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PNNL-20827

Prepared for the
U.S. Nuclear Regulatory Commission
under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

Improved Criteria for the Detection, Characterization, and Repair of Fabrication Flaws

FA Simonen
SR Doctor

April 2012

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Summary

This technical letter report was motivated by U.S. Nuclear Regulatory Commission (NRC)-sponsored Pacific Northwest National Laboratory (PNNL) research results. The original work objective was to develop density and distribution functions for reactor pressure vessel fabrication flaws. The work was expanded to include fabrication flaws in dissimilar metal welds and primary circuit piping. There was very little information in the public domain addressing this topic. This work was, therefore, ground-breaking, unique and provided some extremely interesting insights into the characteristics of fabrication flaws in light water reactor components. As PNNL reviewed the research results with NRC staff, it became apparent that the insights gained from this work needed to be made available to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section III, "Rules for Construction of Nuclear Facility Components," and Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components."

PNNL prepared a draft white paper that was presented to ASME Code Sections III and XI at meetings in Hollywood, Florida, during September 2002. The response from the Code committees was that this work was interesting but there was little motivation to look into this topic and assess how to upgrade inspection and repair requirements. A paper describing the results of the work at PNNL was published in the proceedings of the 17th *International Conference on Structural Mechanics in Reactor Technology,* August 17–22, 2003, Prague, Czech Republic. Recently, there has been a revised interest in this topic as a result of flaws being discovered in certain components at operating nuclear power plants which emanated from repaired areas, and the new nuclear power plants that are under construction or are being proposed. This white paper was updated to reference all of the latest published PNNL work on this topic.

This report was not designed to recommend specific Code changes. It suggests some ideas that should be considered that range from no changes to a fitness-for-service evaluation before any repair can be implemented to ensure that the selected repair option results in the minimum impact on the structural integrity of the component. It also provides some discussion on each of the options.

Acknowledgments

The original work was conducted under JCN N6604 with Debbie Jackson as the RES Program Manager and now it is being published under JCN N6398 with Wallace Norris as the RES Program Manager. The authors wish to thank the NRC staff for their comprehensive review and comments which have clarified this report and provided valuable input regarding the NRC perspective on use of these research results. Fred Simonen is now retired from PNNL. Thanks also to Kay Hass for working on the white paper and making it into a technical letter report.

Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
NDE	nondestructive examination
NRC	U.S. Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
PTS	pressurized thermal shock
PVRUF	Pressure Vessel Research Users' Facility
PWR	pressurized water reactor
PWSCC	primary water stress corrosion cracking
RES	(NRC) Office of Nuclear Regulatory Research
RT	radiographic testing
UT	ultrasonic testing
VCSNS	V. C. Summers Nuclear Station

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1.0 Introduction

During May 2000, Pacific Northwest National Laboratory (PNNL) received a request to support the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) Operating Plan for Reactor Safety Research. The request was stated as follows:

> *"Complete a white paper for ASME presenting the technical basis to change the inspection criteria/flaw evaluation methods presently in the code. The white paper would present the empirical data from the generic flaw distribution work, which states that repairing flaws in welds/base metal introduces larger, more complex flaws. A fracture mechanics evaluation would present a basis to show that certain types of flaws do not need to be repaired."*

PNNL's response to this request was the development of a draft white paper. The next steps were a comprehensive review of the white paper by RES staff, followed by discussions of these review comments, and final revisions to the draft white paper by PNNL. The revised white paper was presented and discussed at meetings of Section III (Rules for Construction of Nuclear Facility Components) and Section XI (Rules for Inservice Inspection of Nuclear Power Components) of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (ASME Code) in Hollywood, Florida, during September 2002. The ASME Code Section III committee chose to not make any Code changes at that time. The information in the white paper was published at a conference (Doctor et al. 2003).

It has been realized that many of the unacceptable flaws that have been discovered during the operation of nuclear power plants emanated from repaired areas due to the high resultant stress fields and artifacts of the welding process. To address this, Section III is currently considering a revision to the ASME Code that would no longer require automatic removal of any fabrication flaw but allow benign, subsurface flaws to remain in place. Because of the recent renewed interest in the potential deleterious effect of repairing benign, subsurface welds, the original work is being updated and published as a technical letter report, as it could be used to enhance the structural integrity of pressure vessel and piping components.

2.0 Background

The rules of ASME Section III govern design and fabrication of nuclear pressure vessels and piping. These rules require radiographic testing (RT) of welds in order to detect flaws that may exist in the welds. If the lengths of the flaw indications as determined from RT images exceed the allowable lengths specified in Section III, the Code requires repairs to the affected welds, and reexamination to ensure that the repaired welds are free of unacceptable indications. Often the requirements in Section III are referred to as a "workmanship standard."

