B.5 "SCC of Ni Alloy 600 and Alloy 182 and 82 Weld Metals in BWR Water," by Peter L. Andresen

Introduction

Nickel alloys were originally specified for BWR components for their resistance to corrosion and stress corrosion cracking (SCC) – as indicated by early laboratory data and field experience – and because their thermal expansion coefficient is similar to the low alloy steel used for the reactor pressure vessel. Typical compositions of the relevant nickel alloys are shown in Table B.5.1. Table B.5.2 provides a list of BWR components where Alloy 600 and Alloy 182 and 82 weld metals have been used.

Intergranular stress corrosion cracking (IGSCC, Figure B.5.1) susceptibility of Alloy 600 and high strength alloys (e.g., Alloy X750) in high temperature water was demonstrated in laboratory testing over 50 years ago [1]. Significant cracking of nickel alloys began to occur in BWR components in the 1970s, and SCC has become the primary materials issue with nickel alloys in light water reactors. For Ni alloy weld metals, so-called interdendritic cracking (actually intergranular, as grain boundaries form as groups of dendrites grow during solidification) is the morphology of SCC observed in plant components and relevant laboratory tests (Figure B.5.1).

While SCC of nickel alloys in PWR and BWR systems has been considered a distinct and different phenomena (e.g., as indicated by the term "Primary Water SCC," or PWSCC in PWRs), there is a evidence showing that there are many common dependencies and a well-behaved "response surface" as a function of changing temperature, oxidant level, H_2 level, and water purity [2-7]. Appendix B.6 [8] provides a detailed description of SCC observed in various nickel alloys in PWR primary and secondary (steam generator) components. In PWR applications, when Alloy 600 components are replaced, it is usually by Alloy 690 and its compatible weld metals, Alloys 152 and 52. These have proven to be more resistant to PWSCC in severe laboratory tests and, to date, after 16 years in service. Alloy 800 steam generator tubes are also quite resistant to SCC, although their tolerance to poor secondary chemistry is probably lower. This Appendix focuses on the operating experience and known dependencies of nickel alloys in BWR environments.

Nickel Alloys Components in BWRs

Nickel-base weld materials are used throughout the BWR [9], and are more prevalent than wrought nickel alloy components (Table B.5.2). Alloys 182 and 82 are used to join the low alloy steel pressure vessel and pressure vessel nozzles to wrought nickel alloys and austenitic stainless steel components. Alloy 182 is typically used as a coated stick electrode designed for manual welding, whereas Alloy 82 is typically used in wire form for automated TIG or MIG welding. Figure B.5.2 provides a schematic of the key components and their locations in GE BWRs, and Figures B.5.3 – B.5.8 show the configurations of various locations where Alloy 182 and 82 welds exist.

There are several different nozzle-to-safe-end welds where Alloy 182 weld metal has been used for the nozzle butter and/or the weld joint. These include the recirculation inlet and outlet nozzles, the core spray nozzles, the jet pump instrumentation nozzles, and the feedwater nozzles; the actual configuration depends on the specific vessel

fabricator. Figure B.5.3 shows the typical details of Alloy 182 and 82 weld build-up used in many BWRs. Alloy 182 was often used to butter the safe end, after which the vessel was heat treated (tempered) to restore its properties. Following this post-weld heat treatment (PWHT), the subsequent weld to the safe end was typically made with an Alloy 82 root pass, and then the weld was completed with Alloy 182. The dendritic structure shown in Figure B.5.1 develops during weld solidification of both Alloys 182 and 82 welds, with the dendrites growing toward the top of the weld. Even when the entire weld was nominally made of Alloy 82, weld repair records at some plants showed that Alloy 82 weld repair was performed by manual welding using Alloy 182 because of the repair geometry or limited access. Weld repairs in general are suspected of being the origin of preferred crack initiation and faster crack growth. Many weld repairs are poorly documented. The start and end point of welds (especially when performed by manual stick electrode) are also areas of concern.

Type 308/L stainless steel weld cladding is deposited over most of the exposed pressure vessel surface. Essentially all internal attachments to the pressure vessel are made using Alloy 182 pads that are welded directly onto the pressure vessel after the stainless steel cladding and before the post-weld heat treatment. Stainless steel weld metal has proved to be more resistant to SCC than Alloy 182 weld metal. The Alloy 182 attachments include the steam dryer hold down brackets, core spray brackets and shroud support structures. The latter was typically constructed of wrought Alloy 600, with Alloy 182 welds used for its construction and attachment to the vessel. This represents the largest circumference of nickel base weld. The structure in many cases is supported by legs that are welded to the bottom head of the RPV. Alloy 182/82 welds were used for many of the penetrations through the bottom of the pressure vessel – the most numerous being the control rod drive (CRD) housings. Finally, in most BWRs, water is pumped through the core using jet pumps, which require circular openings in the Alloy 600 support ledge, and are attached using Alloy 182/82 welds.

In the standard BWR environment (normal water chemistry, or NWC), the water chemistry is oxidizing and Alloy 182 is susceptible to SCC. Alloy 182 cracking was first discovered during replacement of weld sensitized stainless steel recirculation piping. Since then, there have been continuing instances of cracking in Alloy 182. This document discusses the field cracking characteristics of Alloy 182, SCC dependencies, mitigation techniques, and improved materials.

History of SCC in BWR Nickel Alloy Components

All of the nickel alloy components and welds listed in Table B.5.2 and Table B.5.3 have experienced SCC at one time or another in BWRs. There has also been extensive cracking of creviced Alloy 600, primarily in the form of shroud head bolts, safe ends, and ledge and access hole covers. For nickel alloys and stainless steels, a high initial incidence of cracking occurred, primarily due to poor water chemistry during the early operation of most BWRs. While dramatic improvements were made in water purity, once cracks nucleated, growth was readily sustained even in good quality water. For example, Figure B.5.9 shows the correlation between BWR water purity and incidence of cracking in Alloy 600 shroud head bolts. In addition to the important effect of *average* water purity, both prediction and plant data show that very high conductivity early in life produced a different population of (more severe) cracking than is reflected by the plant *average* conductivity.

The overall experience with wrought nickel alloys in BWRs has been better than with welded austenitic stainless steels, where IGSCC has been widely observed in the heat affected zone of types 304 and 316 stainless steel (but rarely in type 308/L weld metal). This is especially true for weld sensitized stainless steel, but unsensitized stainless steel has also cracked extensively, primarily due to the combination of weld residual stresses and weld shrinkage strains. Residual strains peak at the weld fusion line and are generally equivalent to 15 – 20% room temperature tensile strain [10, 11].

There has been very good experience with Alloy 600 in the welded, uncreviced condition, particularly in the bottom-head region; extensive SCC of Alloy 600 has occurred in the creviced condition. Alloy 182 weld metal has not performed nearly as well. Initial concerns for the SCC performance of Alloy 182 were raised in laboratory test data from the US [12] and subsequently confirmed internationally, e.g. [13]. This led to the recommendation to inspect weld metal butters during replacement of recirculation piping that was necessitated by IGSCC of weld sensitized, large diameter Type 304 stainless steel pipes. The first inspection, performed at a BWR/3 in the 1984 timeframe, revealed cracking in several welds. Inspections were performed in the recirculation inlet and outlet safe ends during the piping replacement [14]. Cracking was detected using dye penetrant exams in 3 of 10 inlet nozzles and 1 of 2 outlet nozzles. The cracking was axial in all nozzle butters, with a maximum depth of about 70% of wall thickness. Boat samples were removed from one weld that attached the stainless steel safe end to the outlet nozzle. Metallography verified that the cracking was confined to the Alloy 182 weld and did not extend into the low alloy steel. It also established that cracking was “interdendritic” (actually along intergranular dendrite boundaries), and did not penetrate into the Alloy 82 root pass (corroborating the higher SCC resistance of Alloy 82 weld metal shown in laboratory data). Many axial segments initiated in the Alloy 182, with several circumferential segments that followed the fusion line.

