-06	No	31	141535	1	325	Circ.	
	PRZ Relief Valve Nozzle To Safe-End Weld *** (82/182)	Mar-06	No	31	141535	2	345	Axial	
DAVIS BESSE†	Cold Leg Drain Nozzle Weld (82/182)	Mar-06	No	28	154417	1	291		
WOLF CREEK 1 [9]	Prz Safety Nozzle (82/182)	Oct-06	No	21	154690	1	345	Circ.	Many Repairs
	PRZ Relief Nozzle (82/182)	Oct-06	No	21	154690	1	345	Circ.	Many And Extensive Repairs
	PRZ Surge Nozzle (82/182)	Oct-06	No	21	154690	1	345	Circ.	Many And Extensive Repairs
BEAVER VALLEY [21]	Crdm Welds (182)	Oct-06	No	19	132110	3			

* EFPH Effective Full Power Hours
** Acceptable Flaws
† Checked by a Utility Representative

Table 2-2
Distribution of PWSCC Events as a Function of Component Type

Components	Types Of Weld	Plants	Date	Operating Time (EFPH)	Number Of Cracked Welds
RPV	CRDM And Thermocouple Welds	OCONEE 1	11-00	169000	6
		OCONEE 2	04-01	179206	4
		CRYSTAL RIVER 3	10-01	127146	1
		TMI-1	10-01	141831	4
		NORTH ANNA 2	02-02	147235	58
		SURRY 1	10-01	170946	6
		OCONEE 3	11-01	175651	5
		DAVIS BESSE	02-02	137807	5
		OCONEE 1	02-02	181400	1
		OHI 3	04-04	97297	1
		DC COOK 2	10-04	136182	2
		PALISADES	10-04	147806	2
		ST. LUCIE 2	01-05	158600	1
		BEAVER VALLEY 2	10-06	132110	3
	BMI Nozzle Weld	SOUTH TEXAS 1	04-03	97350	2
	HL Nozzle Weld	RINGHALS 4	08-00	116139	1
		RINGHALS 3	09-00	118143	1
		VC SUMMER	10-00	112449	1
		TIHANGE 2 **	10-03	145140	(1)
Total					**104**

** Not confirmed

Table 2-2 (continued)
Distribution of PWSCC Events as a Function of Component Type

Components	Types Of Weld	Plants	Date	Operating Time (EFPH)	Number Of Cracked Welds
SG	Tube Sheet Plate Cladding	ST LAURENT B1	09-95	77000	1
	Channel Head Drain Nozzle Weld	CATAWBA 2	09-01	104533	1
		CATAWBA 2	09-04	128647	2
		WOLF CREEK	04-05	143700	1
	Manway Drain Nozzle Welds (Hot And Cold Legs)	RINGHALS 2	05-04	105000	2
	Tube To Tubesheet Welds	CATAWBA 2	09-04	129914	196
Total					**203**

** Not confirmed

Table 2-2 (continued)
Distribution of PWSCC Events as a Function of Component Type

Components	Types Of Weld	Plants	Date	Operating Time (EFPH)	Number Of Cracked Welds
Pressurizer	Instrumentation Nozzles Weld [Welding Defect Present]	ST LUCIE 2	03-94	~7500	3
	Instrumentation Nozzles Weld [HAZ]	SAN ONOFRE 3	08-95	~75000	2
	Instrumentation Nozzles Weld	CALVERT CLIFFS 2	07-98	53400	1
		FT CALHOUN	10-00	167033	1
	Heater Sleeve Weld	PALO VERDE 3	02-04	117281	1
	Safety Line Piping Nozzle Weld	TSURUGA 2	09-03	121375	1
		TMI-1	10-03	156330	1
		CALVERT CLIFFS 1	03-06	141535	1
		DC COOK 1	04-05	164260	1
		WOLF CREEK 1	10-06	154690	1
	Relief Line Piping Nozzle Weld	TSURUGA 2	09-03	121375	1
		WOLF CREEK 1	10-06	154690	1
	Surge Nozzle Weld	TIHANGE 2 **	10-02	138000	(1)
		WOLF CREEK 1	10-06	154690	1
	Spray Nozzle Weld	MILLSTONE 3	10-05	116460	1
Total					**17**

** Not confirmed

Table 2-2 (continued)
Distribution of PWSCC Events as a Function of Component Type

Components	Types Of Weld	Plants	Date	Operating Time (EFPH)	Number Of Cracked Welds
Primary Loop	Hot Leg Nozzles Welds	ARKANSAS 1	02-00	147618	7
	Hot Leg Surge Nozzle To Safe End Weld	CALVERT CLIFFS 1	03-06	141535	1
	Hot Leg Piping Nozzle To Safe-End Weld For The Drain RCS	CALVERT CLIFFS 2	Spring 2005	130000	3
	Cold Leg Piping Nozzle To Safe-End Weld For The Letdown/Drain Line RCS	CALVERT CLIFFS 2	Spring 2005	130000	1
	Cold Leg Drain Nozzle Weld (82/182)	DAVIS BESSE	03-06	154417	1
Total					**13**

** Not confirmed

Figure 2-1 shows the typical locations of the welds that have experienced PWSCC. One notable absentee from the list of affected nickel-base weld metals is that attaching the core radial supports to the RPV, which is always stress relieved with the RPV. Other absentees are the dissimilar metal butt welds of steam generators (which is difficult to understand given the history of cracking of similar welds on the RPV and pressurizer) and the butt welds of the steam generator divider plate.

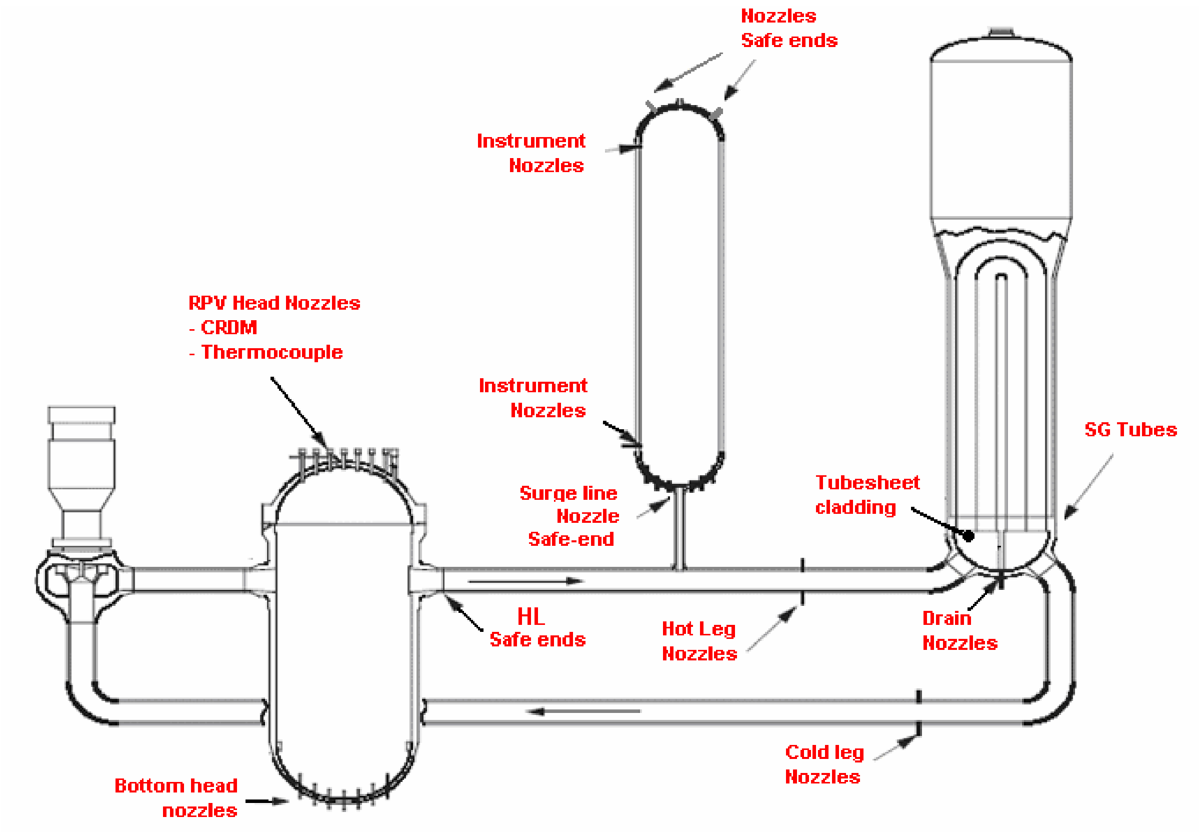

Figure 2-1
Location of Cracked Nickel-Base Welds in the Primary Circuit of PWR Units

As mentioned earlier, since 1994, more than 300 nickel base Alloy 82 or 182 welds have cracked in service under normal operating conditions. The statistics are, however, somewhat distorted by the fact that many welds were cracked in just two incidents; 58 J-groove welds at North Anna 2 and 196 steam generator tube to tubesheet seal welds at Catawaba 1. It can also be noted that only welds that were not stress-relieved with adjacent low alloy steel components have cracked to date.

When butt welds were first detected with PWSCC, the cracking was often associated with significant weld repairs. However, later incidents have not in general been linked to the presence of weld repairs. A Belgian study of the difference between stress relieved and non stress relieved butt welds showed that hoop stresses in the former were expected to be well below the threshold stress for PWSCC of ~350 MPa (50 Ksi) and the latter close to the threshold. [22]. Repairs would be expected to induce locally high residual stresses that, based on experience, can be anticipated to extend in highly restrained geometries up to ~30 mm from the fusion line with the repair weld. This would represent a step change in susceptibility to PWSCC for welds that had previously been stress relieved. Finite element studies of generic RPV and Pressurizer butt welds have shown that weld repairs should also increase hoop stresses significantly even in non stress relieved butt welds but not to the same relative extent as for stress relieved welds. [23] In addition, hoop and axial stresses after repairs become more comparable in magnitude although internal surface hoop stresses are still predicted to be greater than axial stresses, the maximum being about 420 MPa (60 Ksi).

