Enclosure C
L-16-327

Technical Basis for Optimization or Elimination of Liquid Penetrant Exams
for the Embedded Flaw Repair, Beaver Valley, Unit 2,
Letter LTR-PSDR-16-008-NP, Revision 0, dated October 2016
(Nonproprietary Version)

(22 Pages Follow)

LTR-PSDR-16-008-NP
Revision 0

TECHNICAL BASIS FOR OPTIMIZATION OR ELIMINATION OF LIQUID PENETRANT EXAMS FOR THE EMBEDDED FLAW REPAIR BEAVER VALLEY UNIT 2

October 2016

Author: W. H. Bamford*, Consulting Engineer, Primary Systems Design & Repair

Verifier: A. Udyawar*, Principal Engineer, Piping Analysis and Fracture Mechanics

Approved: J. R. Stukus*, Manager, Structural Design and Analysis Engineering

Electronically approved records are authenticated in the Electronic Document Management System.

Westinghouse

FOREWORD

This document contains Westinghouse Electric Company LLC proprietary information and data which has been identified by brackets. Coding (a,c,e) associated with the brackets sets forth the basis on which the information is considered proprietary. These codes are listed with their meanings in WCAP-7211 Revision 8 (September 2015), "Proprietary Information and Intellectual Property Management Policies and Procedures."

The proprietary information and data contained in this report were obtained at considerable Westinghouse expense and its release could seriously affect our competitive position. This information is to be withheld from public disclosure in accordance with the Rules of Practice 10CFR2.390 and the information presented herein is to be safeguarded in accordance with 10CFR2.903. Withholding of this information does not adversely affect the public interest.

This information has been provided for your internal use only and should not be released to persons or organizations outside the Directorate of Regulation and the ACRS without the express written approval of Westinghouse Electric Company LLC. Should it become necessary to release this information to such persons as part of the review procedure, please contact Westinghouse Electric Company LLC, which will make the necessary arrangements required to protect the Company's proprietary interests.

The proprietary information in the brackets has been deleted in this report, the deleted information is provided in the proprietary version of this report (LTR-PSDR-16-008-P Revision 0).

Technical Basis for Optimization or Elimination of Liquid Penetrant Exams for the Embedded Flaw Repair

ABSTRACT

The embedded flaw repair for reactor vessel head penetrations was first applied at the DC Cook plant in 1996, and since that time it has been implemented on over 50 reactor vessel head penetrations world-wide. The technical basis for the approach has been accepted by the Nuclear Regulatory Commission (NRC) through their published Safety Evaluation of WCAP-15987-P Rev 2-P-A [1], December 2003. As an additional requirement of the safety evaluation, a liquid penetrant examination was imposed on the embedded flaw repair weld each refueling outage after its implementation. While this requirement may have been a reasonable one when the process was new, the dose required for implementation of this examination is no longer justified.

This report provides a technical justification for eliminating the liquid penetrant examination. Some of the key points to be covered in this report are listed below:

- The original technical basis for these repairs has stood the test of time. Multiple layers have resulted in an impervious barrier of highly resistant material, which continues to fulfill its intended purpose.
- The service history of these repairs has been excellent, with no failures of the repair to protect the head penetrations from Primary Water Stress Corrosion Cracking (PWSCC).
- Alloy 52/Alloy 152 applied weld material is highly resistant to PWSCC, with no crack initiations in over 22 years [5].
- The initial and post installation PT's performed on the embedded flaw repair weld established the integrity of the repair. Degradation with service leading to PWSCC is highly unlikely. No PWSCC of these repairs has been experienced to date.
- Follow-up PT exams have not revealed any service-induced cracking or structural degradation. A boat sample removed and examined at San Onofre proved that the penetrant indication found in the Embedded Flaw Repair (EFR) weld during service was not PWSCC [3].
- Continued UT examination of the repaired nozzle is sufficient to find degradation of the EFR and nozzle material.
- The UT leak-path examination technique is demonstrated per 10CFR50 and is the current standard for inspection of nozzles which have not been repaired. This approach has become accepted since the embedded flaw repair was first licensed and will provide the same level of confidence/safety for the embedded flaw repaired nozzles. Therefore, additional examination of these welds by PT adds little or no value.
- There is significant radiation dose associated with the penetrant examinations. This extensive dose is not justifiable in light of the extensive positive service experience for this repair technique.
- The zinc addition implemented at Beaver Valley Unit 2 adds further benefit towards mitigating PWSCC of the already resistant Alloy 52 weld material.

1. BACKGROUND AND PURPOSE

The embedded flaw repair technique was developed by Westinghouse in 1994, and involves the deposition of at least two layers of Alloy 52 weld metal to isolate existing flaws and susceptible material from the primary water environment (three layers on welds, to avoid chromium dilution).

The embedded flaw repair technique is considered a permanent repair because as long as the degraded region remains isolated from the primary water (PW) environment, flaws cannot initiate or propagate due to PWSCC. Since Alloy 52 weld metal is highly resistant to PWSCC, a new PWSCC crack will not initiate and grow through the Alloy 52 overlay permitting the PWR environment to contact the susceptible material. In fact, these repairs have been in service for over 20 years now, with the longest single repair in place for over 10 years, and they have performed well.

The resistance of Alloy 690 and its associated weld metal, Alloys 52 and 152, has been demonstrated by laboratory testing in which no cracking has been observed in simulated PWR environments, and by approximately 25 years of operational service in steam generator tubes, where no PWSCC has occurred. The crack growth resistance of this material has been documented in reference [2], as well as numerous other papers.

When the embedded flaw repair process was developed, as part of the regulatory review process, liquid penetrant examinations were required every outage, to ensure the reliability of the process. Although these examinations may have been warranted initially, the extensive service experience to be discussed here will demonstrate that they are no longer needed.

