Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division VI

DESIGN AND ANALYSIS OF A FULL STRUCTURAL WELD OVERLAY FOR A FEEDWATER NOZZLE-TO-SAFE END DISSIMILAR METAL BUTT WELD

Robert Engel, Jens Heldt, and Christoph Krause

Leibstadt Nuclear Power Plant, Leibstadt, Switzerland (robert.engel@kkl.ch)

ABSTRACT

During the refueling and maintenance outage in the Fall of 2012 at Leibstadt Nuclear Power Plant in Switzerland, a deep axially-oriented planar indication was detected by nondestructive examination in a feedwater nozzle-to-safe end weld (N-5 nozzle at the reactor pressure vessel). The indication was located in the dissimilar metal circumferential butt weld in the vicinity of an inside surface weld repair. Its axial length was restricted to the butter, made of Alloy 182 material, and the Alloy 82 weld deposits. The weld defect was connected to the inside surface. The depth of the indication exceeded 75% of the wall thickness and was thus not acceptable according to ASME Code Section XI, IWB-3640 for Class 1 components. Therefore, the defective weld required repair prior to the restart of the plant.

The plant decided to perform the full structural weld overlay repair method according to ASME Code Case N-740-2 at the affected feedwater nozzle. The Swiss regulatory authority initially approved this repair as a temporary repair measure until the 2015 outage. Continued operation beyond this date is subject to additional review.

The objective of the present paper is to summarize the results of all structure and fracture mechanics evaluations performed for the design and analysis of the weld overlay according to the Code Case mentioned above. From the results of the analyses and the fact that weld overlay repairs have been used with excellent operational experience since the mid 1980s, it has been concluded that the overlaid feedwater nozzle-to-safe end weld in question provides full structural margins and can be considered a long-term repair.

BACKGROUND

Leibstadt Nuclear Power Plant (KKL) is located on the Rhine River in northern Switzerland. It is a General Electric BWR/6 single unit Boiling Water Reactor (BWR) plant with a Mark III containment. The plant was commissioned in December 1984. With power uprating, the current level of net-rated electrical output is 1,220 MW. KKL is the country's newest and largest nuclear unit and generates approximately 15% of the annual Swiss electricity demand.

During routine inservice inspection (ISI) at KKL during the 2012 refueling and maintenance outage, a deep axially-oriented planar indication was identified by qualified automated ultrasonic (UT) examination in one of six feedwater (FW) nozzle-to-safe end welds with an outside diameter of 374 mm and a wall thickness of 28 mm. The indication was discovered in the 262° position (clockwise from top dead end) of the circumferential weld in the vicinity of an inside surface weld repair performed during the original weld fabrication process. Its axial length was fully contained within the weld and butter. The flaw was connected to the inside diameter (ID) surface and was sized greater than 75% through-wall. A sketch of the weld in question is shown in Figure 1.

The axial weld defect did not affect the structural integrity of the nozzle and thus posed no significant safety implications because an axially-oriented flaw is arrested by extending out of the high residual stress field of the weldment. Therefore, there was only a potential for local leakage. The event was classified by the Swiss Federal Nuclear Safety Inspectorate (ENSI) as Level 0 (deviation) according to the 7-level INES scale (International Nuclear and Radiological Event Scale).