All indications of PWSCC in butt welds have been axial with two exceptions, a short and shallow circumferential crack in Alloy 182 of the same hot leg that had an axial flaw and leaked at V.C Summer [6] and the recent observation of three bimetallic butt welds at Wolf Creek with circumferential indications [9]. The shallow circumferential crack detected at V. C. Summer arrested when it reached the low alloy steel nozzle base metal. Cracks are generally expected to be predominantly axial due to sum of the hoop operating and residual stresses in this type of weld being higher than the sum of axial stresses, as mentioned in the previous paragraph. The maximum possible length of axial cracks in dissimilar metal butt welds is then obviously bounded by resistant low alloy steel and stainless steel materials on each side of the weld. The particular circumstances surrounding the Wolf Creek observations of three welds with circumferential indications are currently the subject of much analysis to understand the fabrication factors that might have favored the development of circumferential cracking.

Concerning J-groove welds, radial-axial cracking as well as circumferential cracking (with respect to the nozzle axis) have been observed (Figure 2-2) consistent with the expected pattern of residual stress following shrinkage of the J-groove weld during fabrication.

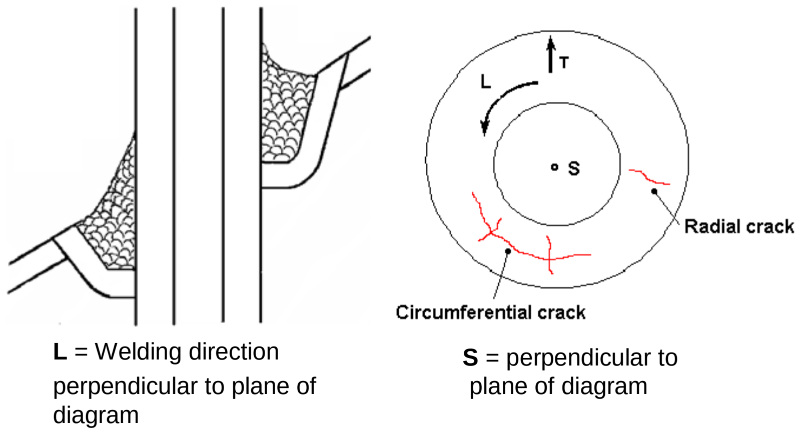

Figure 2-2
Orientation of Radial-Axial and Circumferential Cracking in J-Groove Welds

One particularly interesting case of PWSCC occurred in the Alloy 82 J-groove welds of the drain lines of both the hot and cold compartments of the channel head of a replacement steam generator at Ringhals 2. [14] This is one of the very few unequivocal examples of in-service cracking of Alloy 82. It appears to be linked to an increase in residual stress at the crack sites relative to other similar replacement steam generators that have not experienced any in-service cracking. The cracks were located at an angular position where most weld beads were started and finished. Several other factors were cited as contributing to increasing the stress above the threshold for PWSCC in Alloy 82, among them the presence of weld defects, a modified weld design with an increased size of weld deposit and a possible contribution from thermal fluctuations in the drain lines. Another unequivocal example of Alloy 82 PWSCC occurred in the Alloy 82 cladding of a steam generator tube sheet that was impacted by a loose part such that the hardness of the cold worked material increased to 350HV. [4, 24] In this case, cracking was confined to the cold worked material.

Where samples of Alloy 182/82 butt or J-groove welds have been taken for destructive examination, it has been observed that the cracking is interdendritic (in fact intergranular when examined in detail) and often, but not systematically, rather branched. [4, 5, 6, 7, 8, 10, 11, 14, 24, 25, 26, 27] The cracks can grow over the whole weld joint area including, in some cases, the buttering of the low alloy steel. Destructive examinations have also shown that cracks can often be linked to the inner or outer surface only by pinholes (VC Summer, Oconee 1, Tsuruga 2…) so that surface grinding may be required to observe the real extent of cracking near the surface by dye penetrant testing. Such behavior is doubtless linked in part to the residual stress distribution near the surface of ground welds but also to the characteristic crystallographic orientations of the grains and grain boundary energies of weld metals, as discussed in more detail in Chapter 3.

In some cases, the cracking has been linked to the surface condition after fabrication. For example, the initiation of cracks from grinding marks in the case of VC Summer and absence of any surface finishing at OHI 3. Occasionally, weld defects have been observed together with the PWSCC, such as lack of fusion or hot cracking, but they have been invoked in only four cases as a key precursor to cracking. Another practically important observation was the re-initiation of PWSCC from surface micro-fissures induced by electro-discharge machining (EDM) that was used to extract boat samples for destructive examination from an Alloy 182 butt weld at Ringhals 3. [25]

The cumulative number of Alloy 182/82 welds affected by PWSCC as a function of operating time is shown in Figure 2-3. It is noted that the phenomenon appears usually after operating times greater than ~90,000 EFPH after excluding special cases such as the earliest events in pressurizers occurring relatively quickly after plant start-up and a steam generator tube sheet cladding impacted by a loose part.

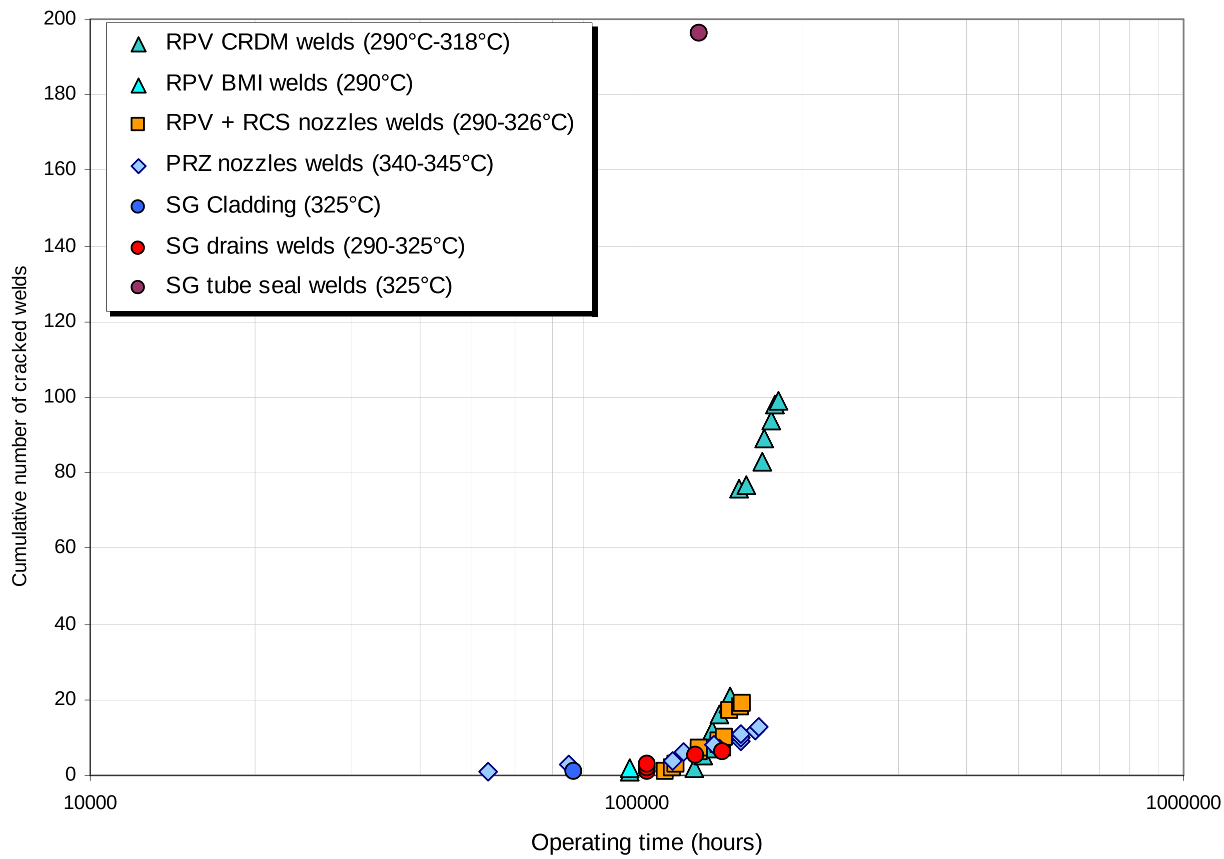

Figure 2-3
Operating Times to Observation of PWSCC of Nickel-Base Welds without any Correction for Operating Temperature

If an activation energy (185 kJ/mole) is used to convert the operating times to observation of PWSCC at the operating temperature to equivalent times at 325°C, as in (Figure 2-4), the scatter in the data is observed to increase rather than vice versa as expected. One possible explanation could be that the value of the activation energy used for this type of conversion to obtain equivalent times to cracking at a single arbitrary temperature is not appropriate (see next chapter for a discussion of the laboratory data). Another possible explanation could be that another variable is dominating the initiation of PWSCC, of which the most likely is residual welding stress. In such a case, a large number of observations would be necessary to determine the distribution of failure times at each temperature before any clear effect of temperature could be discerned. It is assumed that such distributions would have large areas of overlap due to the dispersion of surface residual stress in welded joints. This argument is developed further in Chapter 4.