2. EMBEDDED FLAW REPAIR: OVERVIEW

J-weld flaws have a complex, three dimensional geometry, which does not lend itself to conventional repairs. Since conventional repair was considered impractical and ineffective, Westinghouse developed a unique repair alternative called the embedded flaw repair method. This method enables the installation of a non-structural Alloy 52/52M weld barrier that effectively isolates the Control Rod Drive Mechanism (CRDM) tube and J-weld from Reactor Coolant System (RCS) water. This Westinghouse design was developed by over 10 years of direct interface with nuclear Owners (both US and international) and regulatory authorities, culminating in a formal Westinghouse report [1] recognized and accepted by the US NRC. Regulatory endorsement of this Westinghouse methodology has become routinely accepted by plant owners and the NRC as an acceptable method to prevent further PWSCC degradation to reactor vessel head penetrations. This repair method has also been licensed and implemented in both Japan and Korea, as well as two countries in Europe.

Several factors make J-weld repair welding difficult to address. The J-welds themselves are located on the inside of the RPV head. The result is that each nozzle is unique, in that its location relative to the outer edges of the head results in a constantly varying degree of curvature in the J-weld itself. Welding challenges associated with this curvature are further complicated by the fact that the CRDM tubes are all vertically oriented. This means that each J-weld, as it extends around the circumference of the CRDM tube, has significant variations in height. Also, the J-weld itself, due to the fact that it welds a vertical CRDM tube to a sloped vessel ID surface, is oval in shape. In light of the high radiation levels (typically 2 to 3 REM per hour) underneath the reactor vessel head, any attempt at manual repair of the J-welds will result in unacceptably high radiation exposure levels; levels that are both undesirable, costly, and contrary to Utility ALARA

(as low as reasonably achievable) objectives. These exposure levels make remote, machine welding a necessity. They also make liquid penetrant examinations of the completed welds a costly endeavor.

To address these and other concerns, PCI designed and manufactured a welding system specifically tailored for installation of a J-weld overlay. This four-axis, custom manufactured weld head is unique in the industry, in that it can deposit a high quality weld in this challenging environment [1]. PCI began this equipment development effort in 2000. Over the following years, PCI has made major upgrades, enhancements, and improvements in this welding equipment. The result is a proven, robust, and reliable equipment set capable of consistent, schedule-effective delivery of quality welds. Specifically, the repair involves at least two (offset) layers of weld metal over the head penetration base metal, and at least three layers over the J-groove weld. The multiple layers are to ensure that no path exists to allow the PWR water to contact the susceptible materials. The additional layer over the weld region is to minimize dilution of the chromium.

3. EMBEDDED FLAW REPAIR EXPERIENCE

Embedded flaw repairs serve to mitigate reactor vessel head penetration (RVHP) flaws in the following locations: Tube-to-vessel J-groove weld, Tube OD, and Tube ID. For purposes of this document, the review of EFR performance history will focus only on OD repairs, i.e., repairs that deposit weld metal on the surface of the Tube-to-vessel J-groove weld and the OD surface of the tube. This constitutes the majority of the repairs which have been implemented.

Over fifty EFR OD repairs have been installed in at least 12 separate nuclear power plants. Thirty six are currently in service; others have been removed from service by head replacement or other reasons not related to EFR effectiveness. These repairs are summarized in Table 1. Nuclear plants where EFR's have been removed from service include North Anna 2, Arkansas 1, Beaver Valley 1, Ohi 3 (Japan), San Onofre 3, Hanbit 3, and DC Cook 2. Nuclear plants with in-service EFR's include Beaver Valley 2, Byron 1, Byron 2, Beznau, VC Summer, Braidwood 1, and Hanbit 4 (Korea). Service exposure duration for individual EFR varies among units, with 10 years constituting the longest period of service exposure to date for an OD repair. (An ID embedded flaw repair implemented at the DC Cook plant was also in service for ten years, without any evidence of degradation, before the head was replaced, in 2006. Details are provided in Appendix A.)

4. PT EXAMINATION DETAILED HISTORY

Every EFR is presently required to be PT examined every outage, as a result of an NRC condition imposed on the generic relief request, which was approved in July 2003 [1]. To date, no PT examination has shown evidence of PWSCC in EFR deposits; however, PT examinations have periodically identified fabrication flaws and/or discontinuities in installed EFR deposits. The following paragraphs summarize PT examination results for in-service EFR welds.

Of the over 50 EFR's of the OD that were placed in service (see Table 1), 13 were installed in 2013 and 2014 (5 at VC Summer, 5 at Hanbit 4, 2 at Beaver Valley 2, and 1 at Byron 2). These newly installed EFRs have not yet completed their first cycle of operating service, and therefore have not been PT examined subsequent to being placed in service. PT examinations have been

performed on each of the remaining repairs during subsequent refueling outages, and these PT examinations have been repeated for the entirety of the service life of each EFR. This means that, for these installed EFR's, a large number of outage-related PT examinations have been performed. The sites with the longest service of these repairs are Beaver Valley, Byron, and Braidwood. The history of these repairs will be reviewed in detail below, and the history of San Onofre will be reviewed, since this was the site of the most in-depth evaluation of an indication found during the required liquid penetrant (PT) exams.

5. BOAT SAMPLE REMOVAL AND TESTING FROM SAN ONOFRE UNIT 3 [3]

The first example of PT indications observed on an embedded flaw repair surface was at San Onofre Unit 3 in October of 2008. As a result of this finding, the NRC was concerned that the observed cracking in the repair weld might be PWSCC, and so a boat sample was removed and examined further. The repair had been in service since the EFR was completed in 2004, and had undergone an acceptable PT examination in 2006, after one cycle of operation. The boat sample contained a rejectable rounded indication, in the EFR for penetration #64.