Subsequently, cracking was detected in other BWRs. The number of nozzle-to-safe end welds affected varied from plant to plant, with one plant having six cracked nozzles. The frequency of cracking has now decreased but leakage has occurred in some smaller diameter pipes. Some cases were associated with weld repair locations and improper classification of inspection findings as weld geometry or internal weld defects. The cracked nozzles included recirculation inlet and outlet, core spray and feedwater nozzles. The cracking has remained primarily axial in nature, although there are some instances of circumferential cracking. Many of these cracked welds have been overlay repaired with a structural build-up of SCC resistant material to restore structural margin / integrity.

Knowledge of cracking in BWR core internal structures was very limited until the late 1990s, primarily because only a limited number of inspections were performed. The first components to be evaluated were the access hole covers, which were welded during plant construction after access was no longer needed to the lower plenum region. These welds were particularly susceptible because crevices existed where the cover recessed into the ledge. While cracking occurred in the creviced wrought Alloy 600 in many plants, it also initiated and/or propagated in the Alloy 182 weld metal. This heightened the concern for SCC of Alloy 182 in other locations.

The first instances of SCC in un-creviced attachment welds were found in hold-down brackets on the reactor vessel head that restrained the dryer assembly. These locations were readily inspected, and subsequent metallurgical evaluations confirmed the extent

and morphology of cracking. The extent of cracking could not be accurately detected visually; only PT examination or proper UT interrogation could accurately characterize the extent of the tight weld cracks. While the cracked areas could be removed or repaired, their proximity to the RPV material heightened the need for periodic inspection of Alloy 182 welds in the reactor. Improved inspection approaches were developed by the EPRI BWR Vessel and Internals Project (BWRVIP) between 1995 and 1998.

Subsequently, extensive SCC was discovered in Alloy 182 welds in the shroud support structure of a BWR-2 during a core shroud replacement in 1999. Visual inspections and liquid penetrant examinations were performed on the shroud support structure, revealing cracks in the attachment welds joining the conical support structure to the reactor vessel wall (Figure B.5.8). This cracking was found in the weld build-up pad on the vessel wall (designated the H9 weld), as well as in other Alloy 182 welds and adjacent Alloy 600 in the lower conical section. The cracking of greatest interest was that found on the inside weld (the lower bottom side) of the H9 weld, where nearly 300 individual cracks were found in 34 locations. These cracks were largely axial in nature (~90%); however, none of the cracks entered the RPV low alloy steel. Since cracking was associated solely with the underside of the actual core support structure, it was not detected during routine visual in-service inspection from the top surface. This led to inspections at other BWRs, and similar cracking was detected in another BWR/2 at the same H9 weld [15]. While the inspection technique was focused on circumferentially oriented cracking because the UT system was deployed from inside the vessel, the cracking appeared to be primarily axial.

Understanding Alloy 182 Behavior in BWRs

Normal water chemistry (NWC) has existed over most of the life of the BWR fleet. NWC is oxidizing because radiolysis forms H_2O_2 and O_2, and oxidizing conditions accelerate SCC initiation and propagation. The oxidizing conditions are properly characterized by their effect on the corrosion potential, which is a kinetic balance between reduction reactions (e.g., O_2 and H_2O_2) and oxidation reactions (e.g., H_2 and metal oxidation). Given the large benefit of reduced corrosion potential, most BWRs have modified their operating environment by adding hydrogen, termed hydrogen water chemistry (HWC). In the last decade, most BWRs have also performed noble metal chemical addition (NobleChem™), which mitigates the oxidizing characteristics of the coolant environment by creating a catalytic surface, and reduces the amount of hydrogen addition required [16,17]. Provided there is sufficient H_2 (i.e., twice the molar concentration of O_2), all of the O_2 that arrives at the surface is reacted to form water and the corrosion potential drops to very low values.

IGSCC in nickel alloys in BWR environments is best described by the slip dissolution / oxidation mechanism, which also applies to austenitic stainless steels. This mechanism accounts for the simultaneous requirement for stress, susceptible material and oxidizing environment [2-7], and quantifies their effects in terms of the *crack tip system* that exists as a crack advances. Over the last two decades the BWR community has performed extensive research to quantify the crack growth behavior of Alloy 182 and other nickel alloys as a function of corrosion potential, water purity, stress intensity factor, etc.

For example, Figure B.5.10 shows the strong dependence of growth rate on ECP in 288 °C water [7]. Figure B.5.11 shows the growth rate response vs. corrosion potential for a wider variety of Ni alloys, including Alloy X750, cold worked Alloy 600 and stainless

steel. It should be noted that weld shrinkage strains are typically equivalent to 15 – 20% room temperature strain in the heat affected zone. Figures B.5.12 and B.5.13 show the typical magnitude and timing of the change in crack growth rate as the water chemistry conditions are changed. An inter-relationship exists among most parameters that affect SCC; thus, for example, the effect of water purity varies with corrosion potential, and the effect of stress intensity factor (K) varies with water and material chemistry. Figure B.5.14 shows a low K dependence consistent with the mechanisms-based prediction for the aggressive water chemistry. In addition to extensive laboratory crack growth rate studies, there have been extensive crack initiation tests, component tests, in-reactor assessments of field cracking, and modelling of SCC growth rate response.

Based on these data, and data from many other investigators, e.g. [18], both NWC and HWC disposition rates for crack growth of Alloy 182 were developed [19]. The data clearly show a lower crack growth rate in HWC compared to NWC. However, measurable crack growth can occur at low corrosion potential, as shown by laboratory data on nickel alloys and stainless steels, and supported by fundamental insights into SCC. Figures B.5.10 – B.5.13 are examples of the crack growth response at low corrosion potential; with typical rates in Alloy 182 weld metal of $\approx 5 \times 10^{-9}$ mm/s, with higher rates up to ~ 5 x 10–8mm/s for higher strength or cold worked alloys. Note however that these rates are still an order of magnitude lower than those expected when compared with comparable material conditions and “normal water chemistry.” The laboratory data and fundamental understanding accounts for the cracking found in BWR operating plants and supports the benefit of HWC in mitigating crack growth.

Comparison with PWR Environments

Many of the factors used to distinguish SCC response in BWRs vs. PWRs have proven to be artificial [2,4,6,25]. The positive experience of thermally treated Alloy 600 in PWRs was considered to contradict the deleterious role of grain boundary carbides and Cr depletion in BWRs. However, grain boundary carbides are in fact beneficial in both environments, although when accompanied by Cr depletion, SCC susceptibility increased in oxidizing environments. This is clearly attributable to the slower repassivation rates at lower Cr concentrations in the pH-shifted chemistries that form when oxidants are present.

BWRs that employ NobleChem™ to catalytically achieve low corrosion potentials operate under conditions that are broadly similar to the PWRs primary environment. There are three primary differences: solution pH, H_2 fugacity, and temperature.

In deaerated (e.g., PWR water), variations in solution pH in the near-neutral regime have little effect on SCC [20], although it has some effect on the corrosion potential (112 mV / pH unit at 288 °C) because the corrosion potential under deaerated conditions is controlled by the H_2O/H_2 reaction. Both pH and conductivity are higher in the PWRs as a result of H_3BO_3 and LiOH additions, and there has been a trend upwards in pH operating point in most PWRs from about pH_{325C} = 6.9 to 7.3 or 7.4. At 290 °C, the pH_{290C} is now typically 6.8 to 7.2 in PWRs (pH_{290C} represents 1100 ppm B and 2 ppm Li, which gives a pH_{325C} = 7.25 and a pH_{340C} = 7.58) vs. 5.65 in BWRs, and the conductivity is 166 µS/cm vs. 5 µS/cm. However, laboratory data show that the higher conductivity is not bad per se in deaerated water, nor is the shift in pH in this near-neutral range [20]. The shift in corrosion potential is unimportant because there is no difference in potential relative to metal – metal oxide phase transitions (esp. important is the Ni/NiO

equilibrium). Also, in the absence of oxidants, there is no potential gradient in the crack and therefore no aggressive crack chemistry develops.