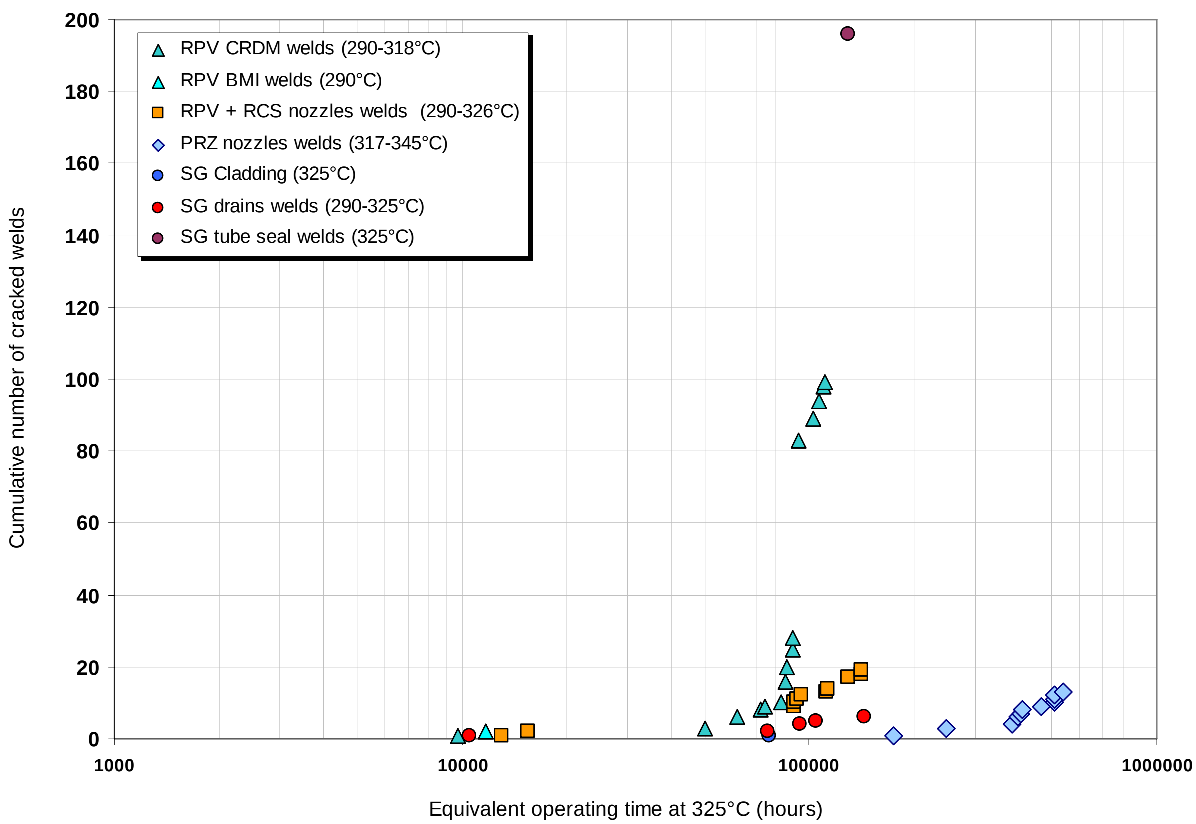

Figure 2-4
Equivalent Times at 325°C to Observation of PWSCC of Nickel-Base Welds

A clearer picture of the susceptibility of Alloy 182/82 welds to PWSCC is seen in Figure 2-5 where the data from Figure 2-3 are re-plotted according to the generic class of weld. The scatter in the observations as a function of time is much reduced and looks to be a potential basis for a Weibull type of predictive distribution for butt welds and J-groove welds. However, the main problem is that it is difficult on the basis of currently available information to know the numbers of inspected welds that were free of reportable indications that would allow the probability of cracking at a given time to be determined. J-groove welds are seen in Figure 2-5 to start cracking after a minimum of ~90,000 EFPH and butt welds after a minimum of ~115,000 EFPH.

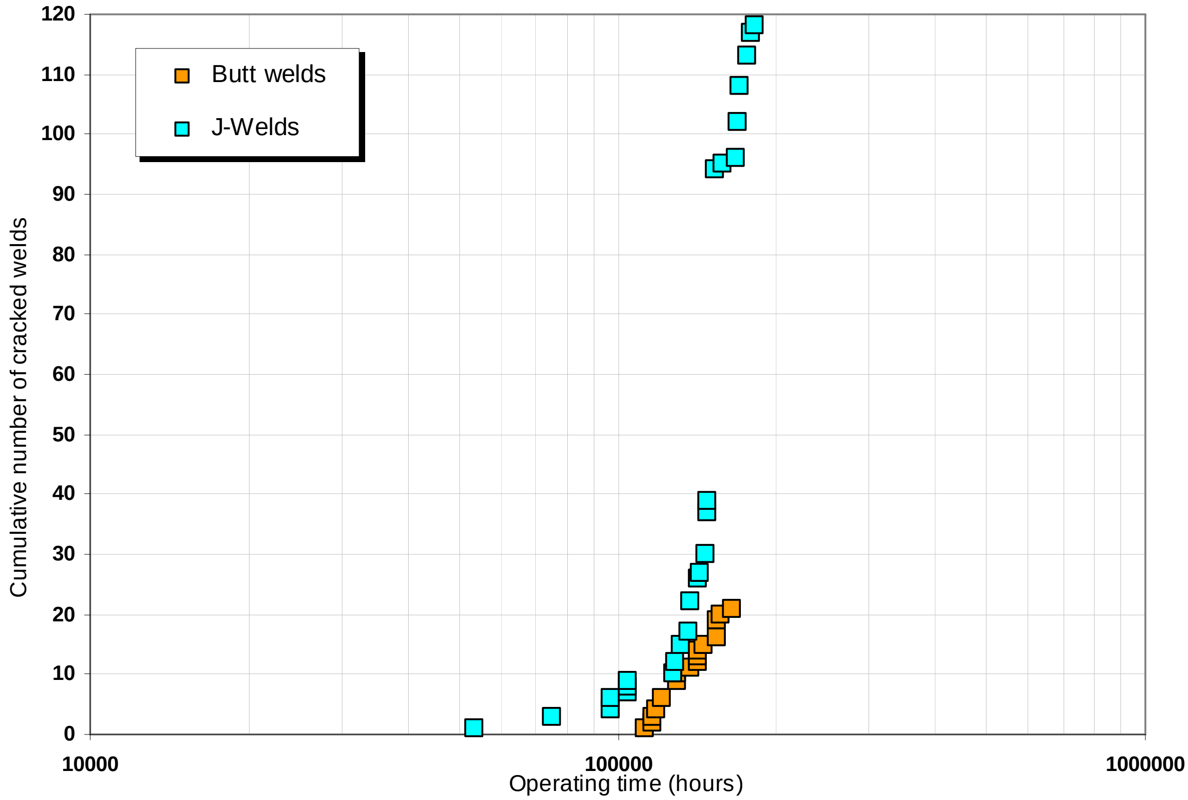

Figure 2-5
Operating Times to Weld Cracking as a Function of Weld Type

In summary, a total of more than 340 Alloy 182/82 welds are known to have had reportable indications attributed to PWSCC although the statistics are distorted somewhat by 196 steam generator tube seal welds to the tube sheet cladding in one plant and 58 J-groove welds at North Anna 2. In only 4 of these cases was the occurrence of PWSCC linked to the presence of fabrication defects. Most cases have been attributed to the presence of high residual stresses that in some cases are associated with repairs or with localized high cold work. The affected welds were not subjected to a stress relief heat treatment with adjacent low alloy steel components. The underlying reasons for these trends are explored in Chapter 4 after a summary of the laboratory data in the following Chapter 3.

3 SUMMARY OF LABORATORY INVESTIGATIONS

Laboratory investigations of PWSCC of the nickel base weld metals Alloys 182 and 82 have been reviewed several times in the last five years or so, including a comprehensive review for the MRP in 2004 (in the context of defining appropriate equations to describe crack growth rates). [2, 24, 28, 29] A summary is presented here, supplemented where necessary by results of recent studies. Some additional information relating to the major improvements in PWSCC resistance of the replacement Alloys 152 and 52 is also available in a review for the MRP carried out in 2004. [30]

Weld Parameters Affecting PWSCC

Microstructure

By its nature, a weld has an as-cast structure that has a strong influence in nickel base welds on how PWSCC initiates and propagates. [28] At the microstructural level, as each weld bead solidifies from the molten state, packets of dendrites, within which the dendrites have the same or very similar crystallographic orientations, grow in the opposite direction to heat flow. As each weld bead is deposited, the crystallographic orientations of dendrites tend to be maintained between the weld beads. Thus a columnar dendritic structure is formed that tends to be perpendicular to the root and crown of the weld in its center and curves towards the fusion lines with the adjacent materials; see for example Figure 3-1.