The examinations included visual inspections, stereo-visual inspections, X-ray radiography, high resolution replication, extended dwell fluorescent PT, scanning electron microscopy (SEM), energy dispersive spectroscopy, and optical metallography. The primary purpose was to identify the most likely cause of the delayed appearance of the PT indication.

Thin fragments of material (0.0005" or less) were identified surrounding the entrance to the rejected void. These ligaments were found to likely explain the delayed presentation of the void, because the underlying cavity had been protected from the surface by a very thin layer of Alloy 52. The exact cause of the failure of this layer is not known, but it is likely that the protective ligaments failed due to operational stresses or cleaning efforts following the 2006 penetrant examination. The evidence obtained did not support PWSCC, thus demonstrating that the Alloy 52 weld material continued to protect the Alloy 600/82/182 from the PWR water.

6. POTENTIAL CAUSES OF PT INDICATIONS IN EFR WELD REPAIRS

Several factors can affect PT examination accuracy and results. These factors can contribute to differing PT results on a given weld from one examination to the next, even when the examination is performed under ideal conditions. These factors include:

Minor Changes in Weld Surface: EFR weld surfaces are PT examined upon initial installation, and rejectable (ASME Section III criteria) indications are removed. Upon initial introduction to service conditions, EFR weld surfaces are ASME Section III compliant. Thermal expansion, vessel head dilation due to pressurization, and water flow can have an effect on the EFR surface. For example, a small welding flaw in an EFR surface may be present, but the flaw face (i.e., the portion of the flaw exposed to the EFR weld surface) may be compressed too tightly to permit penetrant absorption. The face of this small welding flaw, when exposed to service conditions, may be slightly changed, widening the gap at the weld surface. Upon subsequent PT

examination, this indication surface may now have sufficient width to enable penetrant entry, causing it to appear as rejectable during subsequent examinations. Such indications do not indicate failure of the EFR; rather, they are indicative of minor change in surface configuration resulting from service exposure.

A similar situation may occur in areas where separate weld passes/beads join together. These areas often constitute geometric discontinuities, and (as explained previously) can cause penetrant to become entrapped. Operating conditions may cause minor additional changes in the surface geometry in these locations, and these slight changes can increase the risk of penetrant entrapment. An example is shown in Figures 1 and 2. These changes may then preclude effective cleaning during subsequent PT examinations. When these situations occur, metal removal is typically required to smooth the area, and restore a configuration suitable for PT acceptance. Again, these minor configuration changes do not constitute weld failure of the EFR; they constitute only a condition warranting surface conditioning to facilitate the PT process, thus confirming the integrity of the weld. This situation is the most common source of indications which are found in subsequent PT inspections. Since the OD of the head penetrations near the J-groove weld is located in a very high dose region, subsequent surface preparation by grinding has a significant impact on personnel radiation exposure, and is only performed when absolutely necessary to facilitate the PT process.

It is also possible that EFR welds contain welding flaws that, at the time of introduction to service, are not open to the weld surface, and are not, therefore, detectable by PT. Service conditions can cause welding flaws of this nature to become surface exposed, and any such exposed flaws would likely appear as PT indications during subsequent PT examinations. Indications of this type may be rounded (i.e., porosity) or linear (i.e., lack of fusion between beads, such as localized flaws at tie-in areas). When flaws of this nature are detected, they are repaired by excavation and, where necessary, localized weld repair (typically manual GTAW). Indications of this nature have occurred in limited situations, and repairs have been successfully performed, as confirmed by subsequent PT inspections. The EFR specifically employs multiple weld layers to ensure weld integrity, and flaws of this nature are typically limited in size and depth to less than one weld layer. As demonstrated by ongoing EFR inservice experience, these types of welding flaws do not compromise the integrity or acceptability of the EFR weld to perform its intended purpose.

As-Welded Surfaces: Embedded flaw repair welds require that the final PT be performed on an as-welded surface, which requires careful and thorough cleaning to adequately remove penetrant prior to developer application. Due to inherent differences in cleaning from one examination to the next, some variation in indication size is an unavoidable aspect of the PT examination process. It is possible, therefore, that the original surface (with or without a preexisting welding flaw) has not changed, but that the more recent PT examination produced different results due to this variability between PT examinations. This is not indicative of an unacceptable examination technique; rather, it is a degree of examination variability inherent in the PT process. The ASME Code recognizes the liquid penetrant test method to be inherently susceptible to indications of this nature, and cites 'surface conditions' (Ref. NB-5351(a)) as a common contributing factor. ASME Section III, NB-5351 (2010 Edition) states:

NB-5350 LIQUID PENETRANT ACCEPTANCE STANDARDS

NB-5351 Evaluation of Indications

(a) Mechanical discontinuities at the surface are revealed by bleeding out of the penetrant; however, localized surface discontinuities, such as may occur from machining marks, surface conditions, or an incomplete bond between base metal and cladding, may produce similar indications which are nonrelevant.

(b) Any indication which is believed to be nonrelevant shall be reexamined to verify whether or not actual defects are present. Surface conditioning may precede the reexamination. Nonrelevant indications and broad areas of pigmentation which would mask defects are unacceptable.

(c) Relevant indications are indications which result from imperfections. Linear indications are indications in which the length is more than three times the width. Rounded indications are indications which are circular or elliptical with the length equal to or less than three times the width.

As confirmed by ASME, 'surface conditions' can produce PT indications which may initially appear rejectable. ASME addresses this issue by specifically permitting minor metal removal to address indications of this nature.