The inspection and repair of components should have as their highest-level objective the prevention of "unacceptable" failures during the operating life of the components. As used here, "unacceptable" means failures that compromise the structural integrity of safety-related components, leakage from components other than from joints, or that would preclude a component from performing its safety-related function. Such rules should be sufficiently conservative to ensure the removal of all flaws with a potential to cause failures, while not requiring repairs for flaws that have no potential to impact structural integrity. Repair procedures should minimize the possibility that the repair process can introduce structurally significant and undetectable flaws that were not present in the original weld. Code rules should recognize that small flaws are inherent to welding processes even for high-quality welds, and that the production of a totally flaw-free weld is not a realistic goal.

The Section III design and fabrication rules have been successfully applied since the 1960s. Operating experience has in general shown a high level of reliability. Failures that have occurred have rarely been attributed to fabrication flaws. Nevertheless there are good reasons to revisit the Section III inspection and repair rules because:

1. The sensitivity of nondestructive examination (NDE) methods including ultrasonic methods have significantly improved since the 1960s; these methods can ensure reliable flaw detection and accurate characterization of the sizes, shapes, and locations of flaws to an extent not possible with past and present RT inspections.
2. ASME Section XI has developed fracture mechanics approaches that allow more realistic evaluations of the impact of flaws on structural integrity.
3. Codes and standards for vessels and piping outside the nuclear power industry have moved to flaw evaluations that are based on fitness-for-purpose considerations.
4. There are now well-documented cases that show that repairs have introduced flaws into components that are more significant to structural integrity than the original flaws that caused the repairs; furthermore, these repair flaws possessed characteristics such that they were very difficult to detect with RT procedures.

3.0 Summary of ASME Sections III and XI Inspection and Repair Criteria

ASME Section III provides rules for the design and fabrication of nuclear pressure boundary components. Under these rules all welds are inspected by radiograph methods, and repairs are required if indications exceed prescribed length dimensions. These length dimensions are based on workmanship standards. Repairs must be made without regard to the potential effects that the flaw indications may have on structural integrity. Section III has a provision for owner-specified preservice examinations by ultrasonic testing (UT) methods, in which case the examinations and acceptance of flaws are in accordance with Section XI. These UT examinations are in addition to and do not replace the RT examinations of Section III. Section III has Code Case N-659-2, "Use of Ultrasonic Examination in Lieu of Radiography for Weld Examination, Section III, Division 1," that allows the use of ultrasonic examination in lieu of radiography for weld examination. However, this Code Case does not apply fracture mechanics-based evaluations for the acceptance of flaws, but continues to reference the length-based acceptance criteria of the Section III RT examinations. The NRC has not approved the use of this Code Case. Part of the basis given by the NRC staff at ASME committee meetings is that research is currently being conducted on a number of issues with respect to using UT to replace RT. While preliminary results suggest that replacement of RT with UT may be feasible, the interchangeability of these techniques has not yet been fully demonstrated, UT acceptance criteria for fabrication/construction weld inspection have not yet been adequately defined, and the applicability of UT in the presence of high levels of acoustic noise such as that found in austenitic materials is not fully understood. The impact and implications of the expanded examination volume (full-thickness) required for UT for fabrication/construction also needs to be more thoroughly assessed.

ASME Section XI provides rules for inspections performed on a periodic basis after components have been placed into service. The volumetric inspections primarily use UT rather than RT methods. These UT examinations may therefore detect fabrication flaws that were not detected by radiographic examinations or there may be service-induced flaws present. Section XI requires repairs on the basis of structural integrity evaluations, which take into account the measured sizes and locations of detected flaws. Section XI provides tables of acceptable flaw sizes, which are based on structural integrity calculations that assume stresses at the flaw locations equal to the full Code-allowable design limits. Because flaw locations are seldom stressed to the full Code-stress limits, detailed fracture mechanics evaluations can also be performed to accept flaws without repair. These acceptable flaws can often be substantially larger than the bounding flaw sizes listed in the Section XI tables.

The inspection and repair criteria of Sections III and XI were developed at different times, for different purposes, and were based on different philosophies. Flaws that may be unacceptable from the standpoint of Section III can be readily accepted by Section XI. The inspection methods (RT and UT) have different capabilities, such that one method may detect flaws that are undetectable by the other method. From the standpoint of characterization of flaw dimensions and locations, UT methods can offer significant advantages over RT examinations. RT examinations provide measurements of flaw lengths, but no information on through-wall dimensions and radial locations of flaws relative to the vessel surfaces, which are critical inputs to structural integrity evaluations.