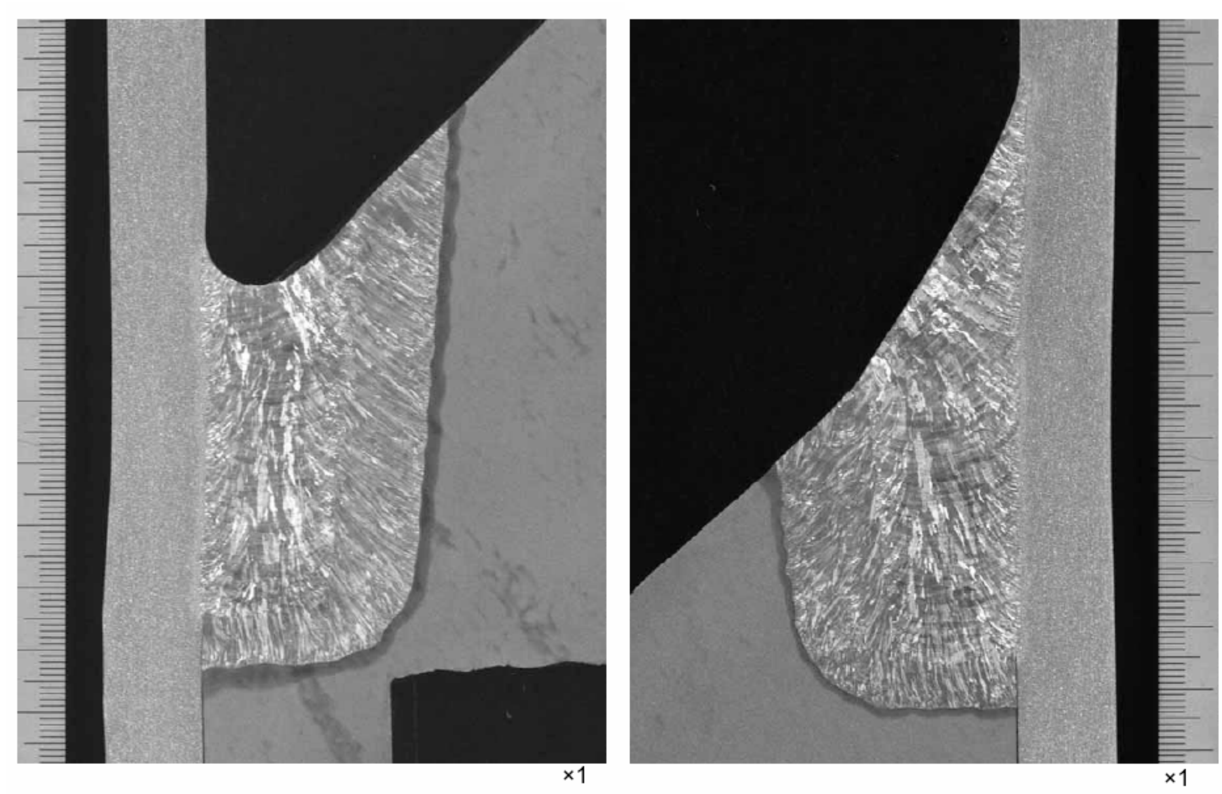

Figure 3-1
Macrograph of a Diametral Cross-Section of a J-Groove Weld

Grain boundaries form between packets of dendrites having different crystallographic orientations and typically have a wavy appearance in contrast to the polygonal shapes of grains in wrought materials. A grain boundary is defined, perhaps somewhat arbitrarily, as the boundary between packets of dendrites with angular misorientations of their crystal structures >15°. These are the preferred location for PWSCC initiation and growth in Alloys 182 and 82. (It should be noted that PWSCC in nickel-base weld metals is often described in the technical literature as interdentritic but, in fact, it is more correct to call the cracking intergranular). Recent work has shown that in these as-cast structures the misorientation between the grains can vary significantly even along the wavy grain boundaries. [31] Cracks may arrest at portions of the grain boundary where the crystallographic misorientation becomes low or where the crystal structures of adjacent grains have special geometric relationships so that they have low energy.

Another consequence of the columnar dendritic structure of nickel base welds is that PWSCC grows much more easily on grain boundaries parallel to the dendrites, i.e. most easily in the through-thickness direction followed by the direction of weld bead deposition. Initiation and propagation is most difficult perpendicular to the general direction of the dendrites. This microstructural influence on the preferred direction of crack growth can also give rise to unusual crack shapes with very low aspect ratios that are unlike the typical semi-elliptical shapes of stress corrosion cracks growing in equiaxed wrought materials (in a uniform stress field). This effect of the weld microstructure is believed to be largely responsible for the observation in field mentioned in Chapter 3 where cracks initiate from or break through to the surface on a very narrow front, thus making detection that much more difficult.

Chemical Composition

During solidification of weld beads of Alloy 182 and 82 and formation of dendrites, a cored structure tends to be produced within the grains with periodic niobium and manganese-rich, chromium and iron-depleted regions that are also rich in niobium carbides. [28, 29] No significant grain boundary segregation of the constituent elements has been observed, including impurities such as silicon, phosphorus and sulfur that have been associated with the risk of hot cracking. No particular link between PWSCC susceptibility and such spatial compositional variations has been established although it has been suggested that the crystallographic misorientation observed between niobium-rich and niobium-lean zones may enhance differences in deformation behavior when strained and which may then be preferred sites for crack initiation. [31] Results vary between different studies as to whether total carbon and silicon content have any measurable effect on PWSCC susceptibility.

It is, however, well established that as the bulk chromium content in nickel base weld metals increases, susceptibility to PWSCC decreases, which explains why Alloy 82 (typically 20%Cr) is significantly more resistant to PWSCC than Alloy 182 (typically 15%Cr). The difference in initiation times has been measured to be at least a factor of 6. [29] Above 22%Cr in both wrought and weld metals PWSCC initiation becomes very difficult, if not impossible, even in the most severe laboratory tests. Interestingly, some very recent work on composite specimens of Alloy 600 and Alloy 152 has shown that PWSCC initiated in the Alloy 600 (14-17%Cr) arrests before the fusion line with the Alloy 152 (28-31.5%Cr) at a point where the chromium concentration had increased by diffusion during welding to ~22%. [32]

In principle, dilution effects with other materials adjacent to the fusion line of nickel-base welds, which would vary significantly with welding parameters and weld design, could influence PWSCC susceptibility but there are no known studies.

Post weld heat treatments such as those given to stress relieve low alloy steel components (the RPV, pressurizer and SG shells) to which Alloy 182 butter layers or completed bimetallic welds are attached could also, in principle, have an influence on the spatial distribution of the elemental constituents of nickel-base welds and hence potentially on their PWSCC susceptibility. In most cases, no detectable metallurgical changes have been observed after typical stress relief heat treatments of welded mockups at 600 to 620°C (in contrast to a significant effect on surface residual stress described in the next section) and with no change in intrinsic susceptibility of the deposited weld metal to PWSCC. [24, 29] Generally, no “sensitization” (i.e. no precipitation of grain boundary carbides with associated chromium depletion adjacent to grain boundaries) has been reported, as might be anticipated from the high stabilizing Nb to C ratio in these materials. However, there are some significant exceptions but again without consequence for PWSCC susceptibility. Additionally, no precipitation of γ’ phase (Ni_3Ti) has generally been observed as a consequence of stress relief heat treatments of Alloy 182, (which has the potential to increase intrinsic strength and hence degrade PWSCC resistance) although again there are exceptions. Also, no γ’ precipitation was detected during high resolution examinations of samples of Alloy 182 removed from the hot leg safe end weld of Ringhals 4 after 17 years service. [26]

Residual Stress, Surface Finish, and Weld Defects

The magnitude and direction of residual stress after welding is affected by many welding parameters such as weld design, heat input, interpass temperature, thermal conductivity of the joined materials and degree of constraint. J-groove welds have a higher degree of constraint than pipe butt welds, for example. The presence of weld repairs is another factor affecting residual stress distributions. The same generic complexity also applies to the extent of cold working experienced by nickel base welds during fabrication, which can potentially increase intrinsic strength and hence PWSCC susceptibility.

The results from finite element studies of residual stresses in welds have already been summarized in the previous chapter. Residual stress measurements in Alloy 182 welds are rare. In the as-welded condition, surface stresses measured by X-ray diffraction depend a great deal on the grinding conditions used and have been observed to vary from -500 to 900 MPa (-70 to 130 Ksi) in both butt welds and J-groove welds. [24] A similar range of surface residual stresses has been recently measured in the authors' laboratory for EDF but extending up to 1200 MPa as a result of abusive grinding. By contrast, fine grinding (usually carried out to facilitate non-destructive examinations) results in surface residual stresses in compression to minimum values of about -300 MPa (-43 ksi). Residual stresses measured by home drilling do not take into account surface effects and have revealed maximum as-welded bulk residual stresses typically between 350 and 450 MPa (50 to 65 Ksi), equivalent to the usual range of yield strengths for Alloy 182. [24, 29] The in-depth stress profile can be complex, however.

Stress relief heat treatments at 600 to 620°C of adjacent low alloy steel components have been clearly shown on mockups to relax very significantly the surface residual stress to about ~100µm below the surface, despite the fact that the heat treatment is not at an optimum temperature to have a strong effect on austenitic materials. The most likely reason for such a strong favorable effect on surface residual stresses and consequently on PWSCC initiation resistance is that the cold worked layer produced by grinding recrystallizes during heat treatment at 600 to 620°C. [29, 33] Even subsequent straining, which might occur during straightening of Bottom Mounted Instrumentation (BMI) nozzles, for example, or during the hydraulic pressure test applied to complex geometries such as the steam generator channel head, cannot develop surface tensile stress to anything like the same degree as in the absence of prior stress relief heat treatment. [33] This is because the recrystallized surface layer does not harden to the same extent as a cold worked layer produced by surface grinding. In any event, these observations clearly underline the favorable effect of stress relief heat treatments of adjacent low alloy steel components on PWSCC resistance of Alloy 182/82 welds observed in service.