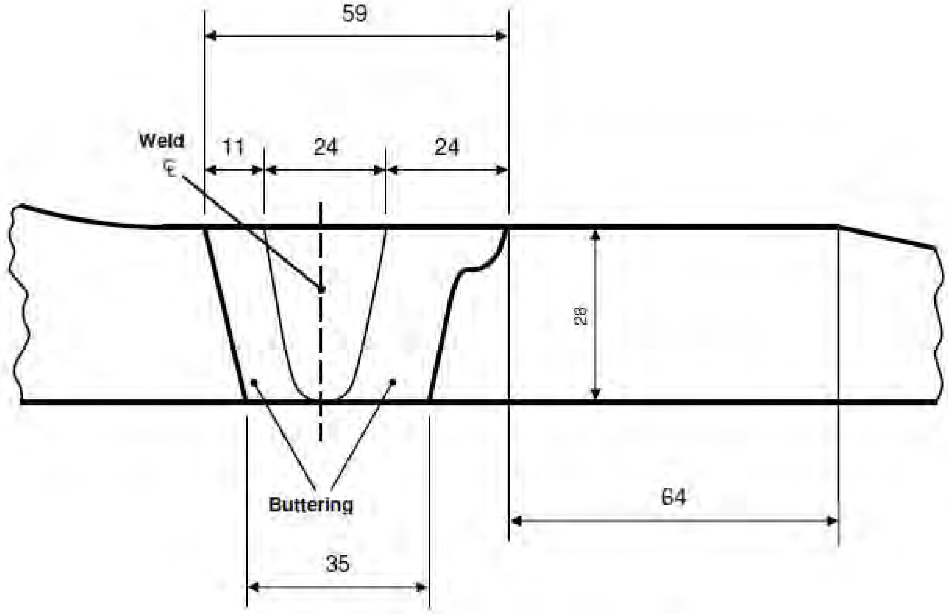

Figure 1. Sketch of the feedwater nozzle dissimilar metal weld
(Units for dimension in mm)

The nozzle-to-safe end butt weld was made of nickel-based Alloy 82 material and was buttered with Alloy 182 at both ends of the weld. The weld is a dissimilar metal weld (DMW) due to the design of nozzle low alloy steel (SA-508 Class 2) to carbon steel (SA-508 Class 1) safe end with high nickel Alloy 82/182 weld metal. Because the UT examination showed branched indications with multiple facets, the flaw was indicative of interdendritic stress corrosion cracking and appeared to have initiated in the Alloy 182 weld butter or from the edge of the circumferential ID weld repair. The repair weld was also made of Alloy 182 material. In addition to laboratory testing, operational experience has demonstrated that Alloy 82/182 materials exposed to BWR environment are susceptible to stress corrosion cracking (SCC), see BWRVIP-222 (2009) and Tsai, Y.L. (2010).

According to ASME Code (2008) Section XI, IWB-3640 for Class 1 primary coolant pressure-retaining boundary components, flaws with a depth greater than 75% of the wall thickness are unacceptable. Therefore, an unplanned repair prior to the restart of the plant was required. Due to the location of the indication and the complex geometrical configuration with a press-fitted triple thermal sleeve in safe end ID, a local repair was not practical. A replacement of the safe end would result in a significant increase of the radiation level and personnel radiation exposure, which is inconsistent with ALARA (as low as reasonable achievable) principles. Therefore, KKL decided to perform the full structural weld overlay (FSWOL) repair method according to ASME Code (2008) Code Case N-740-2 at the concerned FW nozzle weld. The Swiss regulator ENSI has accepted this repair method as a "Prototype Solution". The FSWOL involves applying a specified thickness and length of weld material over the DMW in a configuration that ensured structural integrity is maintained. The applied high chromium weld overlay (WOL) material Alloy 52M forms a corrosion-resistant structural barrier to possible leakage and the welding process produces a compressive residual stress field at the inner portion of the nozzle-to-safe end region to prevent initiation or to inhibit further extension of an existing crack.

The ambient-temperature temper bead welding technique prescribed in ASME Code (2008) Code Case N-740-2 was used to fabricate the WOL on the nozzle forging made of low alloy carbon steel (P-No. 3 material) to avoid embrittlement without the need of post weld heat treatment.

To reduce the personnel radiation exposure during the welding process the FW nozzle was flushed in advance.

Weld overlay repairs must be carefully controlled in order to assure the integrity of the overlay and the underlying weldment. Therefore, four different mockups were built prior to the on-site implementation of the WOL repair. The mockups served for welder training and qualification, to address ENSI technical issues, and to demonstrate welding and nondestructive examination capabilities for the entire overlay welding process. In addition to nondestructive examinations, metallographic and hardness testing were performed. The required system leakage test after the completion of the weld overlay repair according to ASME Code (2008) Code Case N-740-2 was carried out in the course of the 10-year Design Hydrotest of the RPV planned during the 2012 outage. All examinations on the mockups, as well as the final UT inspection of the FSWOL, and the leakage test revealed no unacceptable deficiency of the FSWOL repair. The entire repair process, beginning with the initial finding on August 28, 2012, took up almost eight weeks. The welding of the FSWOL itself lasted about ten days and was finished on time with 60% of planned radiation dose. The extension of the outage due to the FSWOL repair was approximately five weeks.