4.0 Examples of Flaws and Structural Damage Caused by Repairs

The following describes some cases to illustrate the potential for repairs to introduce structural damage into a repaired component.

4.1 Vessel Flaws

The original white paper from which this technical letter report was written was motivated in large measure by findings of research performed by PNNL for the NRC. The objective was to develop density and distribution functions for reactor pressure vessel fabrication flaws. The PNNL strategy included getting representative material from all the nuclear steam supply system suppliers and examinations of material taken from reactor pressure vessels of cancelled nuclear power plants (Schuster et al. 1998; Schuster et al. 1999; Schuster et al. 2000; Jackson et al. 2001). The material was examined in detail both by high-sensitivity nondestructive and destructive methods to detect, classify, locate, and measure the sizes of fabrication flaws in the welds and base metal regions of vessels. The methodology developed by PNNL is documented in NUREG/CR-6989 (Schuster et al. 2009). The examinations covered vessels fabricated from the middle 1960s to the early 1980s and were vessels considered to be typical of those that are currently in use at operating nuclear power plants in the United States.

The PNNL studies on fabrication flaws provide some interesting insights into the flaw origins. Figure 1 is a cross section of a pressurized water reactor (PWR) circumferential weld at the transition to the nozzle shell course. It was found by looking at the construction records for three reactor pressure vessels that more documented repairs were present at locations where the welding becomes more challenging as a result of geometry conditions. Because of the high importance of flaws located in repairs, PNNL documented in a single report these repair flaws from all reactor pressure vessel and piping materials inspected in the PNNL studies (Schuster et al. 2008).

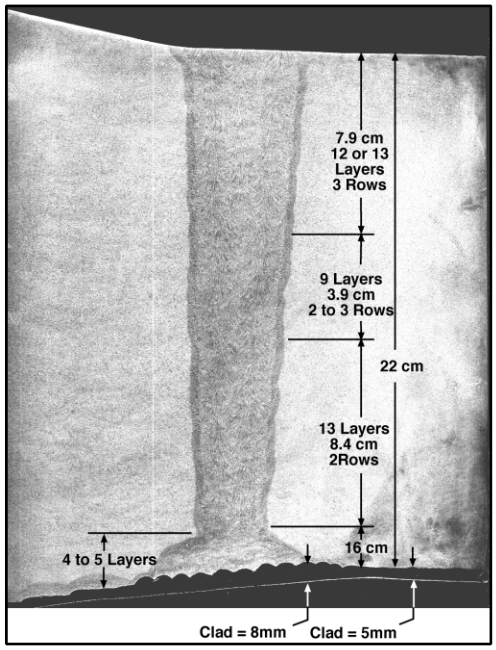

Figure 1. Cross Section of Thickness Transition Single V Weld for PVRUF Vessel

The work showed that the majority of the flaws with a measurable through-wall dimension were located in the welds rather than base metal. About 95% of the welding flaws were located along the weld fusion lines. Examples of complex fabrication flaws are shown in Figures 2 and 3. Figure 2 shows an area where contamination was left in during back gouging resulting in a complex flaw that contained inclusions, slag, porosity, lack of fusion, and a crack. The largest flaws detected were validated and found to be located in areas where repairs had been conducted. These weld repair flaws were in all cases found to be complex and consisting of inclusions, slag, porosity, and lack of fusion. The repair flaws tended to be located at the ends of the repair cavities and they tended to be three dimensional in the sense that they extended around the end of the repair cavity.