Experiments have been conducted to evaluate the influence of various surface preparation procedures such as lathe turning, fine grinding and electrolytic polishing on PWSCC resistance. [24, 30] Mechanical properties, particularly yield stress, in the superficial cold worked layer can be very different from those of the bulk material. Detrimental effects of surface cold work on the resistance to PWSCC have been observed after plastic deformation of the superficial cold worked layer. Surface stresses in excess of 1,000 MPa (145 Ksi) have been measured on lathe turned specimens that were then subjected to 2 % or more plastic deformation. Similar values of surface residual tensile stress have been measured on ground surfaces subject to subsequent plastic deformation. [33] Comparisons between lathe turned surfaces and electrolytically polished surfaces under the same experimental conditions revealed nearly an order of magnitude reduction in time to failure by PWSCC caused by prior surface cold work due to lathe turning. [24]

Weld defects such as gas pores, slag inclusions, lack of fusion and hot cracks are potential sources of stress concentration that could enhance PWSCC initiation susceptibility and accelerate growth if such defects are intersected by a growing crack. Such fabrication defects would not be expected to be surface breaking in service due to the dye penetrant examinations carried out both during and at the end of welding but buried defects are possible. Only gross sub-surface defects affecting the stress concentration in the ligament between it and the water exposed surface would likely exert any effect on PWSCC initiation, as may have been the case in the cracking observed in the BMI nozzles and J-groove welds at South Texas Unit 1 in 2003. [10] Small surface breaking defects such as gas pores and slag inclusions have been observed not to be preferred sites for PWSCC initiation. [31]

As mentioned earlier, no significant grain boundary segregations of elements known to be linked to the formation of low melting point phases that are responsible for solidification and liquation cracking have been found either in laboratory studies or in examinations of samples of Alloy 182/82 removed from service. Another form of hot cracking known as ductility-dip cracking is associated with a trough in intergranular ductility at intermediate temperatures and can occur at relatively high strains in the heat affected zone of the previously deposited weld bead. [28] Unequivocal evidence for the involvement of this process in PWSCC propagation is rather difficult to obtain since no low meting point phases are involved but the balance of evidence suggests that such defects do not play a significant role in PWSCC.

PWSCC Initiation

Experimental studies have allowed the quantitative influence of stress and temperature on PWSCC initiation in Alloy 182 to be evaluated. [24] Stress corrosion cracking of Alloy 182 in PWR primary water is thermally activated although the available data on the effect of temperature are rather scattered and not really sufficient to give an adequate fit to the Arrhenius equation. [24, 28, 29] For experiments carried out at temperatures between 330°C and 360°C, the results have been judged to be consistent with an activation energy of 185 kJ/mole, which is identical to that used for Alloy 600. However, recent experimental work by AREVA NP suggests that the activation energy is nearer 230 kJ/mole although this remains to be confirmed.

The available data for the stress dependency of PWSCC in Alloy 182, normalized to a temperature of 325°C using an activation energy of 185 kJ/mole, are plotted in Figure 3-2. The intrinsic susceptibility of Alloy 82, as measured in terms of time to observable cracking, has been shown to increase by about a factor of 6 relative to Alloy 182 under equivalent test conditions, consistent with their relative performance in the field. [24, 29]

Constant load and capsule experiments between 300 and 600 MPa (43 to 87 Ksi) on Alloy 182 in PWR primary water at 330 or 350 °C lasting up to 21,500 hours have shown that cracking only occurs when the applied stress exceeds the yield stress, for which the average value is about 350 MPa (50 Ksi) in a range of 300 to 380 MPa (43 to 55 Ksi). [24, 29] This can be compared with the lower threshold for PWSCC initiation of 250 MPa (36 Ksi) derived for Alloy 600. Welded mock-ups of nozzles in plates have also been tested in PWR water at 360°C but in no case has residual stress alone been sufficient to cause stress corrosion cracking, even in the as-welded condition. It appears that despite surface residual stresses being sufficient to initiate PWSCC, in many cases the bulk residual stresses are too low over a sufficient depth to continue significant propagation in the absence of service stresses. No significant effect of "ripple" (high R cyclic) loading on the threshold for cracking in Alloy 182 has been observed [29].

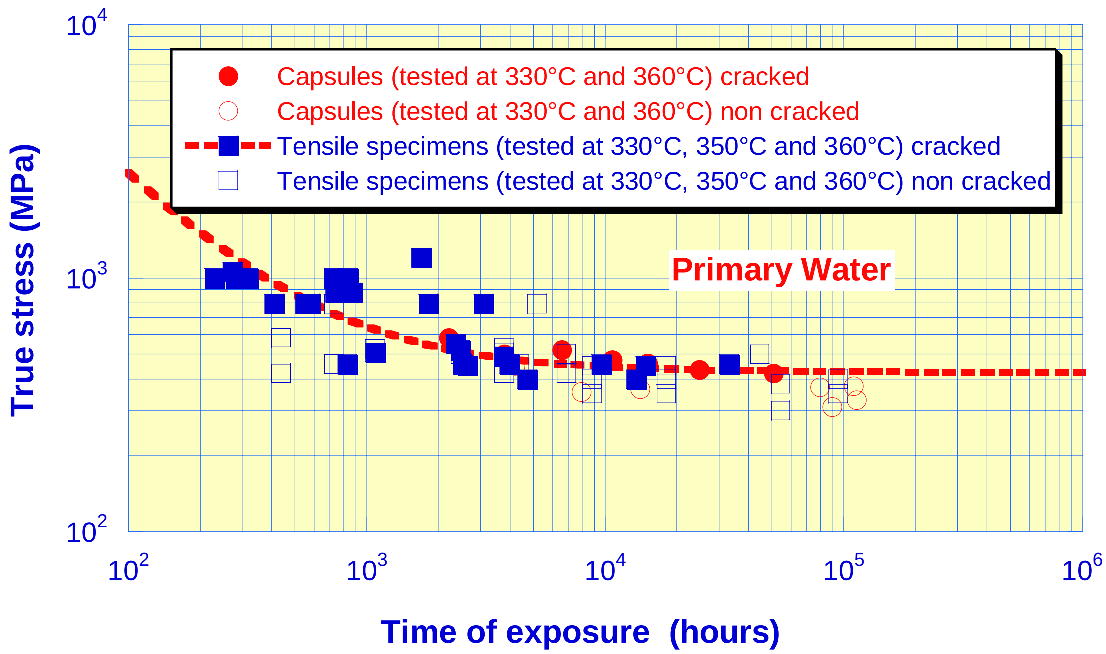

Figure 3-2
Cracking of Alloy 182 in PWR Primary Water – Stress as a Function of Time (Converted to a Temperature of 325°C Using an Activation Energy of 185 kJ/mole) [24]

For applied stresses above 450 MPa (65 Ksi), a lower bound parametric equation giving the failure time for Alloy 182 as a function of stress can be written as follows [24]:

$$t_f = k\sigma^{-7} \quad \textbf{Eq. 3-1}$$

While a simple power law is superficially attractive for structural evaluations, such an approach gives only a very approximate and pessimistic estimation of failure times likely to be relevant to an operating plant. This is because the trend between 450 MPa (65 Ksi) and the threshold stress, necessarily giving rise to very long exposure times, has not been adequately characterized. Moreover, as discussed in the previous section, the surface condition can have a very large effect on the time to crack initiation.

In normal service, the low alloy steel of dissimilar metal welds is covered by a continuous cladding layer of austenitic stainless steel or nickel base alloy so that there is no contact between the low alloy steel and PWR primary water. However, in some circumstances following in-service repairs, the low alloy steel near bimetallic welds can be wetted by primary water and consequently the question of a possible effect of galvanic coupling can arise. From a fundamental electrochemical viewpoint, galvanic coupling between low alloy steel and the nickel based weld metals is not expected in deoxygenated and hydrogenated PWR primary water and could only occur during shut-down when the primary circuit is open to oxygen of the atmosphere.

PWSCC Propagation

PWSCC propagation rates in Alloys 182 and 82 were extensively reviewed for the MRP in 2004 and appropriate parametric equations were derived for dispositioning weld indications found by in-service inspection. [28] A brief summary is given here.

More laboratory studies have been devoted to measuring crack propagation rates as a function of the linear elastic crack tip stress intensity factor, K_I, than time to crack initiation as a function of applied stress. Given the complexity of the metallurgical factors influencing PWSCC in nickel base weld metals, it is not surprising that the available crack propagation data for Alloy 182 (and the similar Alloy 132 used in Japan) show considerable scatter, typically around two orders of magnitude of growth rate, even after careful screening to ensure adequate and consistent data quality (Figure 3-3).

An important feature of laboratory crack propagation studies attributable to the complex metallurgy and grain boundary structure of nickel base weld metals is the difficulty encountered in ensuring even growth across the whole crack front. Islands of material resistant to crack growth are often observed, which varies considerably from heat to heat and gives rise to large variations in observed average propagation rate. One potentially important effect of superimposed cyclic loading can be to rupture unbroken bridges of material often left behind the main stress corrosion crack front. Experimentalists favor such high R cyclic loading because it facilitates measurement of crack growth by the potential drop technique. However, this may artificially increase crack growth rates compared to those observed in PWR components although in practice the factors observed have not been large. In real components where cracks are not constrained into one plane, as in laboratory specimens, cracks can propagate around the obstacle.

The way in which average growth rates are derived from the experimental observations or whether maximum observed growth rates are more appropriate remain controversial issues. [24, 28, 29] The approach taken in MRP-115 [28] was to fit the screened data to a lognormal distribution of crack growth rates as a function of a power law in K_I. For this purpose, it was decided that the database did not justify including a threshold although previous attempts to derive crack growth laws included a threshold crack stress intensity value (of 9 MPa$\sqrt{m}$) that was the same as that adopted previously for Alloy 600. An equation bounding 75% of the data was chosen from the lognormal distribution. The resulting crack growth equation for Alloys 182 and 132 is shown in Figure 3-3 where it is compared with prior proposals based on less data.