Accessibility for Examination: As described in the preceding paragraphs, as-welded surfaces pose unique challenges to the PT process. Careful removal of penetrant from valleys between weld beads is essential for accurate EFR PT, and this process can be challenging. EFR repair welds are located in the high radiation environment within the Reactor Pressure Vessel head, and radiation controls require strict limitations on entry times. Work near the surface of the RPV head, which is an inherent aspect of EFR PT's, increases radiation exposure levels. The welds themselves are located overhead, requiring the PT examiner to reach upward and apply considerable pressure to the surface of the weld, in order to achieve effective penetrant cleaning. Accessibility to these welds may be limited by thermal sleeves, guide funnels, and other obstructions, any of which increase the difficulty of the examination. These factors combine to increase the difficulty of precise implementation of the PT process, and introduce an inherent level of variability in the examination process. This inherent variability may result in differences in examination results from one examination to the next, even when no changes have occurred in the weld surface. Variability in the PT examination process is unavoidable, and may lead to differences in PT examination results. It is well known that, although these differences exist, they do not affect the functional integrity of the embedded flaw repair, or any other pressure boundary structure. If they did, the ASME code would not allow this flexibility. This is one of the most important reasons that the EFR requirement for PT should be eliminated.

7. BRAIDWOOD PENETRATION 69 RESULTS:

In 2012, Westinghouse implemented an Embedded Flaw Repair (EFR) to mitigate flaws in RPV Head Penetration P69 at Braidwood Unit 1. This repair weld was successfully installed, accepted by liquid penetrant (PT) testing, and the unit was returned to service. After one cycle, PT examination was re-performed on the P69 EFR as required. This examination identified 27 PT indications.

All indications were rounded; none were linear. Of the 27 indications, 5 were non-relevant (i.e., <1/16" diameter), and 9 were acceptable (i.e., not rejectable in accordance with ASME Section III PT acceptance criteria). The remaining 13 rounded indications were deemed rejectable and required remediation. Minor grinding completely removed two of these welding defects, leaving 11 that required additional remediation. Continued grinding removed the remaining welding defects, and localized manual welding was performed where it was necessary to restore EFR thickness. Final PT accepted these localized weld repairs.

As explained elsewhere in this report, a number of factors can contribute to detection of PT indications in previously accepted EFR weld surfaces, and any of these factors may have played a role in this application. An exact explanation regarding the nature/cause of these PT indications is not possible. Lacking other exculpatory evidence, it must be acknowledged that there were 11 EFR weld defects in Penetration 69 requiring excavation, and application of three layers of weld metal. The nature and extent of these welding defects is evidenced by the extent of the repair effort required to mitigate each. This repair effort was localized and limited in extent, demonstrating that none of these 11 welding defects adversely affected the EFR's continued suitability for service. Each flaw has subsequently been removed (with removal verified by PT examination) and repaired. No degradation of the original Alloy 600/82/182 material was identified during any of these repairs.

8. SERVICE HISTORY OF EMBEDDED FLAW REPAIRS AT BYRON AND BRAIDWOOD PLANTS

Table 2 provides a summary of the repair history of the head penetrations at Byron and Braidwood units. No indications have been found in Braidwood 2, but the other three units have had indications, and therefore embedded flaw repairs have been performed.

In reviewing Table 1, it becomes clear that there is a cost to the PTs that have been carried out as an additional requirement of the repair methodology. Also, when indications are discovered and grinding or welding is required, the man-rem dose increases significantly. This dose needs to be compared with the benefits obtained by the process.

Since no PWSCC flaws have been found, the cost, once welding flaws have been eliminated, is not justified. In light of the service experience of Alloy 52 welds, which will be discussed below, PWSCC is not likely to occur in the remaining operating life of the plant.

9. SERVICE HISTORY OF EMBEDDED FLAW REPAIRS AT BEAVER VALLEY PLANT

Table 3 provides a summary of the repair history of the head penetrations at Beaver Valley Units 1 and 2. The head at Unit 1 was replaced in 2006, so the history is rather short, but that has not been the case for Unit 2.

Review of Table 3 further supports the conclusion that the implementation of penetrant exams for the embedded flaw repair has been costly, in terms of radiation exposure. Although there were several cases where grinding was required to eliminate the PT exam indication, there is no evidence that the grinding extended beyond the repair, into the original base metal. As with Byron

and Braidwood above, the dose associated with grinding and/or welding of these already completed repairs is significant, and provides no added value.

Beaver Valley Unit 2 implemented zinc addition to the primary coolant in October of 2010, and the zinc deposits have been building since that time. The progress of the zinc buildup on the primary system surfaces is measured in terms of ppb-months, which is the product of the concentration of zinc in the chemical mitigation, and the time over which it has been applied.

By the end of November 2016, the plant is expected to have reached 300 ppb-months[6], at which time significant chemical mitigation will have been achieved. This will benefit the resistance to cracking in the head penetration materials significantly.

10. RESISTANCE TO CRACKING OF ALLOY 690 AND ITS ASSOCIATED WELDS

Alloy 690 is known to be much more highly resistant to PWSCC than Alloy 600. This conclusion is also true for its associated welds, Alloy 52 and 152, and results from increased resistance to crack initiation, as well as crack growth.

From the standpoint of crack initiation, there are no known incidents of PWSCC for Alloy 690 materials in service. While this does not prove that the material will not initiate cracks, it does argue strongly that the material is much more resistant than Alloy 600. One of the most challenging locations for either Alloy 600 or Alloy 690 is the steam generator, where the use of Alloy 600 has been prevalent since the earliest steam generators. Leaks were observed in the original Alloy 600 steam generator tubing in several plants after the first few fuel cycles. The leakage and detected SCC cracks led utilities to replace steam generators when the percentage of plugged and degraded tubes rose to levels that caused operational and economic difficulties. As a result, some Alloy 600 steam generators were replaced within 7 years of service and as little as 3.6 EFPY of operation. Conversely, Alloy 690 steam generator tubes have been in service since 1989, a period now exceeding 25 years, with no observed stress corrosion cracking.