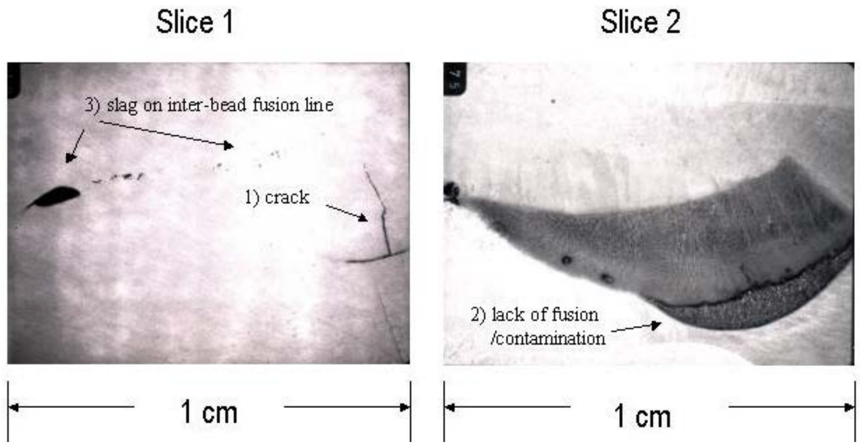

Figure 2. Complex Fabrication Flaw as a Result of Contamination

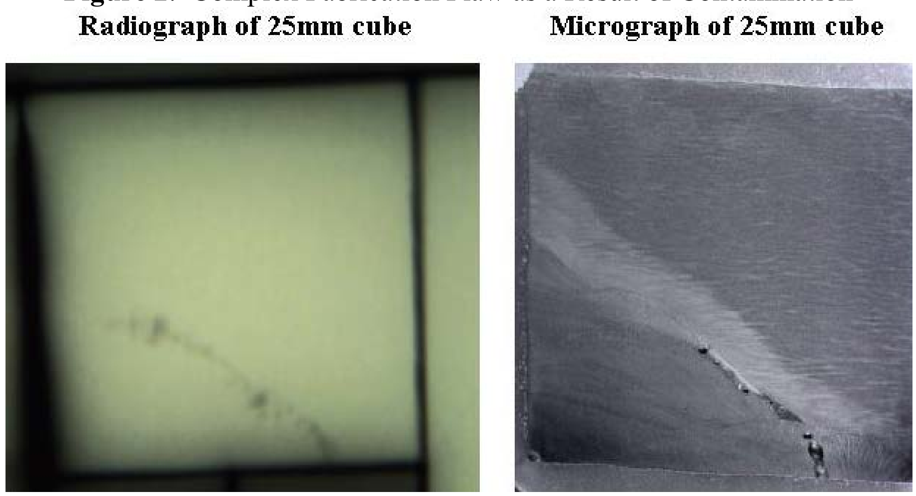

Figure 3. Validated Complex Repair Flaw in the Beltline Weld of PVRUF

The very sensitive examinations showed that there were a large number of small flaws in all of the examined welds; these small flaws were too small to have any impact on the structural integrity of the vessel. Even high-quality nuclear welds should be expected to have such flaws and there is no reason to perform repairs for small flaws as there would be no benefit—the repair process would be expected to introduce similar, and sometimes, more significant, flaws.

4.2 Piping Flaws

The failure of the main coolant piping weldment at V. C. Summers Nuclear Station (VCSNS) in 2000 was analyzed extensively because this was the first through-wall flaw that has been found in the main coolant piping of a PWR plant (illustrated in Figure 4). An extensive root cause investigation was conducted on the “A” loop hot leg weldment that was cut out. The Root Cause Report (Moffatt et al. 2001) states that:

1. “Extensive repairs on the VCSNS reactor vessel “A” hot leg nozzle to pipe weld created high welding residual stresses in a material (Alloy 182/Alloy 82) and in an environment known to cause Primary Water Stress Corrosion Cracking (PWSCC).”
2. “Neither the codes, standards nor the welding process recognized or required consideration of the cumulative effect of multiple repair weldings and weld grinding in the creation of high residual stresses.”