The objective of the present paper is to provide a summary of the results of all structure and fracture mechanics evaluations performed for the design and analysis of the FSWOL repair according to the ASME Code (2008) Code Case N-740-2.

WELD OVERLAY DESIGN

The FSWOL design requirements specifically for safe end regions have been formalized in ASME Code (2008) Code Case N-740-2. This Code Case has been approved by the ASME Code and site approved by the U.S. Nuclear Regulatory Commission for FSWOL applications across the U.S. fleet. The required basic structural sizing calculation was based on plant specific geometry and assumed conservatively a circumferentially-oriented flaw that extends 100% through the original pipe wall thickness for the entire circumference of the pipe. Furthermore, as required by ASME Code (2008) Section XI, IWB-3640 the following plant specific bounding load combinations of internal pressure, deadweight, seismic, and other dynamic loads were used in the design of the FSWOL repair:

Service Level A (Normal):	Pressure (PO) + Deadweight (DW)
Service Level B (Upset):	PO + DW + Design Mechanical Loads
Service Level C (Emergency):	PO + DW + Seismic Primary (PRI)
Service Level D (Faulted):	PO + DW + 2·Seismic PRI

The weld overlay sizing is an iterative process. To determine the overlay thickness, the first step of the iteration was done using the analytical requirements of ASME Code (2008) Section XI, IWB-3640, which are primarily intended to provide justification for additional service without repair of an inservice identified flaw. The rules of IWB-3640 allow a maximum flaw depth of 75% of the pipe wall thickness. Since the assumed flaw in case of a FSWOL repair is equal to 100% of the wall thickness, the minimum overlay thickness is calculated to be 33% of the original pipe wall thickness. If this thickness is exposed to the plant specific load combinations mentioned above and meets the allowable stress intensities according to ASME Code (2008) Section III, NB-3200 for pure general primary membrane, P_m, and combined primary membrane-plus-bending, P_m+P_b, then no additional iteration steps are required. If the allowable stresses are not met, then the overlay thickness must be increased until the ratio of the computed stress to the allowable stress is less than or equal to 1.0. The WOL length must consider three requirements:

(1) length required for structural reinforcement,
(2) length required for preservice and inservice examinations of the overlaid weld, and
(3) limitation on the area of the ferritic nozzle and safe end surface that can be overlaid.

In accordance with ASME Code (2008) Code Case N-740-2 the minimum WOL length required for structural reinforcement was established by evaluating the axial shear stress due to transfer of primary axial loads from the safe end into the overlay and back into the nozzle. Additional thickness and length was added to fulfill the requirement of the Code Case regarding UT inspection as well as fatigue and crack growth concerns. Therefore, a maximum overlay thickness, typically additional 6-7 mm, and a maximum overlay length were determined. The calculation of the maximum length is based on implementation factors and is intended to be large enough so as to not unnecessarily constrain the overlay process. The overlay on the nozzle side was smoothly blended into the taper of the nozzle to eliminate any discontinuity on the surface of the nozzle and hence any stress risers. The gas tungsten arc welding machine process of the FSWOL included seven layers.

The resulting minimum required overlay thickness and length are shown in Figure 2. In Table 1 the measured as-built thickness and length of the overlay, after final contouring, are compared to the minimum required values. These measurements exceed the minimum required structural design dimensions demonstrating the adequacy of the as-installed repair.

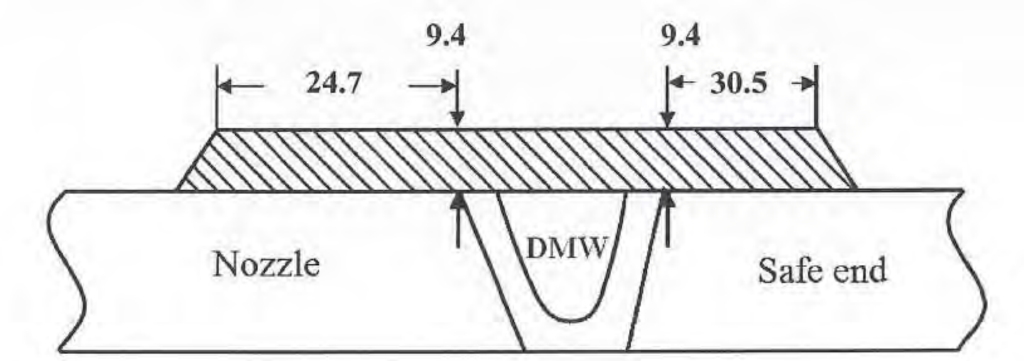

Figure 2. Full Structural Weld Overlay geometry, minimum required dimensions in [mm]
(Schematic representation)