Looking at this susceptibility another way, one could compile the 'effective degradation years' (EDY) when cracking occurred for the two materials. An effective degradation year has been defined as one effective full power year at 600°F (316°C) [1]. Looking at the service experience from this point of view, we see that the earliest steam generator replacement occurred in Alloy 600 mill annealed after 4 EDY due to extensive SCC problems, while the longest service for an Alloy 690 steam generator has been over 30 EDY, with no cracking.

In the US fleet of PWRs, 59 PWRs started operation with mill annealed Alloy 600 steam generator tubes. As of the end of 2009, 52 of those 59 PWRs have replaced their steam generators, principally due to stress corrosion cracking issues. Forty-one of those utilities have replaced their steam generators with new steam generator tubes with thermally treated Alloy 690 tubes. Considering that there are typically 8000 to 20000 steam generator tubes in a PWR and multiple high stress locations in a single tube, the Alloy 690 operating experience is impressive. The remaining replacement steam generators and some 10 original steam generators were tubed with thermally treated Alloy 600 that had improved microstructural features and lower residual stresses. The lead plants with this tubing had operated about 35 EDY when the first SCC related plugging operations occurred. The operation of thermally treated Alloy 690 tubing would be expected to be significantly improved over the Alloy 600 TT.

Based on the above, there is at least a 27 calendar year lead time which would provide advanced warning of any potential trouble for Alloy 690. Similar service experience has been recorded for Alloy 152/52 welds, except that the first weld went into service in contact with a primary water environment in 1994, about five years later. Therefore, operating history provides evidence of at least 22 years of crack-free service for Alloy 152/52 welds.

From the standpoint of crack growth, it is clear that PWSCC has been observed in laboratory tests for Alloy 690 in the standard PWR environment. Experimentally, it is difficult to get a crack to initiate, and also very difficult to keep the crack growth going long enough to obtain a measurement. The only successful attempts have employed a fatigue pre-sharpened crack, and the growth rates that have been obtained are about two orders of magnitude slower than that of Alloy 600 [2].

Therefore, we can conclude that these materials are very highly resistant to PWSCC. Although cracking can be measured, crack initiation has not been seen in service or in the lab, and if a flaw does not initiate, it will certainly not propagate.

11. DISTORTION EFFECTS OF THE EMBEDDED FLAW REPAIR PROCESS

One factor which can enhance the PWSCC growth rate of both Alloy 690 and Alloy 52/152 welds is cold work [2]. Although cold work has not been purposely applied, analytical work was recently completed to quantify the amount of distortion introduced by the EFR process.

The embedded flaw repair was developed, and continues to function as an effective SCC-resistant barrier between the RCS water and the SCC-susceptible J-weld and CRDM tube. The repair is not intended to be structural, and therefore does not need to meet ASME Section III requirements. It is also important to mention that there are no Section III design requirements for residual stresses, since they do not affect potential failure (even though they do affect crack growth).

That said, however, great care was taken in the design of the repair technique, and especially the weld thickness of the EFR, to minimize any distortion of the tube as a result of the welding process, and the repair has been effectively applied to many head penetrations over the past 20 years. Since it is well known that cold work can degrade the SCC resistance of Alloy 52/152 welds, it is important to examine the amount of distortion imposed by the embedded flaw repair. To investigate this issue, a detailed analysis was recently completed for the repair method, as applied to an operating plant [4]. The maximum distortion of the tube ID was estimated to be 0.01 inch from this analysis. Measurements were made of the actual distortion of the tube after the embedded flaw repair was actually completed, and the maximum distortion of the tube was determined to be less than 0.1 mm, or 0.0039 inch [4].

Therefore it can be concluded that the entire repair causes little or no distortion or cold work of the tube. A small area of welding to refill the area removed by grinding would cause even less distortion, and would therefore be of no concern.

12. SUMMARY AND CONCLUSIONS

The embedded flaw repair (EFR) process has been described in detail, and it was pointed out that the requirement for PT of the OD of the repair surface was not part of the original proposed inspections, but was added as part of the Safety Evaluation Report for the process. At the time of the original implementation of the generic relief request, the UT leak path examination was not accepted, but now it has replaced the need to even examine the J-groove welds.

The summary provided in this report indicates excellent service performance of Westinghouse Embedded Flaw Repairs. The penetrations with PT indications represent a relatively small portion of installed EFR welds, and all of the embedded flaw repairs continued to perform their function, which is to protect the susceptible Alloy 600 tubes from the water environment. Each of these penetrations which were found to have indications has subsequently been repaired and PT-accepted. The nature of each of these repairs confirmed no PT indications compromised the integrity or performance of the associated EFR. In each case, each EFR was restored to a fully acceptable condition by minor buffing/grinding and, where needed, limited manual repair welding. In no case was PWSCC identified in these welds. Furthermore, the absence of PT indications for the remaining PT examinations demonstrates that PT indications are not typical in these repair welds. As can be seen in these results, the quantity of PT indications detected on the Braidwood P69 EFR differs significantly from all prior PT examination results, making P69 results atypical.

Significant radiation dose is incurred as the result of each liquid penetrant exam, and this dose is increased by an order of magnitude if grinding or welding is needed to clear the PT indications. Counting the man-Rem dose for just the Beaver Valley and Byron/Braidwood plants, the dose exceeds 85 man-Rem. This dose is not justified in light of the negligible advantage gained with respect to the integrity of the head penetration.