Secondly, the difference in H_2 fugacity is about 60X, from 40 to 60 ppb H_2 in BWRs to about 3000 ppb in PWRs. This produces only a small change in corrosion potential of about 100 mV, which can nevertheless be important to SCC of Ni alloys. Its role is related to a shift in the stability of Ni vs. NiO, which is affected by both H_2 and temperature (Figure B.5.15). No potential gradient forms in the crack because H_2 is not consumed (unlike oxidants), so no aggressive crack chemistry forms whether the H_2 level is high or low.

The third difference is temperature. The temperature of most structural components is 274 °C in a BWR (the feedwater reduces the recirculating core outlet water from 288 °C to 274 °C); thus, this is the temperature in the recirculation and clean-up piping, the annulus between the shroud and the pressure vessel, and the lower plenum region. In a PWR, the core inlet temperature is about 286 °C, the core outlet temperature is typically 323 °C (ranging from ~316 to 323 °C), nearly 50 °C hotter than most structural components in a BWR. For nickel alloys, this difference (323 vs. 274 °C) leads to a significant increase in crack growth rate of about 14X [7,21]; compared to the 345 °C PWR pressurizer, the difference is about 40X.

Improved BWR Nickel-base Weld Metals

Research has shown that SCC susceptibility is affected by the chromium level, including Cr depletion at the columnar dendrite boundaries of nickel base weld metals. The material parameters that affect chromium depletion include the nominal chromium level, the carbon level, and the concentration of “stabilizing” elements (Nb and Ti) that form non-detrimental carbides in preference to chromium carbide. These factors have been used by the BWR industry to rank materials and guide selection of optimized alloys for new reactors and structural weld overlays. An N-bar parameter has been used to assess susceptibility for Alloy 182 [22], with values below 12 indicating moderate susceptibility:

N-bar = 0.13*(Nb+Ti)/2*C (in weight percent)

A more recent measure is the Stress Corrosion Resistance Index (SCRI), which includes chromium level in the assessment [23]. A value below 30 represents significant susceptibility:

SCRI = Cr + (Nb+Ta)*5 + Ti*10 - 116.5*C (in weight percent)

Higher crack growth rates have also been measured in tests performed to evaluate the effects on SCC susceptibility of other alloying impurities, such as phosphorus, sulphur and silicon, but this may be due to synergistic effects with Cr-depleted boundaries. These elements, especially elevated silicon and lower manganese, adversely affect weldability by leading to a higher potential for hot cracking that could aid initiation and accelerate crack advance.

The PWR industry has shifted to Alloys 52 and 152 weld metal, and Alloy 600 has been replaced with Alloy 690. The BWR industry continues to view Alloy 82 as an optimum choice when fabrication concerns are included in the decision process. This alloy has

been used in Advanced BWRs for 10 years and its selection and good performance reflect the value of automatic welding processes [24] and the ability to perform Alloy 82 welds without re-work. The industry targets specific compositions to achieve high resistance to SCC, with initial carbon levels commonly of 0.01% or less. While the chromium levels are not as high as in Alloy 52, there is 20 years of good component performance in BWRs. Avoiding the use of Alloy 182 – and the associated elements of manual welding, weld repairs, and reduced Cr – has significantly reduced SCC of nickel weld metals.

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Table B.5.1 Compositions of Nickel Base Alloys Used in BWRs

	Alloy 600	Alloy 182	Alloy 82	Alloy X750
Nickel	Bal.	Bal.	Bal.	Bal.
Chromium	14-17	13-17	18-22	15-17
Iron	6-10	≤10.0	≤3.00	8-9
Titanium		≤1.0	≤0.75	2.5-3.0
Aluminum				0.7-1.0
Niobium plus Tantalum		1.0-2.5	2.0-3.0	0.8-1
Carbon	≤0.05	≤0.10	≤0.10	0.05-0.08
Manganese	≤1.0	5.0-9.5	2.5-3.5	0.1
Sulfur	≤0.015	≤0.015	≤0.015	<0.03
Phosphorus		≤0.030	≤0.030	<0.03
Silicon	≤0.5	≤1.0	≤0.50	0.1-0.2
Copper	≤0.5	≤0.50	≤0.50	<0.50
Cobalt	≤0.10	≤0.12	≤0.10	<0.10

Table B.5.2 BWR Components That Use Nickel Base Alloys

BWR Components	Nickel Base Alloy Grades Used
BWR Shroud Head Bolts	Alloy 600
Press. Vessel Attachment Pads	Alloy 182
Control Rod Penetrations	Alloy 600
Control Rod Penetration Welds	Alloy 182
Core Shroud Support Welds	Alloy 182
Pressure Vessel Nozzles	Alloys 182 and 82
Safe Ends	Alloy 600
Weld Metal Deposits	Alloys 82 and 182
Jet Pump Beams	Alloy X750
Fuel Rod Spacers	Alloy X750

Table B.5.3

Alloy 82/182 Field Cracking in One Set of BWRs

Material	Component	Part	BWR Type	First Synch	Find Date	Cause
Alloy 182	Feedwater Sparger	End Bracket	2	Sep-69	Oct-2000	IGSCC
Alloy 82/182	In Core Monitor	Penetration		May-84	Aug-97	Most likely original fabrication weld defects (one possible exception on 08-41).
Alloy 182	RPV Head	Bracket	Non-GE BWR	Jan-81	Jan-95	IGSCC
Alloy 182	RPV Head	Bracket	Non-GE BWR	Jun-80	Jan-95	IGSCC
Alloy 182	Shroud Support	Leg	3	Mar-71	Dec-99	Probable IGSCC

Alloy 182 Field Cracking in a Second Set of BWRs

Plant	System	Year of Detection	Location of Indication
E-1	Recirc	1990	Main Loop
E-2	Recirc	1985	Flange
E-2	Core Spray	1999	Brackets
E-3	Recirc	1996	Pipe weld
E-4	Recirc	1997	Pipe weld
E-4	Core Spray	1999	Brackets
E-5	Core Spray	1999	Brackets
E-6	Feedwater	1985	Nozzle
E-6	RPV	1986	Head spring beams
E-6	RPV	1986	Flange
E-6	Feedwater	1997	Nozzle
E-6	RHR	1997	Safe end
E-7	RPV	1985	Head spring beams
E-7	RPV	1990	Flange
E-7	Feedwater	1995	Nozzle
E-8	RPV	1994	Head spring beams
E-8	Core Cooling	1991	Nozzle
E-8	RPV	1995	Head spring beams