Table 1: Full Structural Weld Overlay dimensions

	Location	Minimum required	As-built
Thickness [mm]	Nozzle Side	9.4	17.5
	Safe End Side	9.4	17.5
Length [mm]	Nozzle Side	24.7	60.2
	Safe End Side	30.5	66.3

This first step in the overlay design is simple and straightforward. However, the overlay must also be qualified for service by meeting the additional requirements of ASME Code (2008) Code Case N-740-2, which include the prediction of crack growth during service (due to both fatigue and stress corrosion under all expected loadings) and a separate determination to ensure that the original requirements of the design code are met at the boundaries of the overlay. The verification process for the overlay design is actually more complex than the overlay design itself.

WELD OVERLAY DETAILED ANALYSES

The detailed analyses, based on the as-built WOL dimensions of the as-repaired condition, consisted of Finite Element (FE) residual stress calculations due to the WOL welding process as input for the crack growth analysis, as well as thermal and mechanical stress and fatigue calculations to meet the ASME Code (2008) Section III, Subsection NB stress and fatigue requirements. In addition, evaluations of WOL effects on the piping system such as shrinkage and additional weight were performed.

Residual Stress Analyses

A two-dimensional axisymmetric FE model was developed using the ANSYS finite element analysis software. The model included, as can be seen in Figure 3, a local portion of the reactor pressure vessel (RPV) shell, the FW nozzle, the safe end with a Type 304 stainless steel ID build up where the two seals of the triple thermal sleeve are pressed in, the nozzle-to-safe end weld, the nozzle and safe end weld butter, a portion of the FW piping, the WOL repair, and a postulated ID weld repair applied to the nozzle-to-safe end weld.