The EFR is a complex repair developed for implementation using entirely remote techniques, so as to minimize man-rem dose. This is counteracted by the requirement for PT every outage. UT inspection of the entire volume of the head penetrations is already required, but this can be accomplished remotely, with minimal exposure. Any evidence of further growth on indications in the susceptible tube material can be obtained from this remote examination.

The resistance to PWSCC of Alloy 52/152 and Alloy 690 continues to be confirmed by testing and operating experience. Currently, at least 22 years of experience exists in the welds with no initiation, regardless of application. Contrast that with only a few years of experience before PWSCC occurred with Alloy 600 and its welds, and the EFR has proven to be a robust process. Efforts are continuing to further improve its reliability.

The first embedded flaw repair to have PT indications (San Onofre Unit 3) has been sampled, and carefully examined, and two key findings emerged. First, it is likely that the protective ligaments failed due to operational stresses or cleaning efforts following the 2006 penetrant examination. The protective boundary provided by the EFR was still intact. Secondly, the evidence obtained confirmed that PWSCC was not present.

Since no PWSCC flaws have been found, and there has been no evidence of new or continued degradation of the original Alloy 600/82/182 material protected by the EFR, the cost of PT exams every outage does not seem to be justified. In light of the service experience of Alloy 52 welds, it does not seem likely that any PWSCC is going to occur in the future, at least for the next 22+

years. Future performance of the EFR can be monitored using the same UT examinations currently performed for the other reactor vessel head penetrations.

13. REFERENCES

1. Bamford, W.H. "Technical Basis for the Embedded Flaw Process for Repair of Reactor Vessel Head Penetrations" WCAP 15987-P, Rev. 2-P-A, December 2003.

2. Bamford, W.H., "Alloy 690 and Weld Metal Reference SCC Growth Rate Models for ASME Section XI" (with Guy DeBoo) in Proceedings Sixteenth International Conference on Environmental Degradation of Materials in Nuclear Power Systems, NACE, 2013.

3. Hyres, J.W., "Final Report: Laboratory analysis of a Boat sample Removed from CEDM #64 at San Onofre," B&W Report S-1456-001, May 2009.

4. Ng, Chris K., "Finite Element Residual Stress Analysis Results for the Yonggwang Unit 3 Outermost Reactor Vessel Control Element Drive Mechanism Penetration Nozzle Before and After the Embedded Flaw Repair Process," Westinghouse Letter report LTR-PAFM-13-43, Rev. 0, April 2013.

5. Gorman, J., "Summary of Available Laboratory PWSCC Initiation Data for Alloys 690, 52, and 152, and Identification of Desired Additional Initiation Data," presented to Alloy 690/52/152 Collaborative meeting, Tampa, FL, November 2013.

6. Jacko, R.J., "Evaluation of the Effects of Elevated pH and Lithium Chemistry on Stress Corrosion Cracking of Primary System Materials for Beaver Valley Unit 2," Westinghouse Letter Report No. MCOE-TR-12-10, Rev. 0, July 17, 2012.

Table 1: History of OD Embedded Flaw Repairs

a,c,e

[ ]

Table 2: Summary of Inspection and Repair History of Embedded Flaw Repairs at Byron and Braidwood Plants

a,c,e

a,c,e

[ ]

Table 3: Summary of Inspection and Repair History of Embedded Flaw Repairs at Beaver Valley Plants

	New Repair	**PT Results**	**Buffing Required**	**Welding Required**	**PT and Repair Exposure**
Unit 1					
1R15	4 Repairs P50 P51, P52, P53	Acceptable after Repairs completed	N/A	N/A	32.0 Rem
1R16		Acceptable	No	No	
1R17 (2006)	Head Replaced				
Unit 2					
2R12	3 Repairs P16, P56, P61	Acceptable after Repairs completed	No	No	N/A
2R13	1 Repair P51	P16 Acceptable	No	No	N/A
2R14	2 Repairs P49, P57	P16 Acceptable P51 Unacceptable	Yes	No	1.323 Rem
2R15		P16 Acceptable P56,P57 Unacceptable	Yes	No	9.435 Rem
2R16	1 Repair P44	P16,P57 Unacceptable	Yes	Yes (P16 only)	6.345 Rem
2R17	1 Repair P41	P16 Acceptable P44 Unacceptable	Yes	No	2.466+ Rem
2R18		P16, P41, P44, P49, P51, P56, P57, and P61 were all Acceptable	No	No	2.401 Rem
					Total: 53.97 Rem