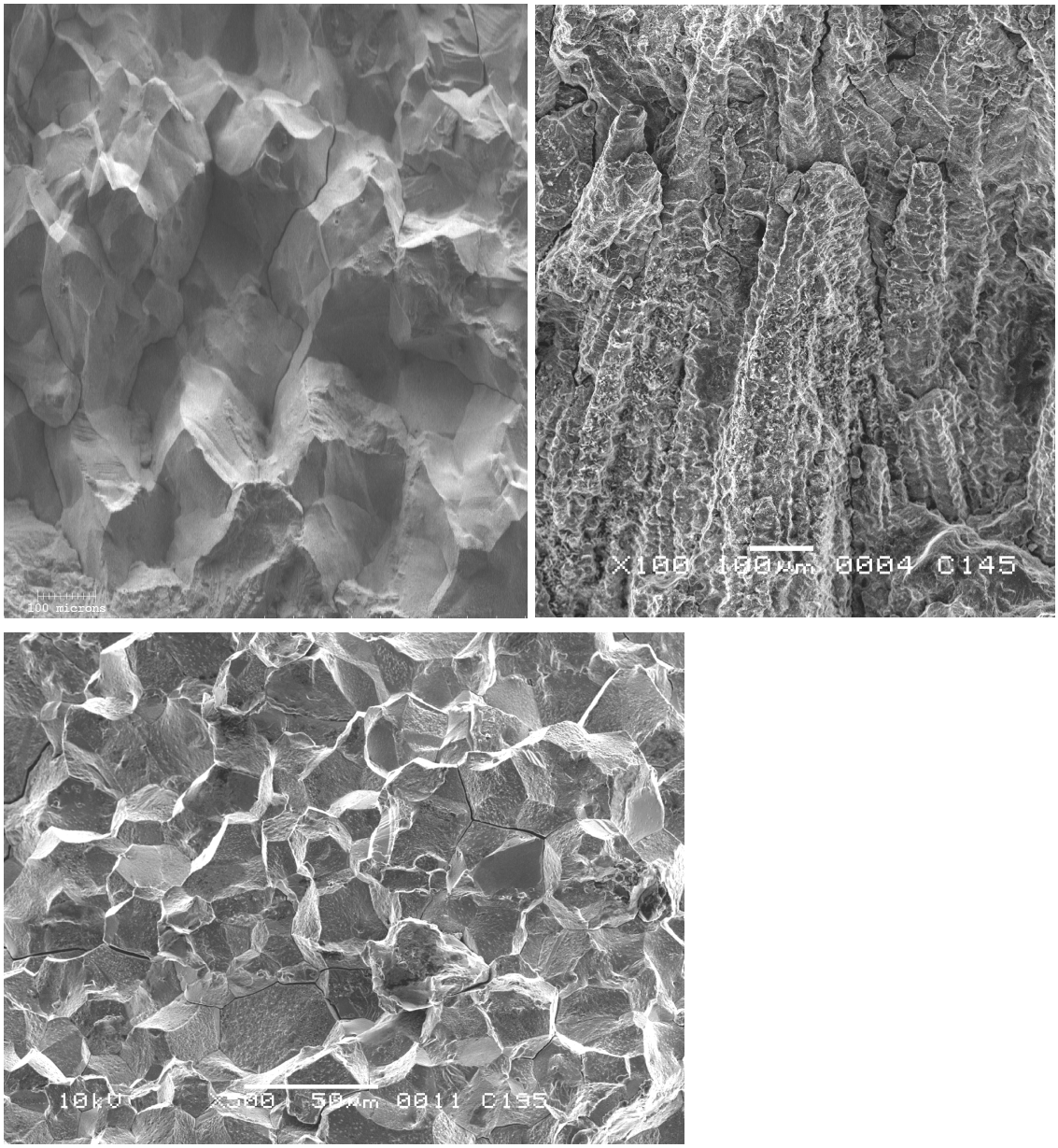


Figure B.5.1. Scanning electron micrographs showing the intergranular fracture morphology of Alloy 600, Alloy 182 weld metal and Alloy X750 when tested in high temperature water. *(© NACE International 2002)*

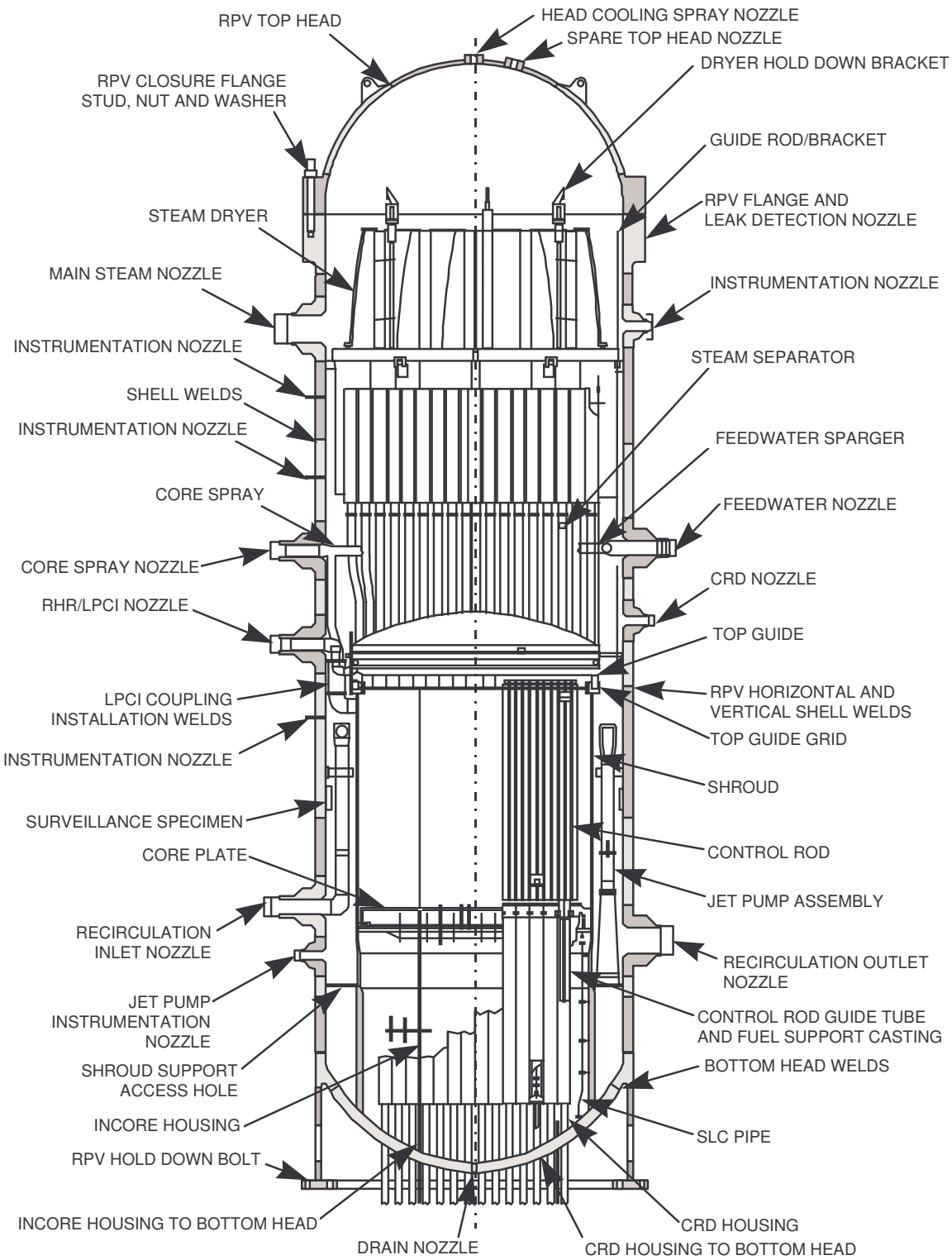


Figure B.5.2. Schematic of typical BWR reactor pressure vessel, nozzles and attachments.

