REQUEST FOR ADDITIONAL INFORMATION
ELECTRIC POWER RESEARCH INSTITUTE REPORT
Topical Report MRP-169
NUCLEAR ENERGY INSTITUTE

1. The optimized weld overlays (OWOL) have less thickness than the full structural weld overlays (FSWOL). The OWOL is unable, by itself, to satisfy structural integrity design requirements. Instead, the OWOL design requires a portion of the underlying Alloy 82/182 dissimilar metal (DM) weld material to remain intact and carry a portion of the loads. This original weld material is susceptible to cracking. In order to understand potential limitations of OWOLs, the staff has considered the possibility that either the OWOL design or installation process or the associated nondestructive examination (NDE) does not perform as expected and a crack grows in the original weld after the OWOL is applied. During initial phases of crack growth, bending and residual stress variations and metallurgical inhomogeneity would lead to uneven growth. However, once a portion of a surface crack grew deep enough to encounter the crack resistant overlay material, it would stop growing in the depth direction at that azimuthal location. Other segments of the crack could continue to grow deeper until they also reach the overlay interface. This could continue until the remaining uncracked ligament of original weld material is insufficient to adequately reinforce the OWOL material, at which point the mitigated weld may fail without prior leakage during a design basis event.

In a FSWOL the corrosion and PWSCC resistance of the overlay material can be credited to prevent crack growth into the overlay in the event that a large pre-existing crack was missed by NDE, or in the event that design deficiencies or misapplication of the FSWOL resulted in unanticipated tensile residual stress fields. If large cracks occur in the original DM weld material under a FSWOL, the FSWOL can withstand full design loading without failing; the PWSCC resistant material preserves the FSWOL load carrying ability and minimizes the likelihood of pipe rupture. In contrast, if the same deficiency in design or application affects the OWOL, the OWOL material, precisely because it is resistant to PWSCC, can cause small circumferential cracks in the original dissimilar metal weld to grow deep around the entire circumference, in which case the OWOL may become unable to withstand its design loading. In light of this possibility, please explain why application of an OWOL to a dissimilar metal weld is an appropriate mitigation method and why its application will not invalidate previously approved leak-before- break analyses.

Response: The hypothetical flaw growth postulated by the NRC staff is unlikely. The combination of residual stress and crack growth analyses conducted as part of the OWOL design process, plus process controls during weld overlay application provide a high level of assurance that the residual stress improvements predicted for the OWOL will indeed be present. Large unidentified flaws, resulting from unexpected flaw growth is further precluded by conducting PDI qualified UT exams before and after application of the OWOL, as well as the periodic in service inspections prescribed by MRP-169 and/or Code Case N-770. For very large flaws of the type hypothesized by the NRC staff, the probability of detection is very close to 100%. Finally, over 30 years of weld overlay operating experience in BWRs (and more recently in PWRs) has demonstrated the validity of weld overlay benefits on crack growth. Hundreds of weld overlays have been subjected to multiple inservice inspections during this time frame, and there has never been any evidence of existing circumferential cracks under a weld overlay extending in length.

To address the NRC staff's concern, additional analyses have been performed to determine the margins that would exist under normal and normal plus upset loading conditions (including OBE seismic loads) in the extremely unlikely event that a flaw might propagate, as the staff hypothesizes, all the way through the original Alloy 182/82 weld and 360° around the nozzle. The analyses are summarized, for three actual large bore overlay designs in Table 1 below.

Table 1 – Net Section Collapse Analyses of Weld Overlays under Limiting Flaw Assumptions

Plant / Nozzle	Case:	Dimensions (inches				360° Flaw Depth (assumed)		Structural Factors	
		OD	t-nozz	t-WOL	t-comb.			Normal Operation	Norm + Upset (w/OBE)
Plant A / RPV Outlet	FSWOL	34.12	2.34	0.98	3.319	2.34	100%	4.75	3.52
	OWOL	34.12	2.34	0.58	2.919	1.755	75%	4.68	3.45
	OWOL1	34.12	2.34	0.58	2.919	2.34	100%	2.49	1.83
Plant B / Pump Suction	FSWOL	36.5	3.25	1.08	4.330	3.25	100%	5.40	4.07
	OWOL	36.5	3.25	0.504	3.754	2.4375	75%	6.75	5.05
	OWOL1	36.5	3.25	0.504	3.754	3.25	100%	2.04	1.52
Plant C / Pump Discharge	FSWOL	34.1	3.05	1.01	4.060	3.05	100%	4.68	3.03
	OWOL	34.1	3.05	0.65	3.700	2.2875	75%	6.51	4.19
	OWOL1	34.1	3.05	0.65	3.700	3.05	100%	2.71	1.74