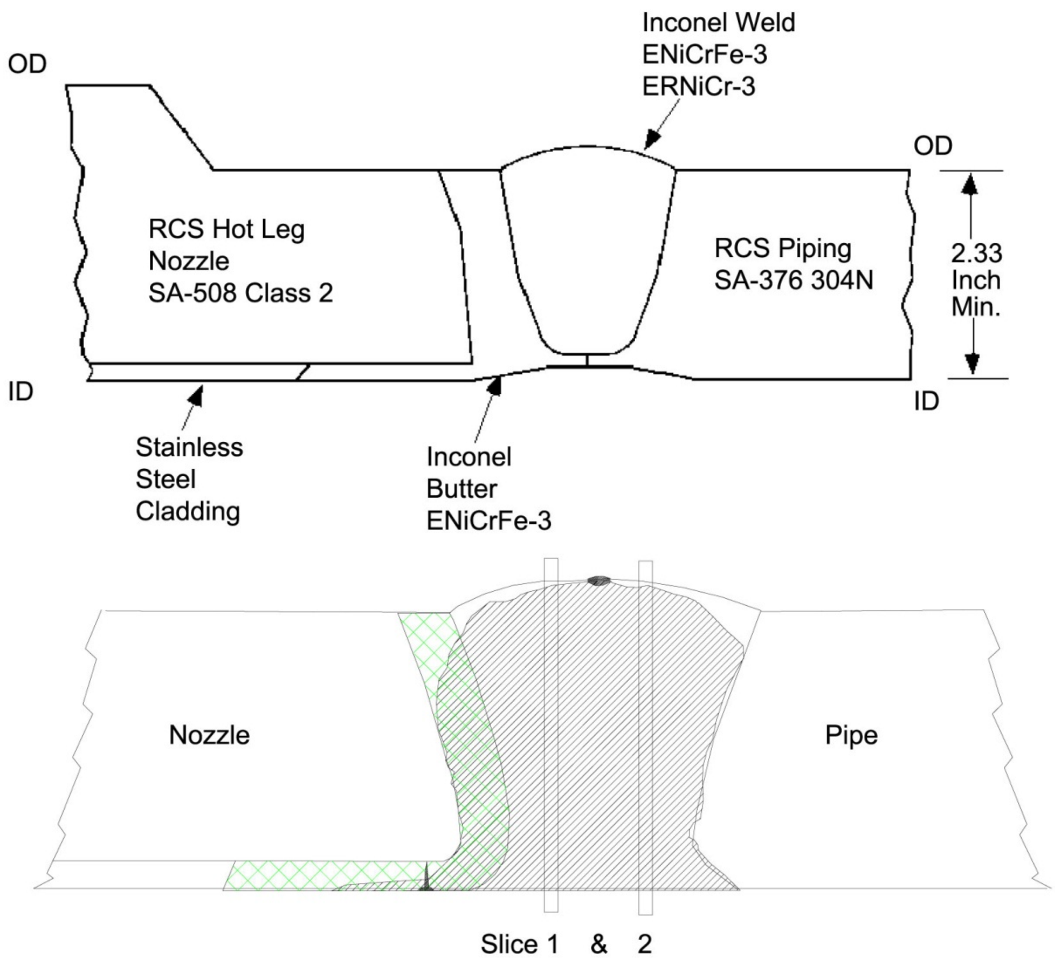

Figure 4. Weld Failure at V. C. Summers Nuclear Station with the Top Image Illustrating the Weld Design and the Lower Image Depicting in the Hatched Area the Through-Wall Crack

The VCSNS cracking incident shows that weld repairs have the potential to introduce several types of damage that can adversely impact the structural integrity of a component. Weld repairs can result in residual stresses that would not be present in the original component. These stresses could be tensile in nature and at higher levels than the stresses present before the repair. In some cases, compressive residual stresses could be replaced with tensile residual stresses. Weld repairs also have the potential to introduce local microstructures that could adversely impact the structural integrity of the component. The material in the region of repair welds will experience unique thermal mechanical histories that could result in atypical and potentially degraded material properties and microstructures. Such material could be of low toughness and sensitive to flaw growth or susceptible to damage mechanisms such as stress corrosion cracking. Current Code rules can dictate repairs for RT indications in cases where the detected flaws have no potential to degrade the structural integrity.

5.0 Inspection/Repair Approaches as Practiced in Other Industries

The technical bases for inspection methods and criteria for repairs of degraded components have evolved in the nuclear power and other industries. ASME Section XI since the 1970s has allowed degraded components to continue operation if engineering evaluations demonstrate that the detected degradation will not impact structural integrity over the remaining life of the component. The ability to perform the needed engineering evaluations has improved over the years with advances in the fields of nondestructive testing, fracture mechanics, and material sciences.

5.1 ASME Section VIII Code Case 2235-3

In 1996, ASME Section VIII approved Code Case 2235 to allow for ultrasonic examination in lieu of RT examinations of Section VIII Division 1 and Division 2 vessels whose wall thickness exceeds 4 inches (101.6 mm). There have since been two revisions to make clarifications and to extend the applicability down to wall thicknesses of 0.5 inch (12.7 mm). Yoemans and Davidson (2001) report on the first Code-compliant inspection performed in accordance with the provisions of the Code Case. The Code Case requires state-of-the-art inspections including automated computer data acquisition and certification of personnel. Flaw acceptance criteria are based on the criteria of ASME Section XI.

5.2 Petrochemical Industry

The petrochemical industry has introduced the concept of "fitness-for-purpose" to evaluate the need to implement repairs and replacements. A review of the American Petroleum Institute publications, codes, and standards could provide useful information and insights into potential improvements to ASME Nuclear Codes and Standards.