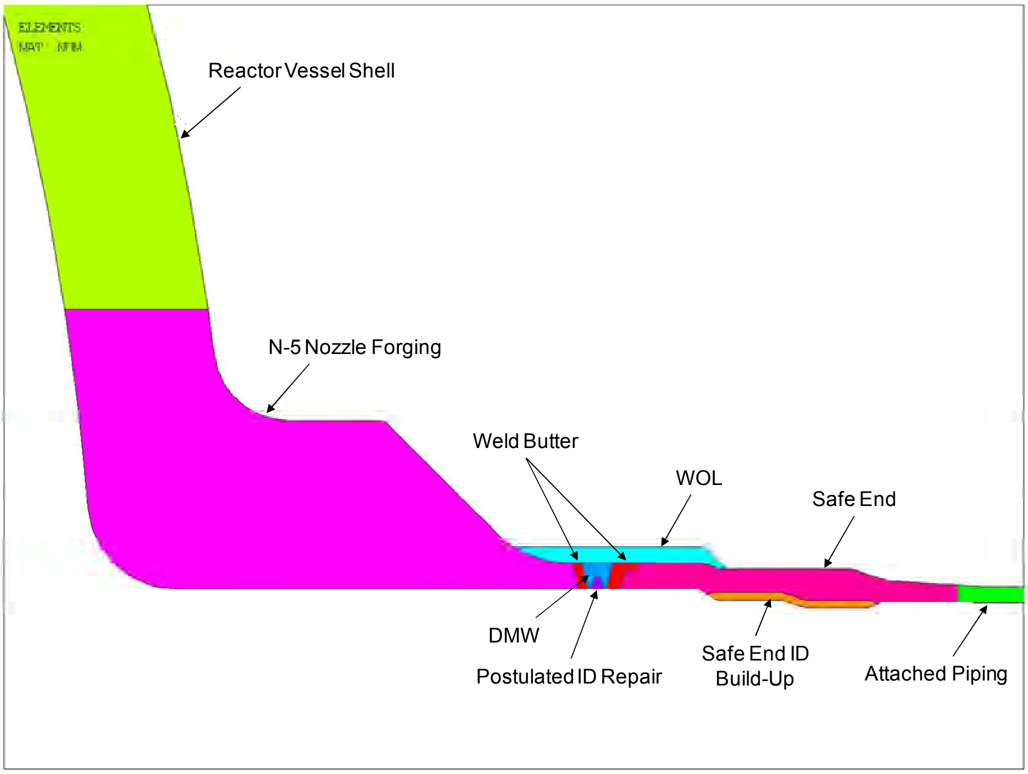

Figure 3. Components included in the Finite Element model

The weld repair was simulated at the center of the DMW with a width of 14 mm and a depth of 50% of the original wall thickness for the full circumferential extent. According to MRP-169 (2008), this assumption was considered to conservatively cover any weld repairs that may have been performed during plant construction from the standpoint of producing tensile residual stresses on the ID surface of the weld. Only structural components to the nozzle were modeled. As such, the triple thermal sleeve was not modeled because it is not a structural component. Instead, effective thermal conductivity was considered over the region covered by the triple thermal sleeve, the annular regions within the thermal sleeve and between the thermal sleeve and nozzle during thermal stress analyses. The FE model was subsequently used to perform the non-linear weld residual stress analysis due to the ID repair and the WOL weldments. Therefore, the model contained detailed modeling of the assumed six layers of the repair weld, the seven WOL layers as well as the weld beads.

By means of a detailed non-linear, elastic-plastic FE analysis, the multi-pass welding processes were simulated. First the ID weld repair was simulated to provide an overall conservative unfavorable high tensile initial stress condition according to Ku (2009). Subsequently the WOL repair and a slow heat up to normal operating temperature and pressure (286°C and 73.1 bar, respectively) conditions were simulated.

The results showed that post-WOL compressive stresses for both the 20°C and normal operating conditions are largely present on the inner portion of the SCC susceptible weld material.

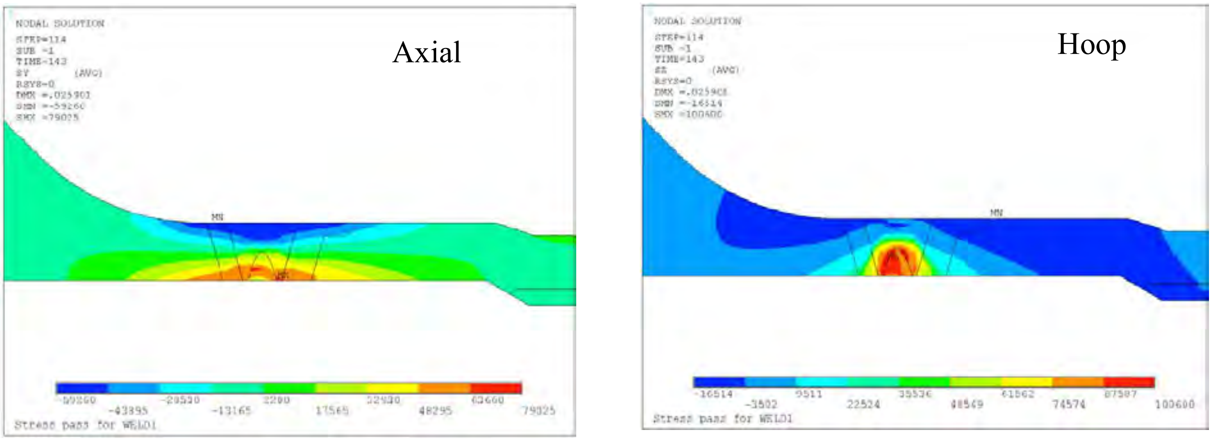

Figure 4. Post-ID weld repair stress plots at room temperature
(Units for stress in psi)