Three different large bore nozzle types were analyzed from three different plants (a Westinghouse plant, a CE plant and a B&W plant). Actual loads, nozzle geometries and weld overlay designs for each plant and nozzle were used in the analyses. The Structural Integrity QA verified computer code ANSC [1] was used to determine net section collapse limit loads for each nozzle for three cases:

1. FSWOL – the plant/nozzle-specific full structural weld overlay design with a flaw assumed 360° and 100% through the original DMW (i.e. the design basis condition for a FSWOL)
2. OWOL – the plant/nozzle-specific optimized weld overlay design with a flaw assumed 360° and 75% through the original DMW (i.e. the design basis condition for an OWOL)
3. OWOL1 - the plant/nozzle-specific optimized weld overlay design with a flaw assumed 360° and 100% through the original DMW (i.e. the flaw assumption hypothesized by the NRC staff)

Table 2 specifies the current ASME Section XI Code margins for piping flaw evaluation [2]. As expected, the structural factors for the FSWOL and OWOL cases in Table 1 meet the required ASME Code structural factors by comfortable margins, since those are the design basis conditions for the overlays. However, even in the conservative flaw assumption hypothesized by the staff, the OWOL designs still demonstrate safety factors greater than one, and greater than 75% of the applicable ASME Code margins.

Table 2 – ASME Section XI Structural Factors for Circumferential Flaw Evaluation

Service Level	Required Structural Factor	
	Membrane Stress	Bending Stress
Level A (Normal)	2.7	2.3
Level B (Upset)	2.4	2
Level C (Emergency)	1.8	1.6
Level D (Faulted)	1.3	1.4

Thus it is concluded that application of an OWOL to a dissimilar metal weld is an appropriate mitigation method and that its application does not invalidate previous load-carrying capacity calculations in approved leak-before- break analyses. Even in the case that a flaw were to propagate 100% through the PWSCC susceptible material under an OWOL and go undetected, considering actual plant geometries and loadings, there would still be adequate margins to failure under normal and upset operating conditions.

2. By letter dated May 2, 2008, NEI responded to the staff's request for additional information (Agencywide Documents and Access Management System (ADAMS) Accession No. ML082610254). Stress Analysis Question 1 asked NEI to justify a target stress at the inside surface of 10 ksi. NEI responded that the 10 ksi maximum tensile stress criterion provides protection against primary water stress corrosion cracking (PWSCC).

ASME Code, Section XI, Code Case N-770 (Reference 1) has established that as part of an effective stress improvement mitigation technique, a compressive stress state was required on the wetted surface of all susceptible material for DM weld application. This is consistent with the staff position and was developed, in part, due to the uncertainties in precise finite element stress modeling of the wetted surface of DM welds. Further, the staff position was not established to define a stress level at which crack initiation could not occur, rather to provide a conservative stress value that along with calculated stress levels throughout the volume of the weld provide a basis for reasonable assurance of structural integrity for a stress improved DM weld.

The NEI's response does not provide sufficient basis to demonstrate that increasing the wetted surface stress limit to 10 ksi would be equivalent to the staff position. The statement that stress corrosion cracking will not initiate on a surface that is below yield stress is not a sufficient basis for this conclusion due to large uncertainties in attempting to precisely model the wetted surface condition of in-service DM welds. Please provide additional basis, including supporting data, analyses and operational experience, to support allowing a wetted surface stress threshold of 10 ksi.

Reference 1:

ASME Code, Section XI, Code Case N-770, Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated with UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities Section XI, Division 1, Appendix I.

Response: MRP-169 has established the following criteria for acceptability of weld overlay residual stresses:

1. Acceptable residual stresses for purposes of satisfying these criteria are those which, after application of the weld overlay, are compressive on the inside surface of the nozzle, over the entire length of PWSCC susceptible material on the inside surface, at operating temperature, but prior to applying operating pressure and loads. After application of operating pressure and loads, the resulting inside surface stresses must be less than 10 ksi tensile.

2. A separate PWSCC crack growth criterion must also be satisfied to demonstrate the acceptability of the post-weld overlay residual stress distribution. This criterion requires that (a) any cracks detected in the pre- or post-overlay inspections or (b) postulated undetected cracks that are not within the applicable weld overlay examination volumes in the PWSCC susceptible material, would not grow by PWSCC and fatigue to the point that they would violate the overlay design basis (75% through-wall for OWOLs or 100% through-wall for FSWOLs). Since there is no generally accepted PWSCC crack growth threshold for Alloy 82/182 weld metals, satisfying this criterion generally requires that the cracktip stress intensity factor due to residual stresses, operating pressure and sustained, steady-state loads, be compressive up to the greater of the maximum flaw size detected (either pre- or post-overlay) or the maximum flaw size in PWSCC susceptible material that could be missed by the applicable inspections.