5.3 Gas Transmission Piping

Gas transmission piping is within the scope of U.S. Department of Transportation regulations. Such piping has large numbers of girth welds for which RT examinations are required. A Canadian study (Wagner and Patchett 1991) reported that about 30 percent of these welds are subject to repairs following inspections. The construction of the Alaska pipeline encountered many difficult decisions regarding RT examinations and whether or not repairs were needed to dispose of RT indications. Jones (1983) presents arguments against field repairs to girth welds. In many cases, linear indications marginally exceeded acceptance standards and were believed to have no significance to the integrity of the pipelines. Repairs required excavation of buried piping, manual repair welding at locations of RT indications, and difficult

RT examinations following the repairs. The detection and repair of minor flaws in the original welds were judged to potentially result in major flaws that could not be detected by RT methods.

6.0 Fracture Mechanics Calculations – Consequences of Large Repair Flaws

Probabilistic fracture mechanics calculations have been performed to evaluate the potential impact of large repair flaws on the probability of failure for reactor pressure vessels and piping components.

6.1 Reactor Pressure Vessel

The significance of repair flaws detected by PNNL in the PVRUF and Shoreham vessels were evaluated by performing probabilistic fracture mechanics calculations with the VISA-II (Simonen et al. 1986) and pc-PRAISE (Harris et al. 1992) computer codes. Flaw distributions shown in Figure 5 in one case included the large flaws found in repair welds and in the other case neglected such flaws. In both cases, the number and sizes of smaller flaws were the same, with the difference limited only to the tail of the flaw depth distribution curve for the larger repair flaws.

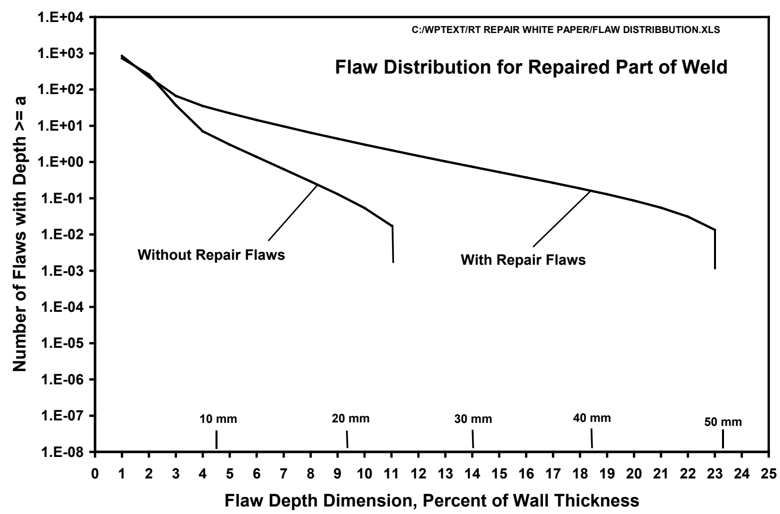

Figure 5. Flaw Distributions With and Without Presence of Repair-Related Flaws

The PNNL calculations predicted failure probabilities for a vessel embrittled by neutron damage. The vessel was assumed to experience a severe pressurized thermal shock (PTS). The fabrication flaws were treated as buried at random locations within the thickness of the vessel wall, such that only a small fraction of the flaws occur near to the highly embrittled inner vessel surface. Figures 6 and 7 present results of the calculations for the PTS transient. Calculated failure probabilities increased as the size of the simulated flaw increased. However, the likelihood for large flaws is very small compared to the likelihood for smaller flaws. The smaller flaws are also quite capable of causing a vessel failure if the small flaw is close to the flaw-sensitive inner surface region of the embrittled vessel. Figure 6 shows that the calculated failure probability of the repair region of the vessel can increase up to a factor of 10 due to the introduction of large flaws by repair welding.