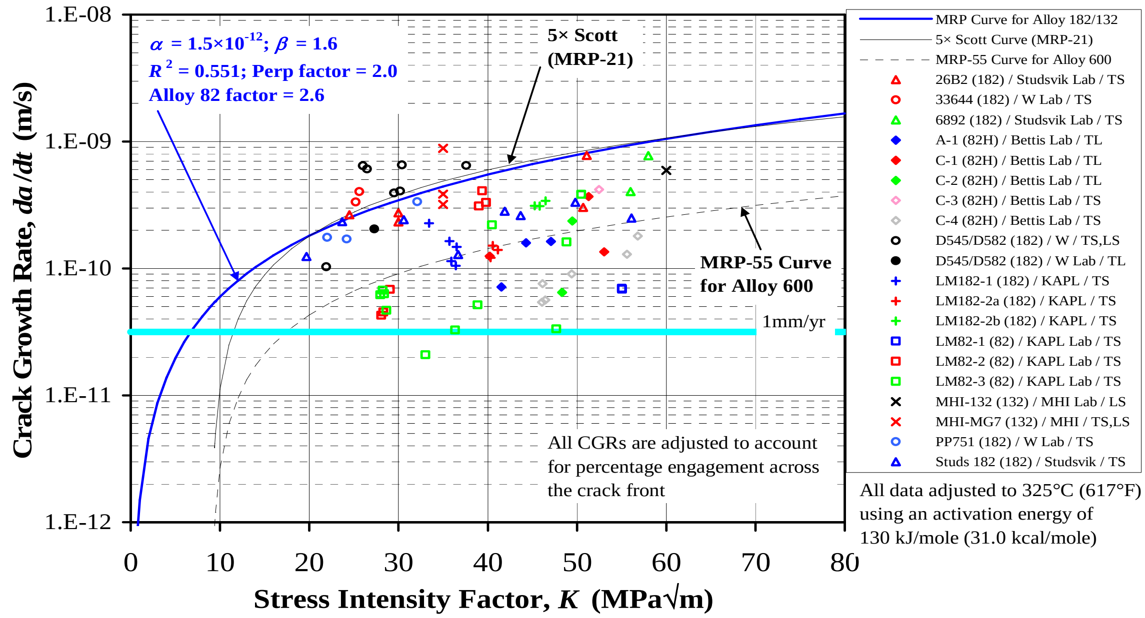

Figure 3-3
Screened MRP Database for Alloy 182/132 Welds Normalized to a Crack Orientation Parallel to the Weld Dendrites [28]

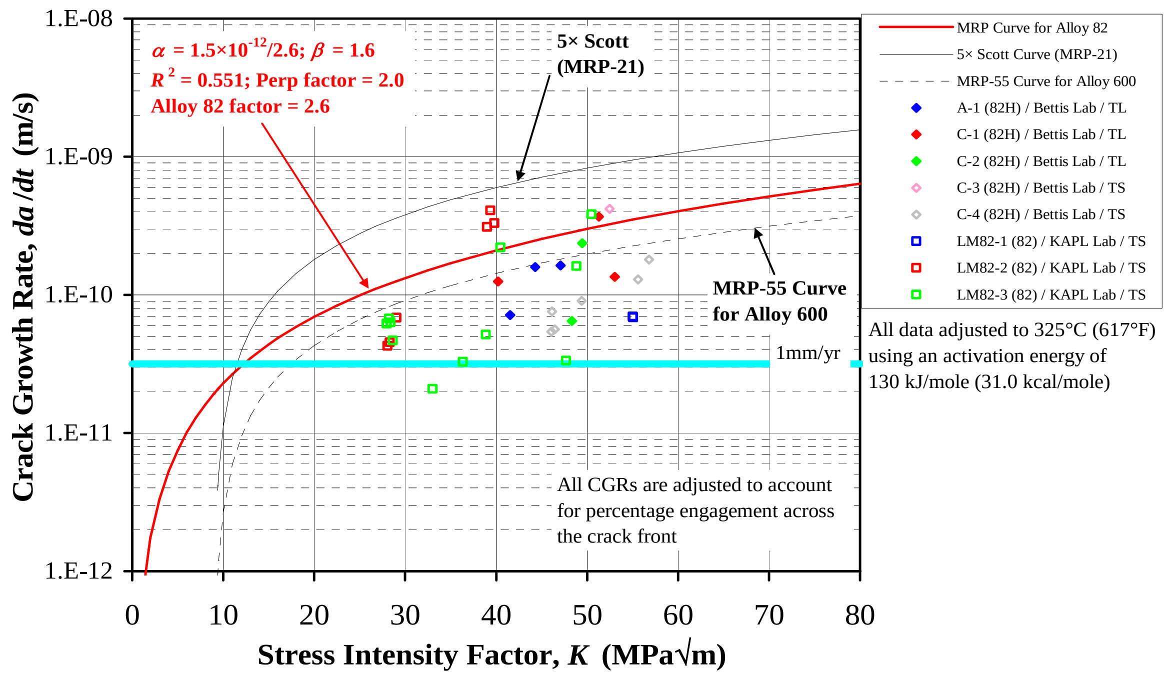

Figure 3-4
Screened MRP Database for Alloy 82 Welds Normalized to a Crack Orientation Parallel to the Weld Dendrites [28]

The direction of crack propagation relative to the weld dendrites is one of the more important parameters affecting the crack growth rate. Cracks are able to propagate about an order of magnitude more rapidly along the dendrites compared to transverse to the dendrites in the same weld deposit. By comparison, other parameters such as the chemical composition within the Alloy 182 (and Alloy 132) specification, thermal treatment at 600 to 620°C and cold work up to about 10% have either small (within a factor of two) or negligible effects on crack propagation rates. Chromium on the other hand has a significant influence on crack growth rates as shown by the screened data for Alloy 82 in Figure 3-4 where growth rates are on average 2.6 times lower than for Alloy 182 (and Alloy 132). [28]

Concerning PWR primary water environmental variables, hydrogen concentration within the specified range in PWR primary water is known to influence crack propagation rates in Alloys 182 and 82 by up to a factor of about 8. However, the database used in MRP-115 was not judged sufficient to model this effect quantitatively. Another environmental parameter, the temperature, also has a significant influence on crack propagation rates consistent with an activation energy of 130 kJ/mole, which was used in normalizing the data in Figure 3-3 and Figure 3-4 to a single temperature of 325°C.

4 DISCUSSION

A consistent picture emerges from a comparison of PWSCC of Alloys 182 and 82 in service and in laboratory tests. Despite the difficulty in some cases of positively identifying the filler metal used in older fabrications, it is clear that many more PWSCC events have occurred in service in Alloy 182 (13-17% Cr) welds than in Alloy 82 (18-22% Cr) welds. Given that times in service to detect PWSCC of Alloy 182 mostly exceed 90,000 hours and that Alloy 82 shows a factor of improvement in laboratory tests of about 6 relative to Alloy 182, all other things being equal, the low number of known Alloy 82 failures in service is easy to understand (and augurs well for the future behavior of Alloys 52 and 152 that contain 28-31.5%Cr).

The laboratory observation that when PWSCC is initiated in a susceptible nickel base alloy it appears to arrest when growing towards material with a chromium concentration equal or greater than ~22% is also consistent with field behavior and emphasizes the fact that Alloy 82 with a specified chromium content of 18-22% is on the borderline of susceptibility. Other factors that appear to enhance susceptibility to PWSCC in service in the two known cases in the field concerning Alloy 82 are an unusually high residual stress due to weld design and constraint or due to impact by loose parts. However, attention should also be drawn to the fact that data on PWSCC susceptibility of dilution zones with chromium-poor materials does not appear to have been investigated in the laboratory (which may also be a concern for the future behavior of Alloys 52 and 152). Attention therefore needs to be focused on the influence of weld design and heat input on the potential for creating local zones of material with less than ~22% Cr. On the other hand, field experience so far suggests that PWSCC has not propagated into the fusion zones with either low alloy or stainless steels of dissimilar metal welds.

Compositional variables other than chromium in Alloys 182 and 82 have only been observed in laboratory work to have either a relatively small or no impact on PWSCC initiation and growth and no such effects have been identified from investigations of in-service failures. Similarly, common and structurally acceptable weld defects such as small slag inclusions, porosity and small sub-surface hot cracks or lack of fusion defects also seem to have had no or only marginal influence both in service and in laboratory testing. However, large weld defects can clearly play a role in terms of local stress concentration if sufficiently close to the surface and if they become flooded due to the ligament between it and the surface being broken, for example by fatigue.

The development of PWSCC of Alloy 182 welds in PWR service as a function of operating time, as shown in Figure 2-3 and Figure 2-5, raises several important questions:

- Why is there no immediately obvious effect of temperature?
- What service parameter(s) determine(s) why some welds develop PWSCC?
- What is the origin of the apparent inconsistency between the timescale for PWSCC in the field data in Figure 2-5 and the normalized laboratory data in Figure 3-2?

Concerning the apparent absence of any obvious effect of temperature in the field experience, the hypothesis has already been advanced in Chapter 2 that another dispersed variable, probably residual stress, could be masking any strong effect of temperature. The origin of this suggestion lies in the authors' prior experience of dealing with a similar anomaly of cracking in service of Alloy 600 CRDM nozzles, although in that case the possible range of temperatures was less. Due to variations in residual stress between nominally similar welds, a distribution (typically lognormal) of failure times would be expected for each type of weld at each temperature (of the cold leg, hot leg and pressurizer, for example). These distributions of failure times would also be expected to overlap considerably because of the high sensitivity to stress of the time to observable cracking (Figure 3-2). Nevertheless, once service cracking in the PWR fleet has developed sufficiently to generate an adequate database, it can be expected that at any given operating time the probability of failure would be greater in the hotter components.