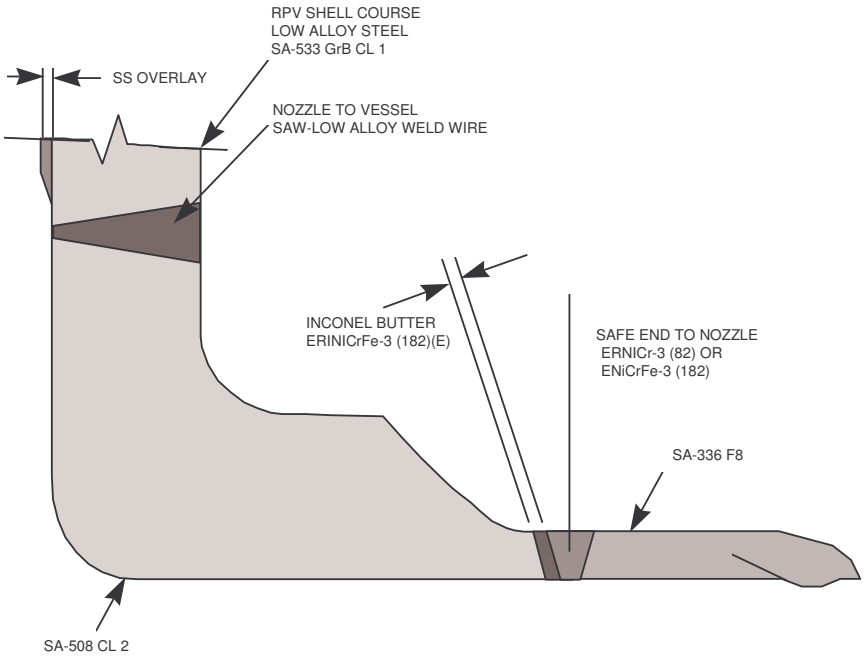
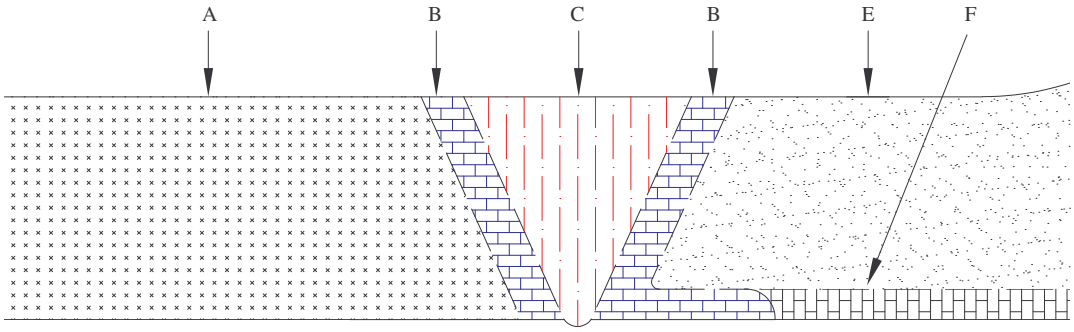


Figure B.5.3. Typical BWR recirculation outlet nozzle, nozzle butter, weld and safe end.



A) Stainless Steel Safe End
B) Alloy 182 Weld Butter
C) Alloy 182 or Alloy 82 Weld Metal
B) Alloy 182 Weld Butter
D) Low Alloy Steel Nozzle
E) E) Low Alloy Steel
F) Stainless Steel Cladding

Figure B.5.4. Enlargement of safe end to nozzle weld region in BWRs using Alloy 182/82 weld metals.

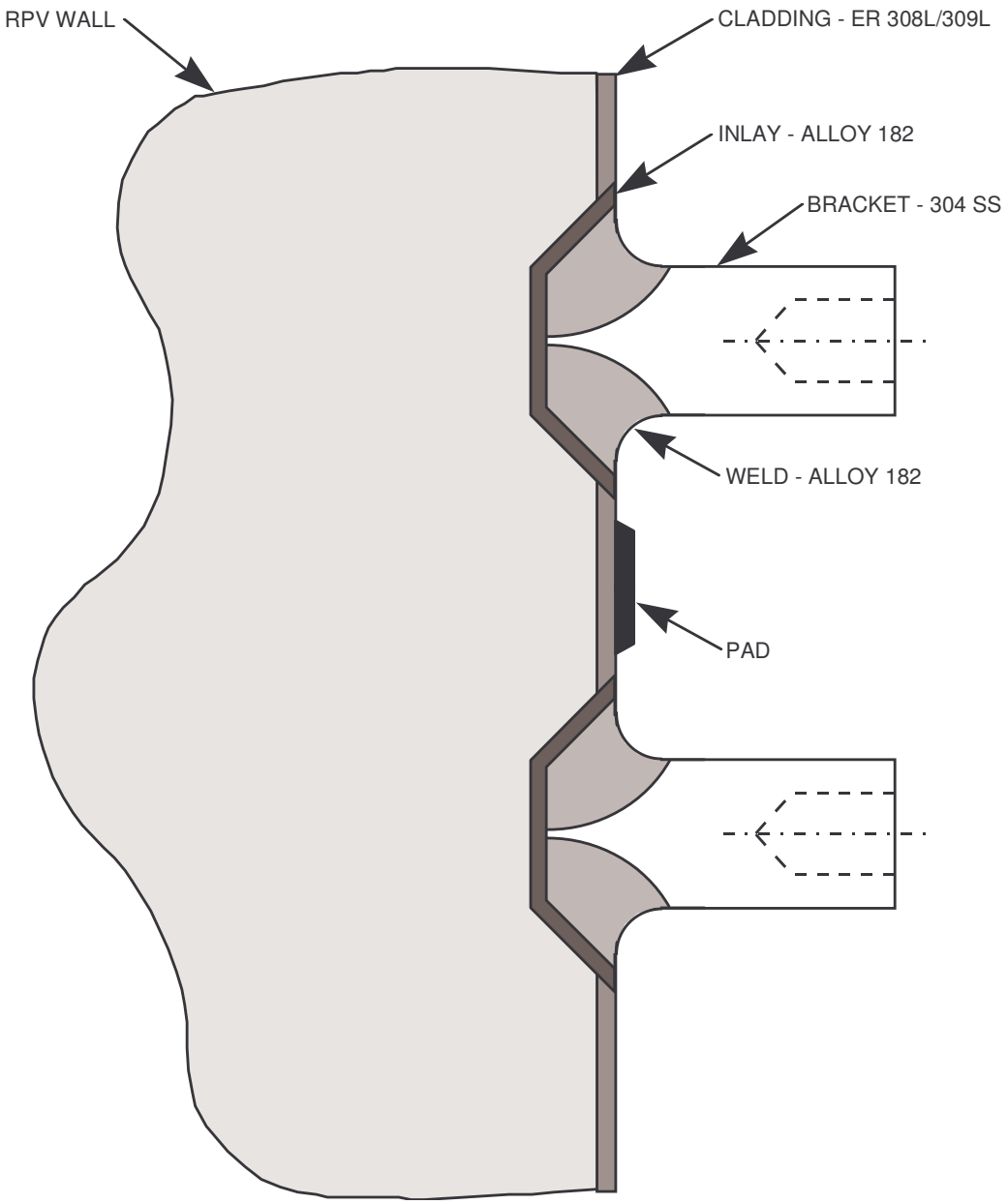


Figure B.5.5. Typical BWR core spray bracket attachment weld configuration. Alloy 182/82 are used.