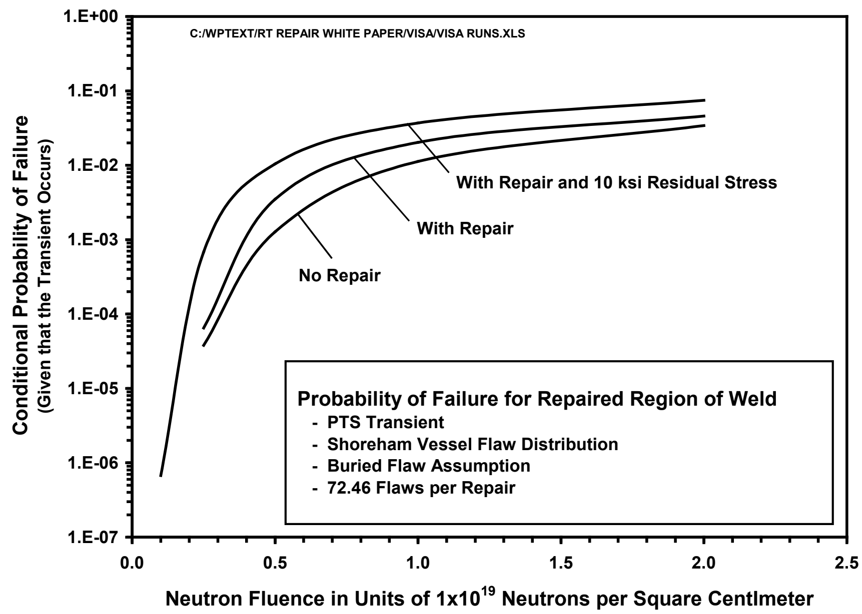

Figure 6. Calculated Vessel Failure Probability for PTS Transient

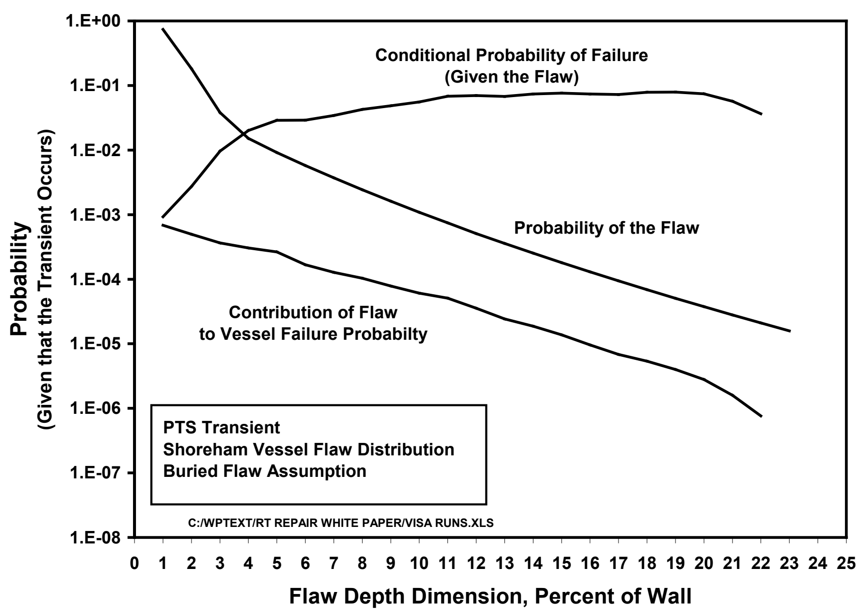

Figure 7. Details of Probabilistic Fracture Mechanics Results That Show Why Large Repair Flaws Make Only a Relatively Small Contribution to Overall Vessel Failure Probability

The calculations in this case show that large fabrication flaws in repairs will increase failure probabilities. Such large flaws will usually not occur in the most embrittled regions, since repairs and these large flaws are randomly distributed, whereas the most embrittled regions will have smaller flaws that could cause a vessel failure. The fracture mechanics model also accounted for a tensile residual stress but lacking any quantitative data on what would be a reasonable value to assume, a value of 10 ksi was chosen to be associated with a repair. Such a residual stress is seen to increase the vessel failure probability about as much as the large repair flaws. This shows the potential importance of residual tensile stresses and requires that further work is needed to develop a quantitative basis for residual tensile stresses associated with repairs.

6.2 Reactor Piping

Flaw distribution data from the vessel examinations were applied to evaluate the effect of large repair flaws on the fatigue life of large diameter pipe welds (24-inch [610-mm] diameter × 2-inch [50.8-mm] wall). When repair flaws were excluded, the flaw distribution has no flaws with depths greater than 50 percent of the vessel wall. Probabilistic fracture mechanics calculations were performed with the pc-PRAISE fracture mechanics code (Harris et al. 1992). Figures 8 and 9 show that large repair flaws can significantly increase the calculated pipe failure probabilities (by a factor of about 100).