+ Does not include dose for touch-up of P44

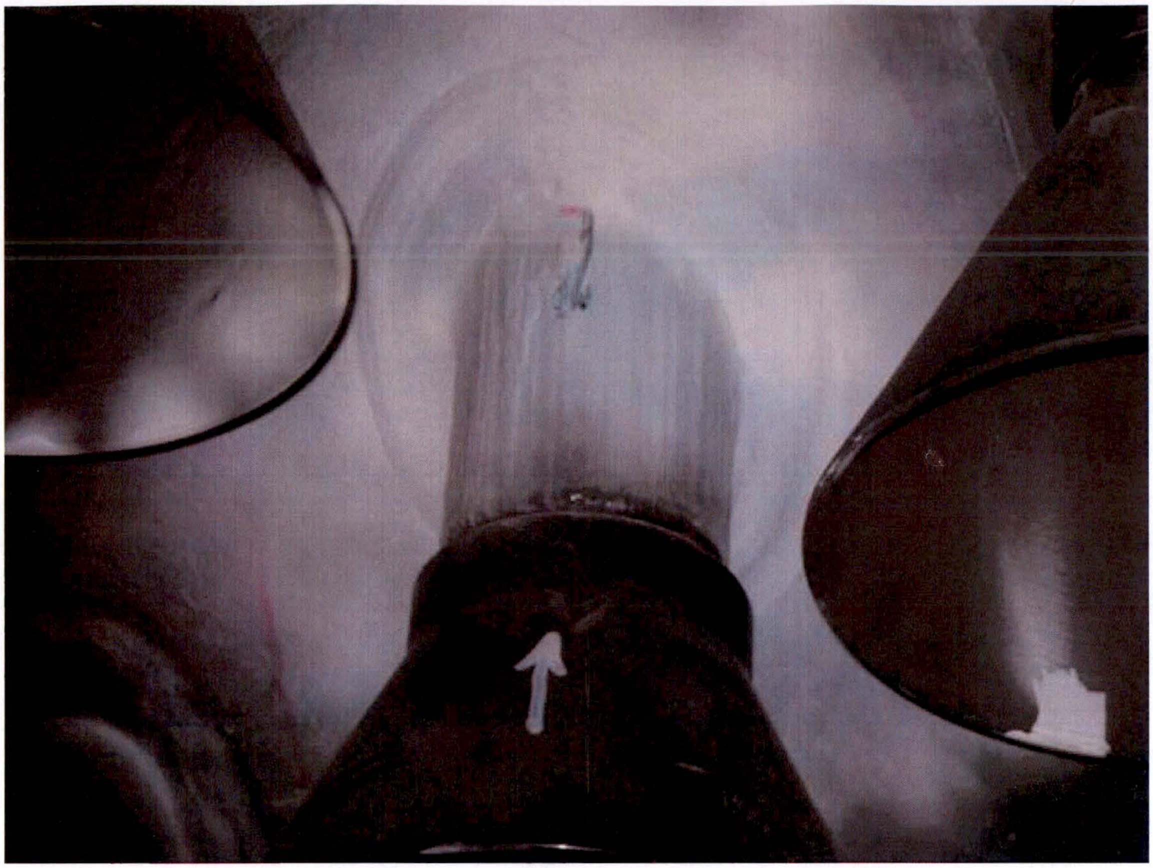

Figure 1: Example of an indication at the boundary of the vertical weld passes on the penetration tube, and the elliptical weld passes on the head

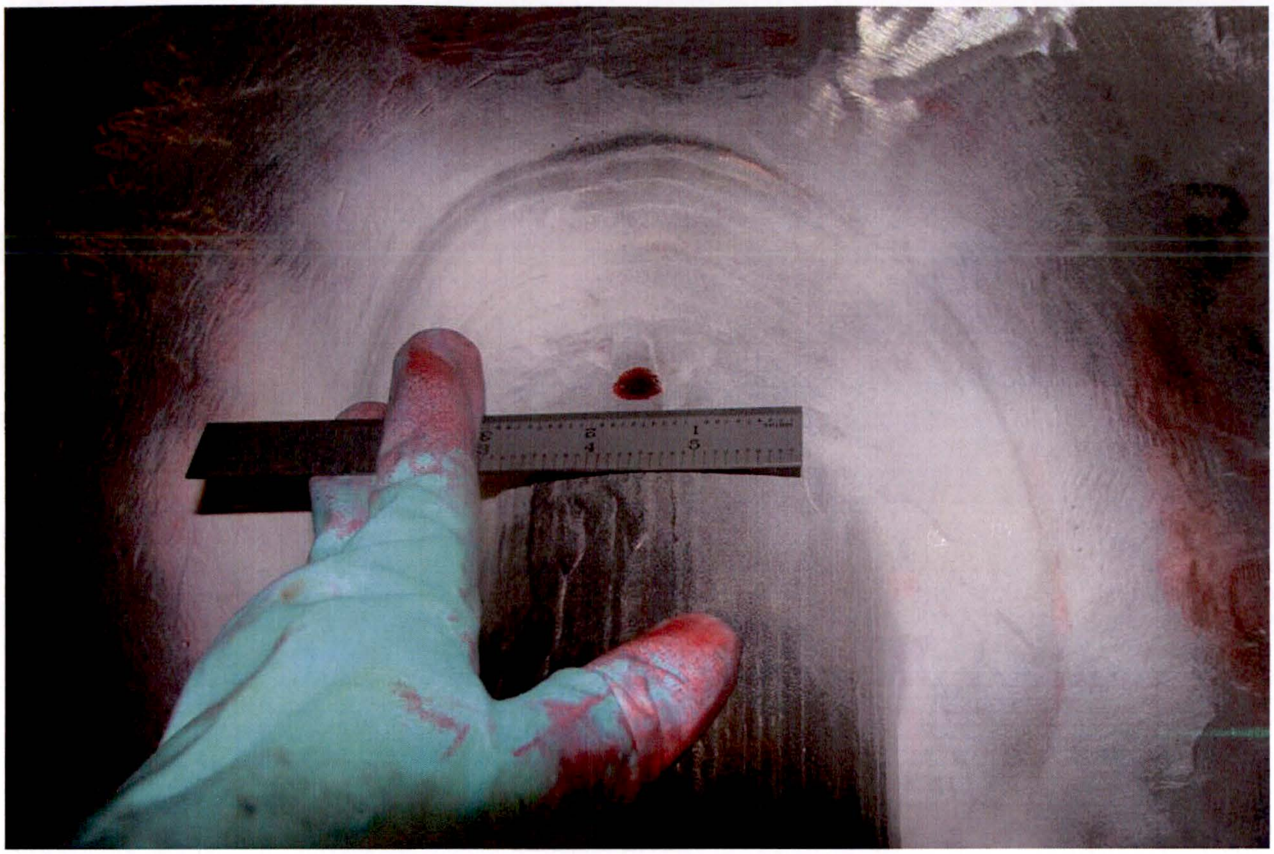

Figure 2: Closer View of the indication of Figure 1

Appendix A
D C Cook Unit 2 Embedded Flaw Repair Experience

One of the best examples of service experience of an Alloy 52 weld repair is provided by the experience of the D.C. Cook Unit 2 embedded flaw repair, because of the length of service provided by this repair. Penetration number 75 at this plant was found to have an inside surface flaw with a depth of approximately 40 percent of the tube wall thickness. This penetration was repaired with the embedded flaw repair process in 1996, and the repair was re-inspected in January of 2002.