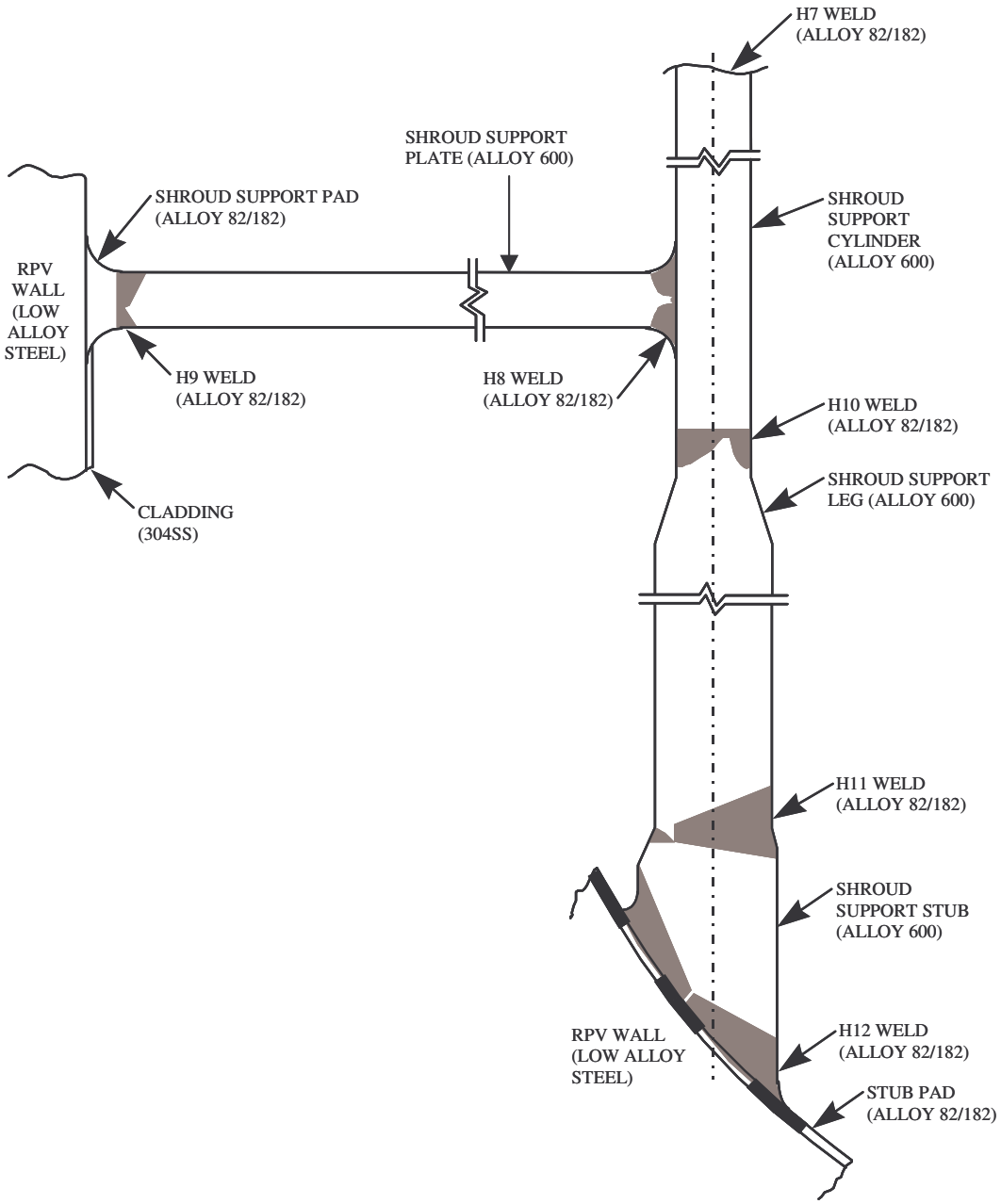


Figure B.5.6. Typical BWR shroud support structure of the leg design. Alloy 182 is used. Also shown are the H9 and H12 welds that join the component to the RPV.

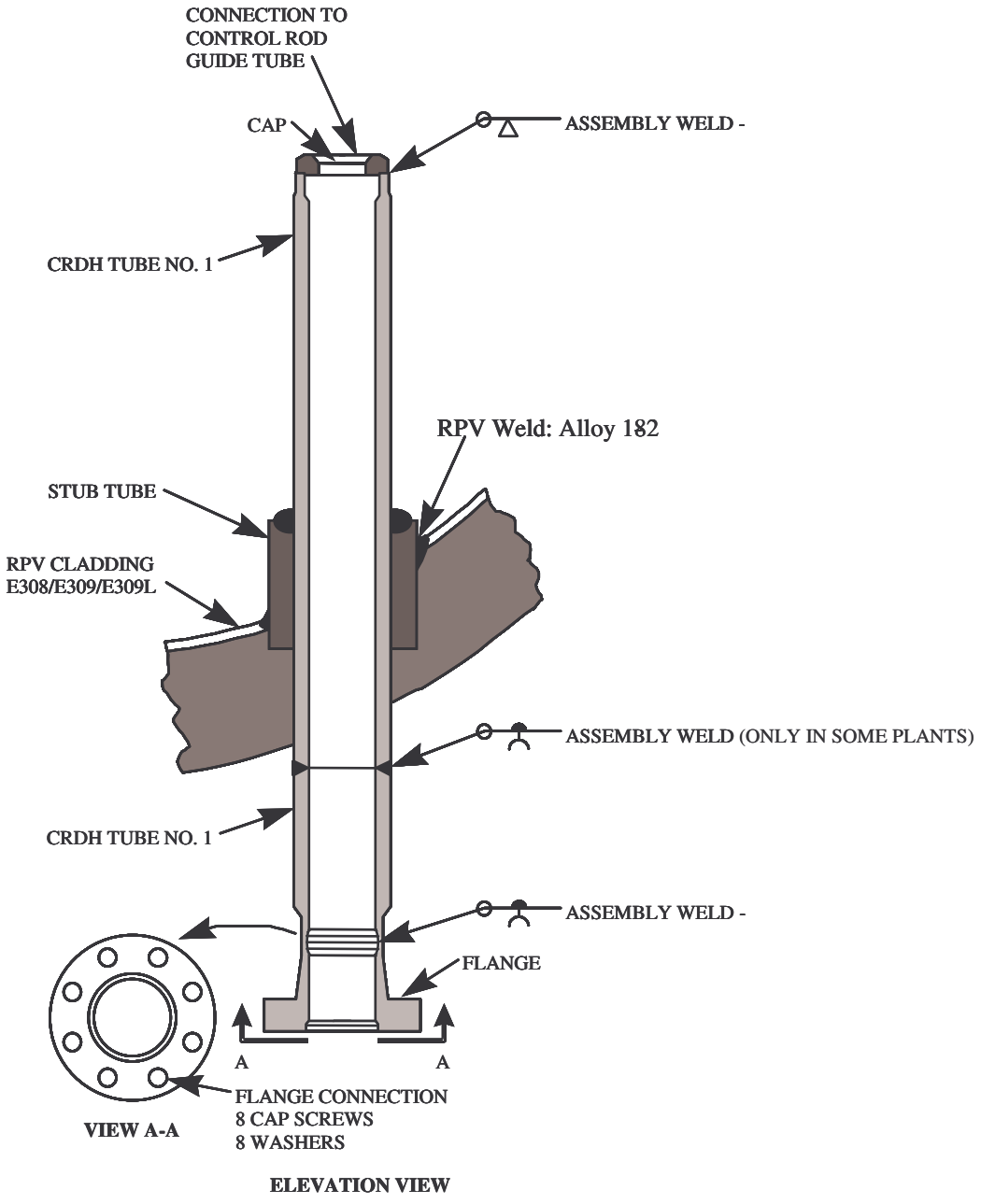
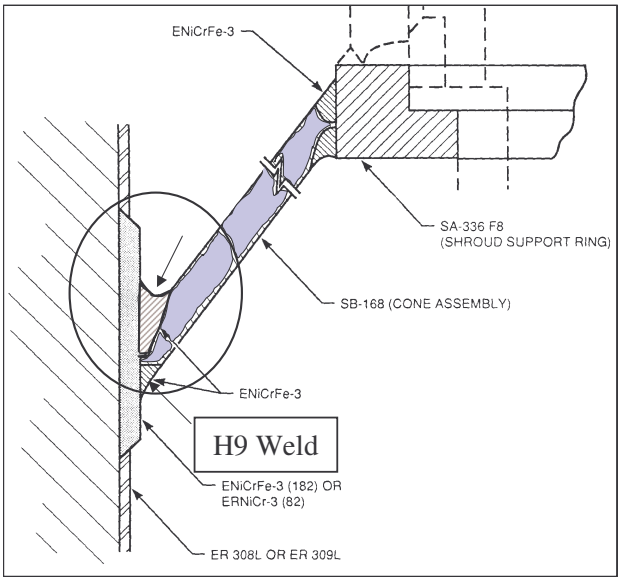
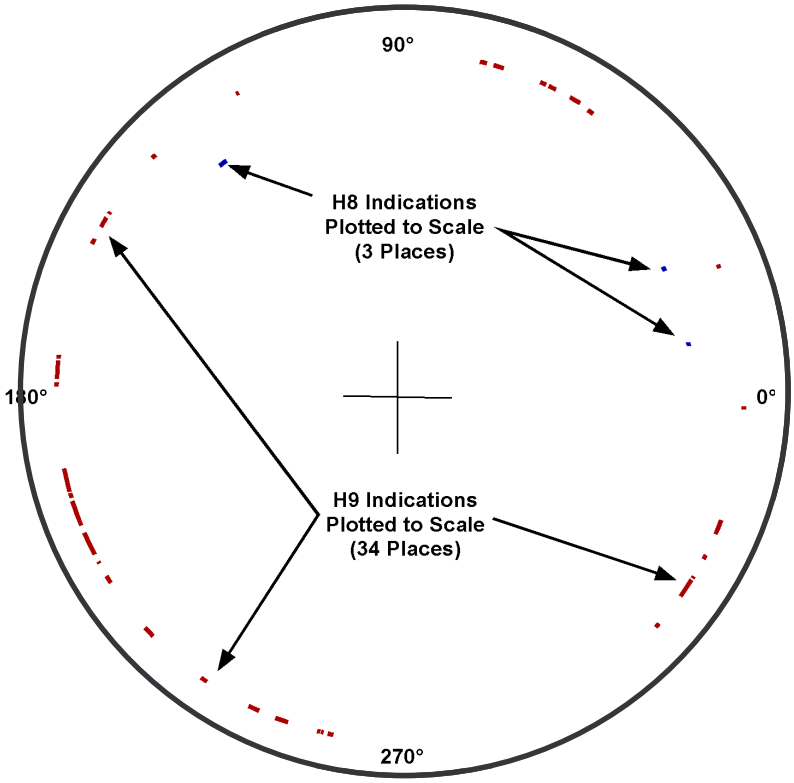