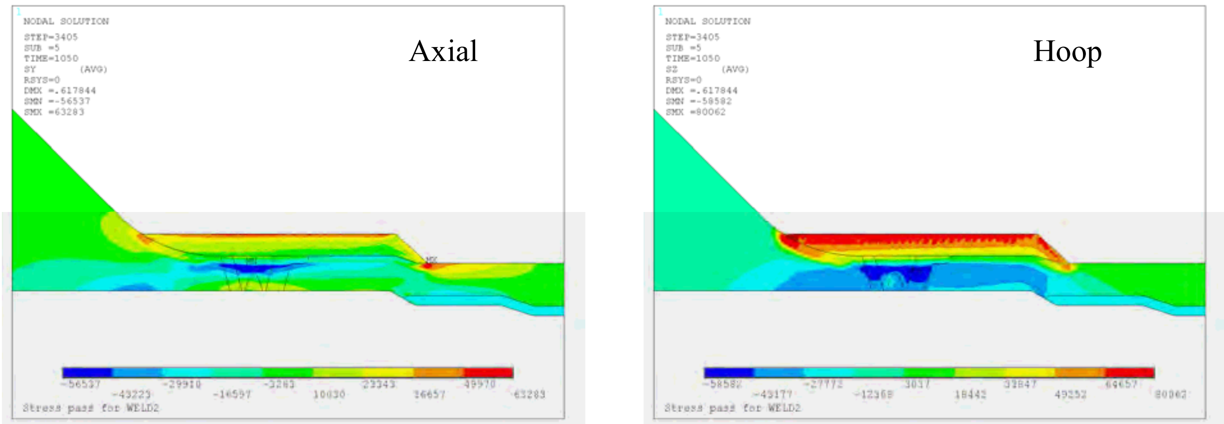

Figure 5. Post-WOL stress plots at normal operating conditions
(Units for stress in psi)

Figure 4 depicts the resultant residual stress distributions after ID weld repair in the axial and hoop directions. Figure 5 shows the resultant residual plus normal operating condition stress distributions for the post-WOL configuration in the axial and hoop directions. The results demonstrate that the WOL has indeed generated a favorable stress condition for the nozzle and safe end by inducing compressive stresses on the ID surface. The favorable stress condition minimizes and/or arrests crack initiation/propagation caused by SCC in the susceptible DMW material. Through-wall residual stress distributions for paths defined through the DMW as a result of these analyses were used as input to subsequent fatigue crack growth calculations and SCC evaluations.

Crack Growth Evaluations

Crack growth calculations for the affected FW nozzle weld were performed. The aim was to demonstrate that an axial as well as a 360° circumferential flaw, both with a depth equal to 100% of the original DMW thickness of 28 mm, would not show unacceptable growth due to fatigue and SCC, so as to violate the basis for the overlay design which allowed a crack propagation into the overlay until the minimum WOL design thickness is reached. The through-wall stress intensity factor distribution was determined with postulated axial and circumferential flaws using the post-WOL residual stresses at normal operating conditions plus sustained and transient operating stresses. Crack growth rates for Alloy 52M in a BWR environment were used as reported in NUREG/CR-6721 (2001) and Andresen (2011). Crack propagation was calculated to determine the number of years required for the postulated axial as well as circumferential flaw, both 100% of the original weld metal thickness, to reach the WOL design basis.

The crack growth results demonstrate that more than 40 years are required for the postulated axial and circumferential flaw in the DMW to reach the WOL design basis.

ASME Code, Section III Stress Analysis

A three-dimensional quarter symmetry FE model, with eight-node structural respectively thermal solid elements and including the same components as in Figure 3, was created using the ANSYS finite element program. With this FE model, thermal and mechanical stress analyses and a fatigue analysis of the nozzle with the as-built WOL repair were performed in accordance with the requirements of the ASME Code (2008), Section III, NB-3200 and NB-3600 for the nozzle and the safe end respectively. Linearized stresses were evaluated through a total of six stress paths. Stress intensities were conservatively determined for the design mechanical loads and thermal transients according to the plant specific Thermal Cycle Diagram and compared to ASME Code allowable values for primary-plus-secondary (P+Q) and primary-plus-secondary-plus-peak (P+Q+F) stress effects. In all cases, the calculated values of stress intensity ranges P+Q were less than their corresponding allowable values with a maximum stress ratio of about 60%. The fatigue analysis was based on ten bounding specified thermal transients, including power uprate: Start Up, Turbine Roll, Weekly Reduction, Turbine Trip, Partial FW Heater Bypass, Loss of FW Pumps, Turbine Generator Trip, Hot Standby, Shut Down, and Turbine Bypass, and one test condition: Design Hydro Test. Three additional non-specified events: thermal stratification, reroute of the reactor core isolation cooling pipe run and final FW temperature reduction that occurred during early life of the plant were additionally considered. The detailed analysis showed that the as-built WOL repair is qualified for the 40 additional years of design cyclic operation beyond the 28 years of design operation prior to the WOL as specified by KKL for the cumulative usage factor in the relevant technical specification for the repair:

$$U_{total} = U_{before\ WOL,\ 28\ years} + U_{after\ WOL,\ 40\ years} > 1.0$$

Evaluation of Weld Overlay Effects on Piping System

Weld overlay installation results in axial and radial shrinkage at the WOL and in additional weight on the piping system.

Axial shrinkage produces tensile secondary stresses in the piping collinear with the overlay, and predominantly secondary bending stresses at locations that are separated and not collinear with the welding location, e.g. locations separated by an elbow. Although there are no ASME Code limits that apply to these stresses, they could, however, potentially increase the SCC susceptibility of other welds in the system. Therefore, the axial shrinkage was measured and the resulting stresses were evaluated via an appropriate piping model developed using the computer program PIPESTRESS. Using the average measured axial shrinkage of 0.9 mm, the highest calculated stress in the FW piping system showed a small value of 8 MPa. All hangers, supports and restraints that could be potentially affected were inspected by KKL after the application of the WOL repair and were found to be acceptable. Thus, the observed axial shrinkage level was deemed to be acceptable.

Since the FW nozzle thermal sleeve at KKL is a triple thermal sleeve with a double piston ring design, it was important to demonstrate that radial shrinkage caused by the WOL repair would not cause negative effects on the functionality of the thermal sleeve seals. Creation of a leakage path would potentially invalidate the existing analyses that address the potential for FW nozzle blend radius rapid thermal cycling and subsequent crack growth, as well as the existing design basis fatigue calculations of the FW nozzle assembly. The radial shrinkage could cause distortion at the thermal sleeve seal locations that could affect the performance of the triple sleeve seal. Consequently, the possibility of FSWOL induced distortion at the FW nozzle thermal sleeve seal locations had to be evaluated and shown to not cause structural failure or degradation of seal functionality. The measured shrinkage in diameter in the full-scale WOL mockup was within the expected range based on comparison to other mockup data. The shrinkage under the overlay was applied to the FE model in order to simulate the rigidity of the RPV, which was not accounted for at the mockup. The predicted radial shrinkage of 0.07 mm and 0.17 mm at the primary and secondary seals, respectively, was used to determine the susceptibility of the thermal sleeve to ring buckling or leakage at the seal locations. Neither buckling nor leakage was predicted. Therefore, the triple thermal sleeve remained functional following installation of a FSWOL.

The added weight of the WOL can be a concern when considering the impact on the dynamic response characteristics of the attached piping system, and therefore on the design loadings. Based on the as-built dimensions, the calculated weight of the WOL adds only 3% to the total weight of the nozzle and safe end forgings. Therefore, the added weight of the WOL does not impact the existing design loads on the attached piping system or its dynamic characteristics.

CONCLUSIONS

A full structural weld overlay in accordance with ASME Code (2008) Code Case N-740-2 was successfully installed on a feedwater nozzle at Leibstadt Nuclear Power Plant. The repair was necessary due to a deep axial indication that was detected by ultrasonic examination during a routine inservice inspection on the feedwater nozzle-to-safe end dissimilar metal weld. The indication exceeded the acceptance standards of ASME Code (2008) Section XI and was characterized as interdendritic stress corrosion cracking in the Alloy 82/182 weld metal.

The full structural weld overlay repair can be considered to be a long-term repair as follows:

- The weld overlay restores the original safety margin of the piping weld since it was designed to meet the requirements of ASME Code (2008) Section XI, IWB-3640. In addition, it meets all of the requirements of ASME Code (2008) Code Case N-740-2.
- In the analyses it was conservatively assumed that the weld defect extended through 100% of the original pipe wall thickness and around the complete circumference.
- The as-built dimensions of the full structural weld overlay exceed the minimum required design dimensions demonstrating additional margin in the overlay repair.
- The weld metal used for the overlay is Alloy 52M providing a stress corrosion cracking resistant barrier. Therefore, no significant crack growth into the overlay is expected.
- Residual stress data after the overlay welding results in beneficial compressive stresses on the inside of the pipe.