The above combination of ID. surface stress and crack growth criteria, in conjunction with required post-overlay inspections, provides preemptive mitigation against initiating new PWSCC cracks after application of the weld overlay. Further it provides assurance that initiation and/or propagation of pre-existing cracks would not violate the overlay design basis.

The 10 ksi tensile stress limit is consistent with the limit of 20 ksi which was used to establish the required examination volume for Alloy 600 RPV top head nozzles [3, 4]. The reduction from 20 ksi to 10 ksi is considered sufficient to address potential differences between the PWSCC susceptibility of Alloy 600 and its weld metals (Alloys 82 and 182).

A significant body of data exists demonstrating a clear justification for the concept of a threshold for PWSCC initiation in Alloy 600 and its weld metals Alloy 82, 132 and 182. [5 – 8] That is, there exist well-documented temperature, impurity concentration in the coolant and stress limits, below which SCC initiation is extremely difficult and is essentially of no engineering significance. Reference [6] defines such limits for Alloy 600 base metal. Reference [5] presents data from two types of tests of PWSCC initiation in Alloy 182 weld metal, as illustrated in Figure 1. These data exhibited no failures at stress levels less than 400 MPa (~58 ksi). Based on these data, Reference [5] concludes that “Alloy 182 is susceptible to stress corrosion cracking in PWR primary water only if the applied stress exceeds the yield stress”. Reference [7] presents similar data from pressurized cylinder experiments illustrated in Figure 2. On the basis of these data, Reference [7] concludes “A relationship between hoop stress and time to leakage was determined from which a threshold stress limit near 400 MPa (~58 ksi) for PWSCC initiation was determined.” Finally, Reference 8 presents crack growth rate data for microcracks initiated in two different types of crack initiation specimens. Although reported as crack growth data, the experiments were actually crack initiation tests, since the crack growth rate was computed based on failure time divided into thickness of the thin walled specimens tested under uniform stress conditions. Samples were tested at stress levels down to 325 MPa (~47 ksi), and at that stress level, the crack growth rates were so slow as to be of little engineering significance (0.03 mm/yr). The10 ksi limit is thus 18% to 22% of the minimum measured stresses at which PWSCC initiation has been observed in Alloy 132 and 182 weld metals in these laboratory experiments. Therefore, this limit ensures a very low probability of initiating new PWSCC cracks after weld overlay application; with significant margin to allow for uncertainties that may occur in attempting to precisely model the magnitude of tensile stress on the wetted surface of in-service DM welds.

But the real strength in the MRP-169 residual stress acceptance criteria is that they impose not just a crack initiation limit, based on inside surface stress, but rather dual criteria to preclude both crack initiation and crack growth. A separate PWSCC crack growth criterion must also be satisfied to demonstrate acceptability of the post-overlay residual stress distribution, not just for observed cracks, but also for conservatively postulated cracks that might escape detection. The weld overlay designer must demonstrate that any cracks in PWSCC susceptible material that are not within the pre- and post-overlay exam volumes would not grow to the point that they would violate the overlay design basis.

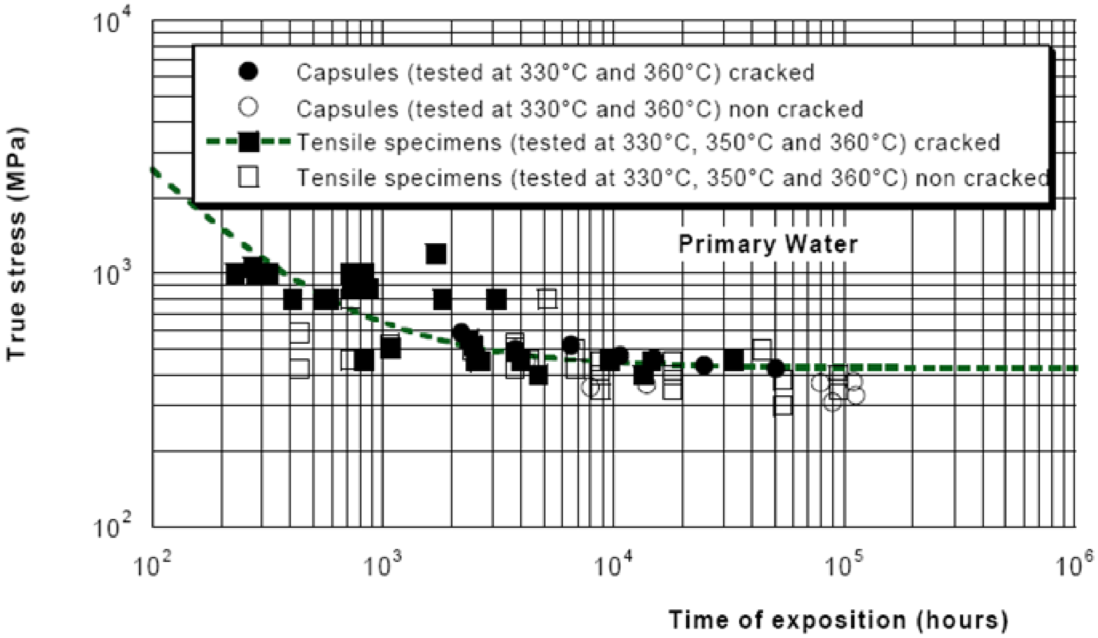

Figure 1. Time to Failure of Alloy 182 in Primary Water as a Function of Stress [4]