Figure B.5.7. Typical CRD stub tube and CRD housing configurations. Alloy 182 used in stub tube to RPV weld.



(a)



(b)

Figure B.5.8. (a) Cross-section of BWR/2 H9 weld. (b) Schematic of the azimuthal orientation and length of the H8 and H9 indications (around vessel circumference) as determined by UT inspection.

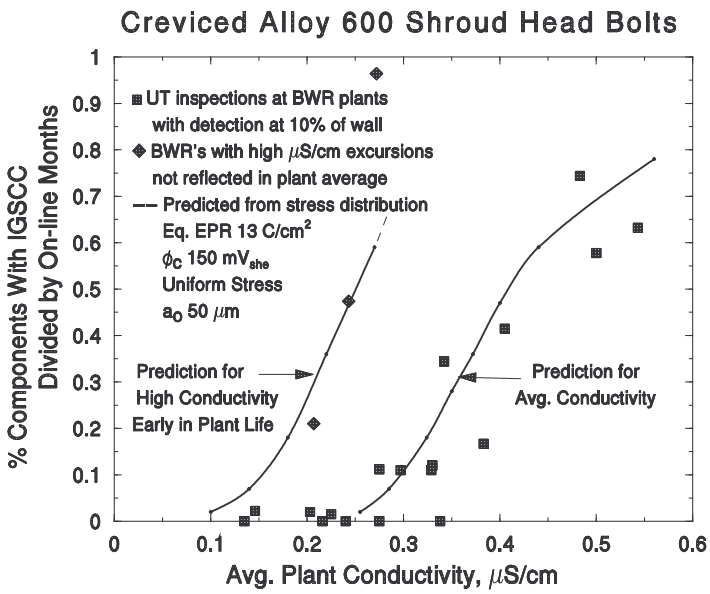


Figure B.5.9. Observation and prediction of the incidence of SCC in Alloy 600 shroud head bolts as a function of average plant conductivity. An unusual population of three bolts showed a much high incidence of SCC because these plants had bad water chemistry early in their life. *(© NACE International 2002)*

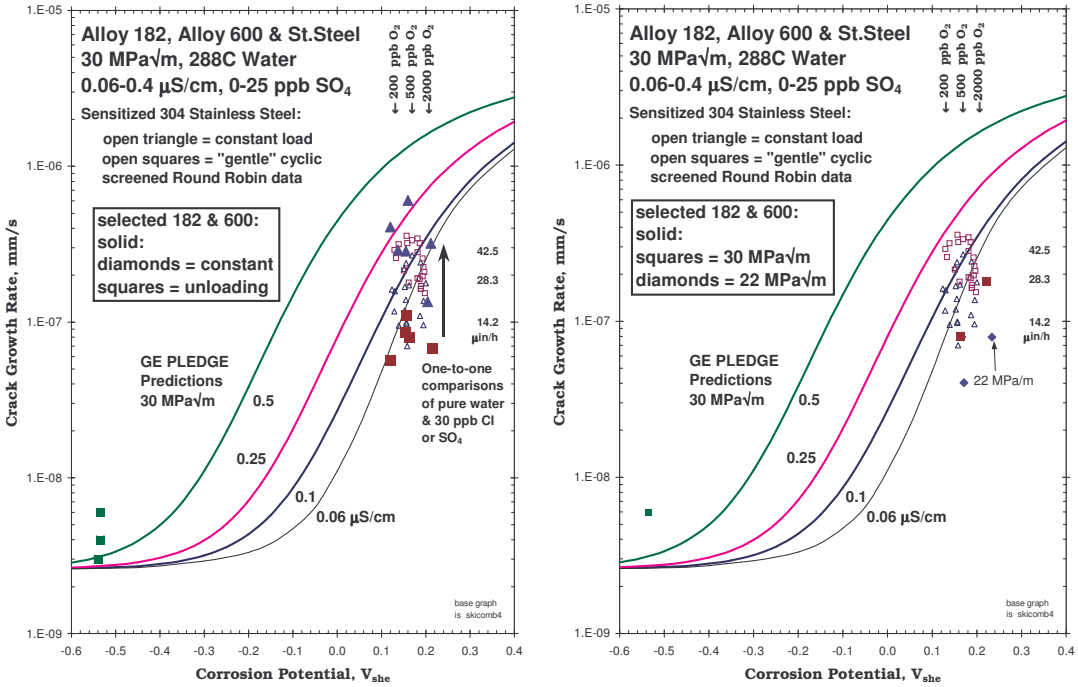


Figure B.5.10. Crack growth rate vs. corrosion potential for Alloy 600 and Alloy 182 weld metal. (Left) The growth rates in high purity water at high corrosion potential fall within the observations for sensitized stainless steel (open symbols), and the effect of low potential or additions of 6 x 10^{-7} N SO_4 or Cl are consistent with the SCC behavior of sensitized stainless steel. (Right) The effect of corrosion potential and stress intensity factor on the growth rate of Alloy 182 weld metal in near-theoretical purity 288 °C water. *(© NACE International 2002)*

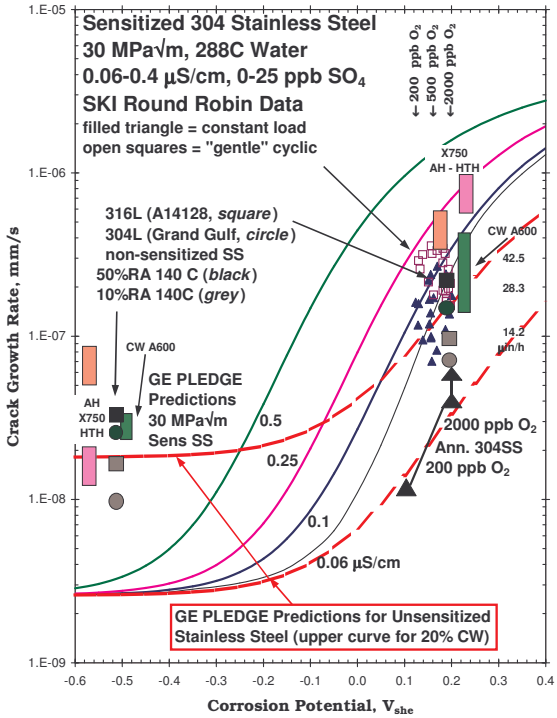


Figure B.5.11. SCC growth rate vs. corrosion potential for stainless steels in various conditions, 20% cold worked Alloy 600, and precipitation hardened Alloy X750 tested in 288 °C high purity water containing 2000 ppb O_2 and 95 – 3000 ppb H_2 [25]. *(© 2003 by The American Nuclear Society, La Grange Park, Illinois)*