An analysis of the data shown in Table 2-1 reveals that the proportion of cracked butt welds and J-groove welds is indeed greater in pressurizers than in hot legs and much greater than in the cold legs. This analysis assumes that all the welds of the same generic type were inspected at the same time as one or more were reported as having reportable indications in any given plant. However, as noted earlier, the statistics of the fraction of components with reportable indications of the same type and at similar temperatures are clearly much too pessimistic when based on Table 2-1 alone because of the difficulty in knowing how many plants have examined similar welds non-destructively and found no reportable indications. This problem is rendered even more acute by the fact that many plants are currently revising inspection plans in line with MRP-139. [1]

In order to probe further the parameters that determine why some welds develop PWSCC, it is noted that the classical approach to assessing the risk of stress corrosion cracking in service, once a given material / environment combination is revealed to be susceptible, is to compare the sum of the service and residual stresses to a stress versus failure time curve such as that shown in Figure 3-2. Stresses determined by finite element analyses are useful for determining crack tip stress intensity factors, K_I, in components with defects that can be sized by ultrasonic inspection in order to estimate their subsequent growth from equations such as those presented in Figure 3-3 and Figure 3-4 but experience has shown that this is not usually a reliable approach to predicting crack initiation. In fact, surface condition has a very important effect on surface stress and consequently on PWSCC initiation times that traditional finite element results, and indeed hole drilling techniques to determine residual stresses as a function of depth in mockups, do not normally take into account. The effect of surface condition on residual surface stresses as determined by X-ray diffraction has been explored in some detail in the context of PWSCC of Alloy 600 CRDM nozzles, pressurizer sleeves and other PWR components where the type and quality of final surface machining has been observed to exert a large influence on failure times. [34, 35, 36]

A quantitative analysis of the effect of surface cold work on PWSCC initiation time in Alloy 600 has been published and is based on knowledge of the thickness of surface cold work layers induced by various machining, grinding and polishing techniques, and the nominal stress such as that which can be determined by finite element analysis. [37] The principle is that when a strain is applied to a component, the stress generated in the surface layer is much higher than in the non-cold worked bulk due to the prior cold work of the former. Although some aspects of the underlying basis of the cited quantitative analysis may be arguable, the results are not disputed. The reduction in lifetime to observable PWSCC in thick section Alloy 600 components as a function of thickness of the cold worked surface layer can be expressed in terms of an effective surface stress that depends on the cold worked layer thickness and the nominal applied stress (assuming for Alloy 600 that failure time depends on stress to the inverse fourth power), as shown in Figure 4-1. As an example taken from Figure 4-1, a component with a 200μm thick cold work layer due to heavy grinding and a nominal applied stress of 500 MPa would initiate PWSCC in an order of magnitude shorter time due to an effective surface stress of 900 MPa than for the case of an electropolished surface at the same nominal applied stress. In the case of Alloy 182, the effect will be accentuated by the greater dependency of PWSCC on stress as a function of time, as described in Chapter 3.

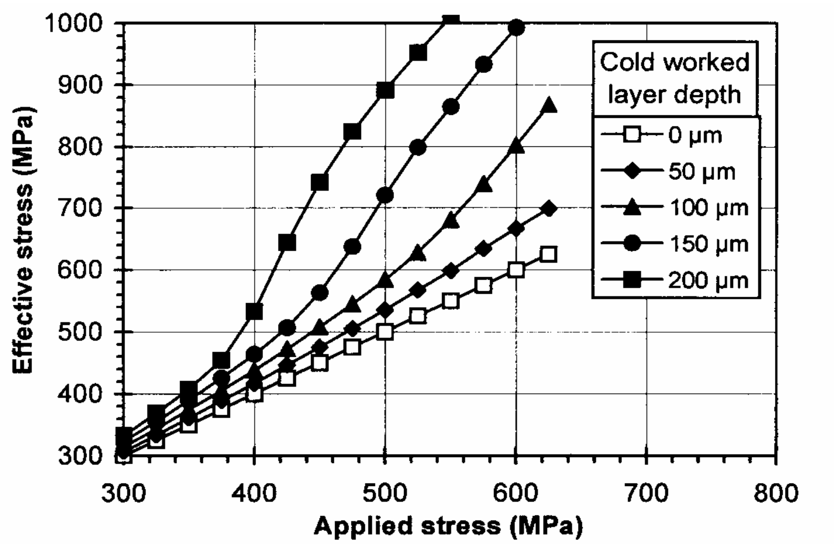

Figure 4-1
Equivalent Stress for PWSCC as a Function of Applied Stress and Thickness of a Cold Worked Layer on Alloy 600 Relative to an Electropolished Surface with No Cold Worked Layer [37]

It can also be noted that this analysis of the effect of cold worked surface layers on PWSCC of Alloy 600 also predicts situations in which cracks may initiate in thin cold worked layers, typically less than ~25 μm thick, but then cease to propagate for all practical purposes at the boundary with the non-cold worked material because the crack tip stress intensity, K_I, at that point is too low for any significant propagation to occur. For Alloy 182, a crack 25 μm thick subject to a nominal stress of 350 MPa (50 Ksi) would propagate into underlying non-cold worked material at ~0.3 mm/year (at 325°C) according to the growth equation given in MRP-115. [28] Such a growth rate would be barely detectable by periodic non-destructive examination even after many years and would be unlikely to pose any long term threat to structural integrity.

In the case of Alloy 182/82 weldments, it is now usual to grind the profile of the weld prior to service. Several studies have shown that heavy grinding or machining can generate cold worked layers easily up to100 to 200 µm thick in both Alloy 600 and Alloy 182.Tensile stresses up to 900 MPa have been measured in the grinding direction. However, the average may be nearly a third of that value and would be more consistent with the field data showing times to detection of PWSCC in excess of 90,000 EFPH. [24, 33, 36] On the other hand, fine grinding to obtain a surface finish suitable for non-destructive examination will typically leave slightly compressive stresses in the surface layer. The difference between the two grinding conditions seems to be related to the surface temperature that is reached due to friction during the process. In the case of heavy grinding to produce a given geometrical profile, tensile stresses are generated by thermal contraction of the surface layer heated by friction. In any event, such surface residual stresses can then be significantly reduced by the stress relief heat treatment given to adjacent low alloy steel components, if applied, and also modified by the hydraulic pressure test prior to service, the extent of the latter depending on the geometry.

It can be deduced from the above discussion that a strong dependence of PWSCC in Alloy 182/82 weldments on surface condition and residual surface stress can be anticipated. Most welds that have cracked to date probably had relatively thick cold worked surface layers due to profile grinding prior to service. In modern fabrication practice, much more attention is paid to surface finish and particularly to avoiding heavily cold worked surface layers. The laboratory study of the effect of surface finish on PWSCC susceptibility of Alloy 182 cited earlier underlines the point. [33] An important conclusion from that work is that the stress relief heat treatment given to low alloy steel components adjacent to dissimilar metal welds leads to a recrystallization of the cold worked layer and with it a substantial reduction in surface stress and susceptibility to PWSCC. This seems to be borne out by service experience where, to date, welds subjected to such a stress relief heat treatment have not experienced PWSCC. On the other hand, while weld repairs are clearly not a necessary condition to develop the surface stress necessary to initiate PWSCC of Alloy 182 in service, the residual stresses developed adjacent to such repairs would be expected to exacerbate susceptibility. Likewise, deliberate or inadvertent plastic deformation after fabrication, such as straightening BMI nozzles, could significantly increase tensile stresses in cold worked layers from prior grinding and with it susceptibility to PWSCC.

Finally, concerning the apparent difference in timescales for PWSCC seen in Figure 2-5 and Figure 3-2, it is clear that defining the stress / failure curve as the threshold for crack initiation (~350 MPa or 50 Ksi) is approached in laboratory work, say between 10,000 and 100,000 hours in Figure 3-2, is very difficult to do precisely. The problem is exacerbated by the apparent strong dependency of time to failure on stress. Consequently, even small differences in applied stress and surface stress due to the initial surface preparation of laboratory specimens can have a very strong influence on failure times. It is therefore considered that the apparent discrepancy between the timescales on the two figures is not as great as first appears. If better information could be obtained regarding the number of welds inspected in service, particularly where no evidence of PWSCC has been found, then Figure 2-5, for example, could be put on a proper statistical footing and potentially provide a powerful means of estimating the probability of PWSCC occurring in service.

5
CONCLUSIONS

Many more PWSCC events have occurred in service in Alloy 182 (13 – 17%Cr) welds than in Alloy 82 (18 – 22%Cr) welds despite the ambiguity that may exist in older fabrications as to which filler metal was used. This is consistent with a factor of improvement in times to observable PWSCC for Alloy 82 relative to Alloy 182 of about 6 in laboratory tests, all other things being equal.

Alloy 82 is on the borderline of susceptibility to PWSCC consistent with laboratory observations that propagating cracks arrest when the chromium concentration exceeds ~22%, which augurs well for the future in-service behavior of Alloys 152 and 52. However, attention needs to be paid to the influence of weld design on residual stress and consequently on the risk of PWSCC occurring in service. Additionally, the effect of heat input on the potential for creating local zones of material with significantly less than ~22%Cr should be examined although field experience suggests that PWSCC has not propagated preferentially into the fusion zones with either low alloy steel or stainless steels of dissimilar metal welds.

Compositional variables other than chromium in Alloys 182 and 82 have been observed in laboratory work to have either a relatively small or no impact on PWSCC initiation and growth and no such effects have been identified from investigations of in-service failures.

Common and structurally acceptable weld defects such as small slag inclusions, porosity and small sub-surface hot cracks or lack of fusion defects also seem to have had no or only marginal influence both in service and in laboratory testing. However, large weld defects can clearly play a role in terms of local stress concentration if sufficiently close to the surface and if they become flooded due to the ligament between it and the surface being broken for any reason.

A remarkably consistent trend line for the cumulative number of reportable indications attributed to PWSCC as a function of operating time for Alloy 182 butt welds and J-groove welds has been derived. This could form the basis of a Weibull approach to the prediction of field failures if the statistical foundation of the probability of failure could be improved, particularly taking proper account of plant inspections that have not revealed any reportable indications.

The effect of temperature in the aforementioned trend of field experience of PWSCC with operating time is not as marked as anticipated from laboratory testing where an activation energy of 180 kcal/mole would suggest well over an order of magnitude difference in times to PWSCC initiation in comparable welds in the pressurizer compared to the cold leg, for example. It is suggested that another dispersed variable, probably residual surface stress, could be masking a strong effect of temperature. In this case, the probability of failure should be greater at the higher temperature, as indeed appears to be the case, despite difficulties in deriving reliable failure probabilities.