Figure 5. Macroscopic view of a failed capsule

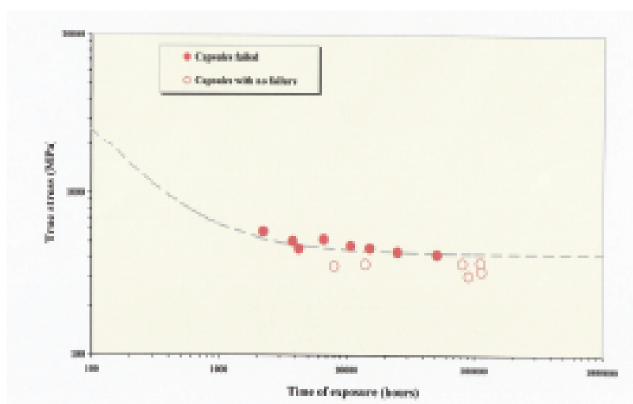

Figure 4. Time to cracking of test capsules with an Alloy 182 weld as a function of the applied stress [3, 4]

Figure 2. Data from Pressurized Cylinder Tests of Alloy 182 Weldments [7]

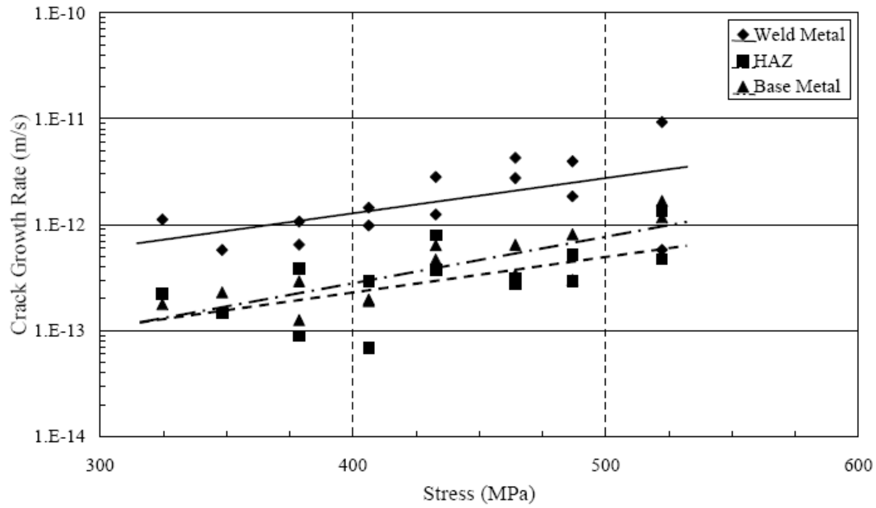

FIGURE 18 - Relationship between Stress and the Crack Growth Rate of PWSCC Microcracks of a Welded Specimen by Alloy 132 in 325 °C

Figure 3. Relationship between Stress and the Crack Growth Rate of PWSCC Microcracks of a Welded Specimen by Alloy 132 in 325°C (617°F) [8]

References:

1. ANSC Software for Determining Net Section Collapse of Arbitrarily Thinned Cylinder, Software User Manual, Structural Integrity Associates, San Jose, CA: 1994.
2. ASME XI, Appendix C, 2004 Edition
3. Materials Reliability Program: Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles (MRP-95), EPRI, Palo Alto, CA: 2003.
4. Code Case N-729, Alternative Examination Requirements for PWR Closure Heads With Nozzles Having Pressure-Retaining Partial-Penetration Welds, Section XI, Division 1
5. C. Amzallag, et al, “Stress Corrosion Life Assessment of 182 and 82 Welds Used in PWR Components,” 10th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, August 5 to 9, 2001.
6. D. Van Rooyen, “Review of the Stress Corrosion Cracking of Inconel 600,” Corrosion, Vol. 31, No. 9, September, 1975, p. 327.
7. P. Scott, et al, “Examination of Stress Corrosion Cracks in Alloy 182 Weld Metal After Exposure To PWR Primary Water,” 12th International Conference on Environmental Degradation of Materials in Nuclear Power System – Water Reactors
8. Y. Nishikawa, N. Totsuka and K. Arioka, “Influence of Temperature on PWSCC Initiation and Crack Growth Rate (Susceptibility) of Alloy 600 Weld Metals,” Corrosion 2004, Paper #04670