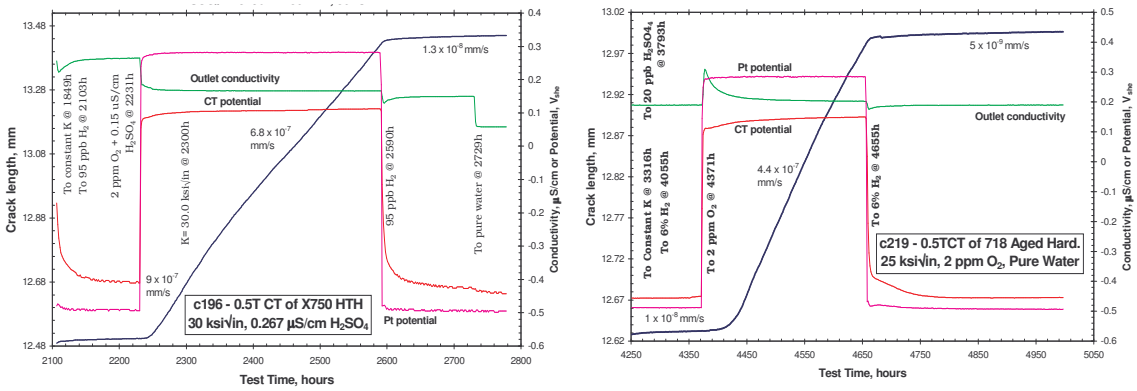


Figure B.5.12. Crack length vs. time for 0.5TCT specimens of Alloy X750 in the HTH condition and Alloy 718 tested in 288 °C water [25]. *(© NACE International 2004)*

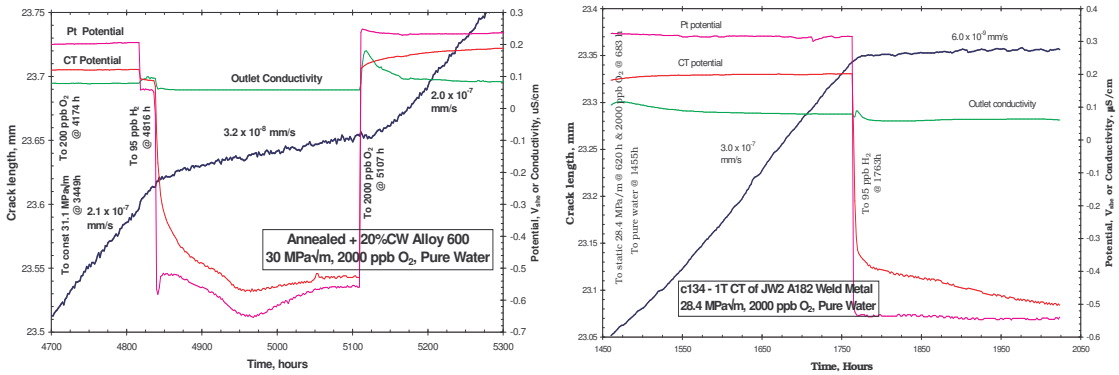


Figure B.5.13. Crack length vs. time for CT specimens of unsensitized Alloy 600 cold worked at 25 °C to 20% RA and Alloy 182 weld metal tested in 288 °C water [7]. *(© NACE International 2002)*

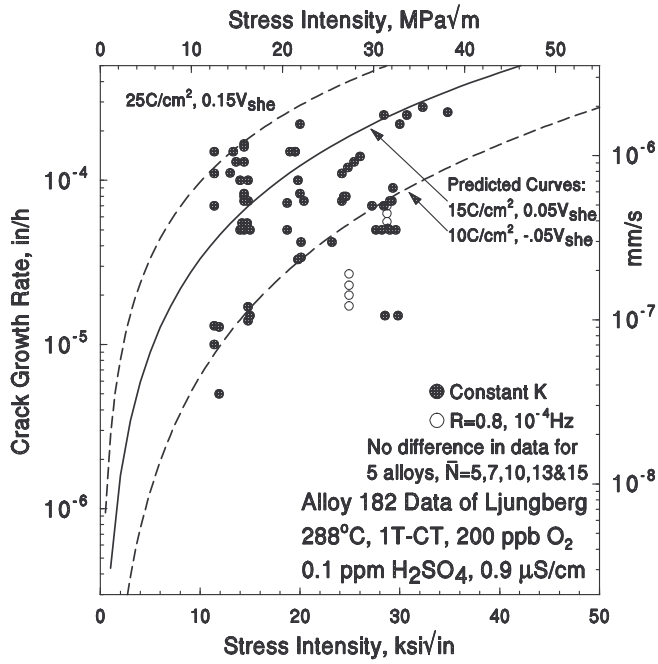


Figure B.5.14. Crack growth rate vs. stress intensity for Alloy 182 weld metal tested in 288 °C water containing 200 ppb O_2 and 100 ppb SO_4 as H_2SO_4. The remarkably high growth rates and low dependence on stress intensity are in fact consistent with predictions based on sensitized stainless steel [2-5], which are represented by the lines on the diagram. *(© NACE International 2002)*

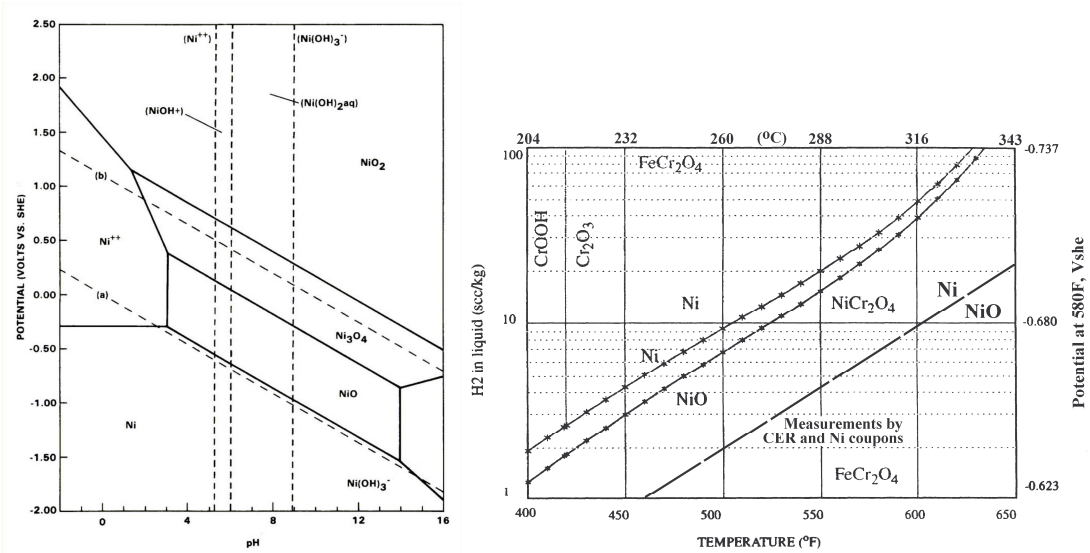


Figure B.5.15. (Left) Pourbaix diagram of the Ni-H_2O system at 300 °C. (Right) Thermodynamic stability of Ni metal (vs. NiO and various spinels) vs. H_2 fugacity and temperature [6,7,26]. The lower line represents more recent, definitive data. *(© NACE International 2002)*