The inspection of January 2002 was carried out with both dye penetrant and eddy current testing. The penetrant examination showed no indications, as did the eddy current testing. The eddy current results are more quantitative, and will be discussed here in some detail. The method was demonstrated and qualified under a program in response to the NRC Generic Letter 91-01. The process uses an eddy current coil with high-resolution gray scale imaging, with a magenta response at 50 percent of the amplitude of the calibration notch (0.004 inch long and 0.040 inch deep). This was shown empirically to correspond to the response to actual PWSCC. An example of such a response is shown in Figure 1, which shows actual clustered axial flaws in a penetration tube. The coil design is optimized for high spatial resolution, in order to distinguish individual responses among clusters of cracks, such as those shown in Figure 1.

This eddy current testing and display process was applied to the D.C. Cook penetration 75 in January 2002, and the results are shown in Figure 2. The results show no evidence of cracking after six years of service. Further inspections conducted up until the head was replaced in 2006 also showed no evidence of cracking. Therefore, the ID embedded flaw repair was confirmed to last at least 10 years with no deterioration.

Figure 1
ECT View of Craze Cracking

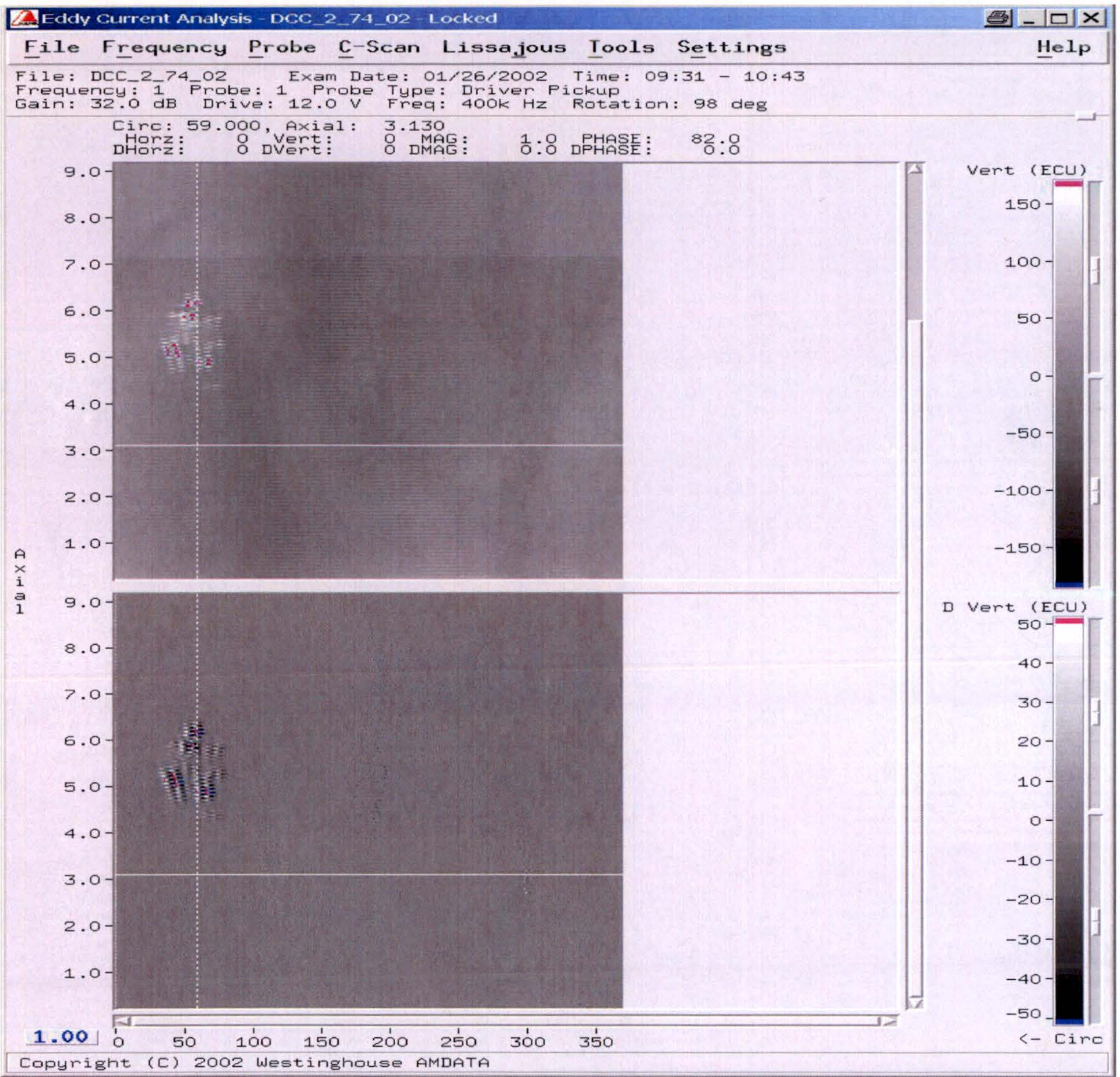

Figure 2
ECT View of 1996 Repair, Taken in 2002