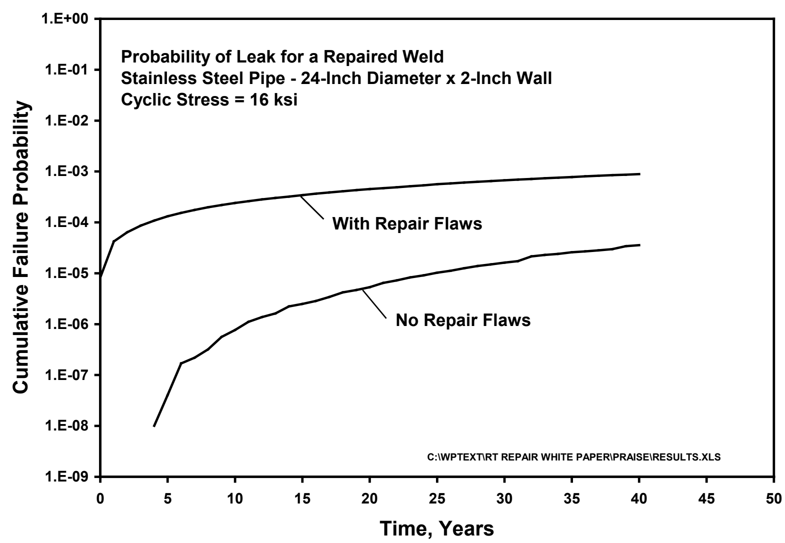

Figure 8. Failure Probability for Piping with Weld Fabrication Flaws

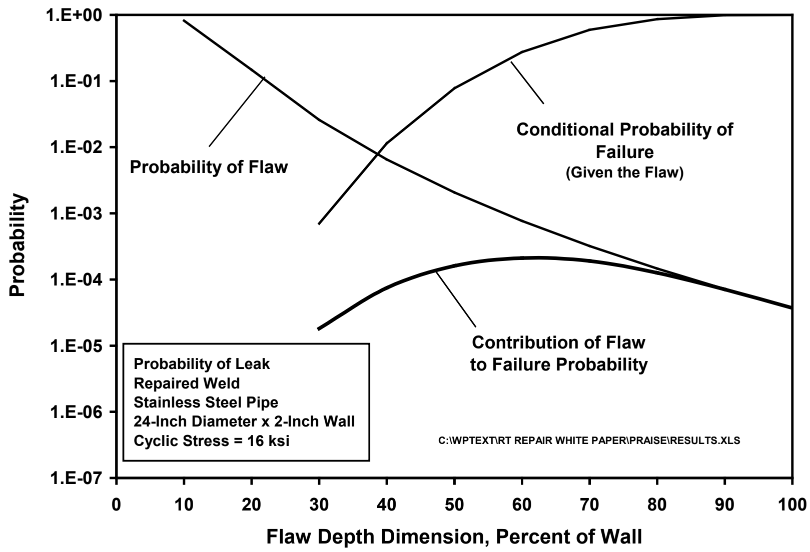

Figure 9. Details of Probabilistic Fracture Mechanics Results That Show Why Large Repair Flaws Make a Larger Contribution to Overall Piping Failure Probability

7.0 Future Approach to Repairs

Based on field experience and the current state of knowledge, it would seem appropriate to conduct a fitness-for-purpose evaluation before any repair can be implemented to ensure that the selected repair option results in the minimum impact on the structural integrity of the component. This approach would take advantage of the progress made in the areas of improved inservice inspections and the ability to evaluate the effects of flaws on the structural integrity. Improved NDE methods make it possible to conduct more sensitive and reliable inspections, which can lead to the detection of flaws that might never have been detected by the methods used in the past. Without the ability to make sound decisions regarding repairs, there could be strong disincentives to the adoption of improved NDE methods.

More information should be collected from the literature, from data bases on component failures (for example, the PIPExp event database does contain fields to capture what is known about failures and their relation to repairs but this database to date has not been analyzed to know how much data it contains or to quantify any relationship), and from contacts with industry experts to establish the number of service failures that have been caused in whole or in part by structural damage introduced by repairs. Information on the circumstances associated with such failures could identify the types of repairs that should be avoided if the detected flaws are benign or if repair procedures are particularly difficult. For example, it might be best to avoid repairing small flaws by the common method of a local excavation (grind out) followed by manual welding to fill the volume of the resulting cavity. If the flaw of concern is sufficiently large to be structurally significant, the recommended repair could be a full removal of the weld, and repair welding by the original welding process.

Section III currently allows no options other than to perform a repair, even if the flaws can be demonstrated to be of no consequence to structural integrity, and even if the repairs are difficult to perform and are likely to introduce significant structural damage in the form of new flaws, adverse residual stresses, degraded material properties, or undesirable microstructures. While the NRC has expressed some concerns with the robustness of certain requirements in the ASME Code fitness-for-service proposed requirements, industry representatives have generally approved of the proposed approach as a means for addressing unnecessary repairs.

Explicit guidance on which repairs should be made or are to be avoided when radiographic indications are found to exceed current Code limits should be developed. The guidance would describe the further examinations (ultrasonics) to better characterize the locations and sizes of flaws associated with RT indications. Other guidance would address structural integrity evaluations to determine the potential of detected flaws to impact the structural integrity of components, and the need for and the nature of future inspections to ensure that the detected flaws do not increase in size during the service life of the component.

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