- A crack growth analysis concluded that more than 40 years are required for the conservatively postulated axial and circumferential flaw in the dissimilar metal weld to reach the overlay design basis.
- A detailed fatigue analysis demonstrated that the as-built weld overlay repair is qualified for an additional 40 years of design operation.
- A conservative shrinkage analysis indicated that shrinkage stresses arising from the weld overlay application are small and do not adversely affect other welds on the feedwater system. All relevant hanger set points and pipe whip restraints clearances were checked after the overlay repair and were found to be within the design ranges.
- The added weight on the feedwater system due to the overlay is small and does not impact the stresses and the dynamic characteristics of the piping system and the nozzle.

From the above observations and the excellent operational experience since the mid 1980s with hundreds of weld overlays in the nuclear industry (as a repair or a preemptive measure), it is concluded that the full structural weld overlay repair on KKL's feedwater nozzle can be considered a life of plant repair.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Josh Faulk from Aquilex WSI Nuclear Services and Mr. Michael Lashley from Structural Integrity Associates and their project teams as well as Mr. Steve McCracken from EPRI Welding and Repair Technology Center for their support and contribution to the overall success of the repair project.

NOMENCLATURE

BWR	Boiling Water Reactor
DMW	Dissimilar Metal Weld
ENSI	Swiss Federal Nuclear Safety Inspectorate
FW	Feedwater
FSWOL	Full Structural Weld Overlay
ID	Inside Diameter
ISI	Inservice Inspection
KKL	Leibstadt Nuclear Power Plant
RPV	Reactor Pressure Vessel
SSC	Stress Corrosion Cracking
UT	Ultrasonic
WOL	Weld Overlay

REFERENCES

Andresen, P.L. (2011), "SCC of High Cr Alloys in BWR Environments", *15th Int. Conference on Environmental Degradation*, TMS (The Minerals, Metals & Materials Society), 267-297.

ASME Boiler and Pressure Vessel Code (2008), Section III, Division 1, Subsection NB, "Class 1 Components - Rules for Construction of Nuclear Facility Components", Edition 2007 with 2008a Addenda.

ASME Boiler and Pressure Vessel Code (2008), Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components", Edition 2007 with 2008a Addenda.

ASME Boiler and Pressure Vessel Code (2008), Code Case N-740-2, "Full Structural Dissimilar Metal Weld Overlay for Repair or Mitigation of Class 1, 2, and 3 Items Section XI, Division 1".

BWRVIP-222 (2009), “BWR Vessel and Internals Project, Accelerated Inspection Program for BWRVIP-75-A Category C Dissimilar Metal Welds Containing Alloy 182”, EPRI, Palo Alto, CA, Report No.1019055.

Ku, F.H., Lohse, C.S., Dijamco, D.G., Fourcade, C.J., Bax, R.L., Cofie, N.G. (2009), “Post Weld Overlay Residual Stresses in Dissimilar Metal Welds Considering Various Butt Weld and Weld Repair Fabrication Sequences”, *2009 Pressure Vessels & Piping Conference*, Prague, Czech Republic

MRP-169 (2008), “Materials Reliability Program, Technical Basis for Preemptive Weld Overlays for Alloy 82/182 Butt Welds in PWRs”, Revision 1-A, EPRI, Palo Alto, CA, Report No.1021014.

NUREG/CR-6721 (2001), “Effects of Alloy Chemistry, Cold Work, and Water Chemistry on Corrosion Fatigue and Stress Corrosion Cracking of Nickel Alloys and Welds”, U.S. Nuclear Regulatory Commission.

Tsai,Y.L., Wang, Li.H., Fan, T.W., Ranganath, S., Wang, C.K. and Chou, C.P. (2010), “Welding overlay analysis of dissimilar metal weld cracking of feedwater nozzle”, *Int. Journal of Pressure Vessels and Piping,* ELSEVIER, 87, 26-32.