Residual surface stress is strongly affected by fabrication parameters and consequently has a large effect on the risk of initiating PWSCC. Weld repairs are an exacerbating factor but are clearly not a necessary condition for cracking in service. Factors giving rise to high surface residual stresses are weld profile grinding and the application of any plastic deformation after weld fabrication that can increase residual stresses very significantly in any cold worked surface layer left by grinding or other machining operations. Factors that ameliorate surface residual stresses are fine grinding that may be carried out to facilitate non-destructive inspections and the application of a stress relief heat treatment to adjacent low alloy steel components after the dissimilar metal weld is completed. The effectiveness of the latter is revealed in the service experience that to date shows no PWSCC in welds that have been subjected to such stress relief heat treatments. The hydraulic pressure test prior to service also usually reduces peak residual stresses in welds but could have the opposite effect in cold worked surface layers depending on the geometry of the component.

It can be deduced from the strong effect of surface residual stress on PWSCC initiation times that much may be gained from surface remedial treatments that reduce them or eliminate the surface layers affected by high residual stress or, alternatively, by the application of layers of more resistant higher chromium containing surface coatings.

The growth and orientation of PWSCC in Alloy 182/82 is strongly influenced by the microstructure as well as the sum of the operating and residual welding stresses. In general axial growth is anticipated in nozzle dissimilar metal butt welds but service experience shows that in a few cases circumferential growth is possible. Weld repairs could conceivably influence crack orientation. In J-groove welds, radial-axial and circumferential cracks (relative to the inserted nozzle axis) are observed in accordance with the expected residual stress fields.

6 REFERENCES

1. "Materials reliability program: primary system piping butt weld inspection and evaluation guideline" (MRP-139), EPRI, Palo Alto, CA: 2005.
2. R. S. Pathania, A. R. McIlree, J. Hickling, "Overview of primary water cracking of Alloys 182/82 in PWRs", Proceedings of Fontevraud V, September 2002, pp. 13-27.
3. B. Grimmel, "U.S. Plant experience with alloy 600 cracking and boric acid corrosion of light-water reactor pressure vessel materials", NUREG 1823, April 2005.
4. C. Amzallag, J. M. Boursier, C. Pages, C. Gimond, "Stress corrosion life experience of 182 and 82 welds in French PWRs", Proceedings of Fontevraud V, September 2002, pp. 69-79.
5. A. Jenssen, K. Norrgård, C. Jansson, J. Lagerström, G. Embring, P. Efsing, "Structural assessment of defected nozzle to safe-end welds in Ringhals 3 and 4", Proceedings of Fontevraud V, September 2002, pp. 43-54.
6. G. Rao, G. Moffat, A. McIlree, "Metallurgical investigation of cracking in the reactor vessel alpha loop hot leg nozzle to pipe weld at the V. C. Summer station", Proceedings of Fontevraud V, September 2002, pp. 29-38.
7. H. Xu, S. Fyfitch, "Laboratory investigation of PWSCC of CRDM nozzle 3 and its J-groove weld on the Davis Besse reactor vessel head", Proceedings of 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 2005.
8. K. Ahluwalia, G. Rao, F. Cattant, N. Peat, R. Barnes, "Non-destructive and destructive examination of the retired North Anna 2 reactor pressure vessel head", Proceedings of Fontevraud VI, September 2006, pp. 291-302.
9. E. Sullivan, "Safety Concerns Regarding Potential Pressurizer Weld Cracking", Presentation NRC, December 20, 2006.
10. H. Xu, S. Fyfitch, J. W. Hyres, F. Cattant, A. McIlree, "Laboratory investigation of the Alloy 600 Bottom Mounted Instrumentation nozzle samples and weld boat sample from South Texas Project Unit 1", Proceedings of 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 2005.
11. Hiroyuki Kobayashi, Kimihito Takeuchi, Shohei Nakama, Masayuki Mukai, Takahiro Ohta, "PWSCC experience of Pressurizer dissimilar metal welds at Tsuruga unit-2", Proceedings of ICONE12, 12th International Conference on Nuclear Engineering, Arlington, Virginia, April 25-29, 2004, ASME 2004.
12. NRC Information notice 2004-11: "Cracking in Pressurizer safety and relief nozzles and in surge line nozzle ", May 2004
13. Press Release Information, NISA/METI, PRI-04-37, October 19, 2004

14. P. Efsing, B. Forssgren, R. Kilian "Root cause failure analysis of defected J-groove welds in steam generator drainage nozzles", Proceedings of 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 2005.
15. "Indications in thermally treated alloy 600 steam generator tubes and tube-to-tubesheet welds", NRC Information notice 2005-09, April 7, 2005.
16. "Cook-2 outage not delayed by nozzle weld repairs", Nucleonics Week, vol. 45, n° 47, November 18, 2004.
17. NRC Event Notification Report, Event Number 41128, October 18, 2004.
18. NRC Event Notification Report, Event Number 41445, February 28, 2005.
19. NRC Current Event Notification Report, Event Number 41602, April 21, 2005.
20. "Westinghouse Document LTR-CI-06-26-NP, Revision 0, dated March 17, 2006", appendix of CE letter, May 31, 2006.
21. NRC Current Event Notification Report, Event Number n° 42917, October 18, 2006.
22. R. Gérard, Ph. Daoust, Ph. Dombret, D. Couplet, Ch. Malékian, "Situation of the Alloys 600 and 182 issues in Belgian nuclear power plants", Proceedings of the 2005 International PWSCC of Alloy 600 Conference and Exhibit Show", MRP-154, EPRI Report 1012089, 2005.
23. J. E. Broussard, G. A. White, E. S. Hunt, "Finite element analysis of welding residual stresses in piping butt weldments and their effect on crack tip stress intensity factors", Proceedings of the 2005 International PWSCC of Alloy 600 Conference and Exhibit Show", MRP-154, EPRI Report 1012089, 2005.
24. C. Amzallag, J-M Boursier, C. Pages, C. Gimond, "Stress corrosion life assessment of 182 and 82 welds used in PWR components", Proceedings of 10th International Conference on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Lake Tahoe, August 5-9, 2001, NACE International 2002.
25. P. Efsing, G. Embring, B. Forssgren, B. Kroes, R. Lundström, "Failure analysis of the Ringhals Unit 3 EDM surfaces removed from the RPV outlet nozzle to safe end weld", Proceedings of Fontevraud VI, September 2006, pp. 283-290.
26. L. E. Thomas, J. S. Vetrano, S. M. Bruemmer, "High-resolution analytical electron microscopy characterization of environmentally assisted cracks in Alloy 182 weldments", Proceedings of 11th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", ANS 2003.
27. L. Thomas, B. R. Johnson, J. S. Vetrano, S. M. Bruemmer, "Microstructural and microchemical characterization of primary side cracks in an Alloy 600 nozzle head penetration and its Alloy 182 J-weld from the Davis Besse reactor vessel", Proceedings of 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 2005.
28. "Materials Reliability Program Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloys 82, 182 and 132" (MRP-115), EPRI, Palo Alto, CA: 2004. 1006696.
29. F. Vaillant, J-M Boursier, C. Amzallag, C. Bibollet, S. Pons, "Environmental behaviour and weldability of Ni-base weld metals in PWRs", Proceedings of Fontevraud VI, September 2006, pp. 271-281

30. "Materials Reliability Program (MRP), Resistance to Primary Water Stress Corrosion Cracking of Alloys 690, 52 and 152" (MRP-111), EPRI, Palo Alto, CA: 2004. 1009801.
31. P. Scott, M. Foucault, B. Brugier, J. Hickling, A. McIlree, "Examination of stress corrosion cracks in Alloy 182 weld metal after exposure to PWR primary water", Proceedings of 12th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 2005.
32. "Program on Technological Innovation: Exploratory Study of an Experimental Technique using Composite Specimens to demonstrate the Resistance of Alloy 152 to PWSCC", EPRI, Palo Alto, CA: 2006. 1013513.
33. O. Calonne, P. Scott, P. Combrade, "Materials Reliability Program: Experimental Program on the Effects of Surface Condition on Primary Water Stress Corrosion Cracking of Alloy 182 welds", (MRP-215), EPRI 1015016, 2007.
34. D. Buisine, F. Cattant, J. Champredonde, C. Pichon, C. Benhamou, A. Gelpi , M. Vaindirlis, "Stress corrosion cracking in the vessel closure head penetrations of French PWRs", Proceedings of 6th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 1993, pp. 845-851.
35. J. F. Hall, J. P. Molkenthin, P. S. Prevey, "XRD residual stress measurements on Alloy 600 pressurizer heater sleeve mockups", Proceedings of 6th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors", TMS 1993, pp. 855-861.
36. Ph. Berge, "Importance of surface preparation for corrosion control in nuclear power stations", Materials Performance, Vol. 36, 1997, pp.56-62.
37. S. LeHong, C. Amzallag, A. Gelpi, "Modeling of stress corrosion crack initiation on Alloy 600 in primary water of PWRs", Proceedings of the Ninth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, (Newport Beach, CA: TMS, 1999), pp.115-122.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), with major locations in Palo Alto, California; Charlotte, North Carolina; and Knoxville, Tennessee, was established in 1973 as an independent, nonprofit center for public interest energy and environmental research. EPRI brings together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. These solutions span nearly every area of electricity generation, delivery, and use, including health, safety, and environment. EPRI's members represent over 90% of the electricity generated in the United States. International participation represents nearly 15% of EPRI's total research, development, and demonstration program.

Together…Shaping the Future of Electricity

Printed on recycled paper in the United States of America

1015427

ELECTRIC POWER RESEARCH INSTITUTE

3420 Hillview Avenue, Palo Alto, California 94304-1395 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com