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Improved Criteria for the Repair of Fabrication Flaws

S.R. Doctor, G.J. Schuster and F. A. Simonen
Pacific Northwest National Laboratory[1], P.O. Box 999, Richland, Washington 99352

ABSTRACT

Section III of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for nuclear power plant components requires radiographic examinations (RT) of welds and requires repairs for RT indications that exceed code acceptable sizes. This paper describes research that has generated data on welding flaws, which indicated that the largest flaws occur in repaired welds. The fabrication flaws were detected in material removed from cancelled nuclear power plants using high sensitivity Nondestructive Examination (NDE) and validated by complementary NDE and destructive testing. Evidence suggests that repairs are often for small and benign RT indications at locations buried within the vessel or pipe wall. Probabilistic fracture mechanics calculations are described in this paper to predict the increases in vessel failure probabilities caused by the repair-induced flaws. Calculations address failures of embrittled vessel welds for pressurized thermal shock (PTS) transients. In this case small flaws, which are relatively common, can cause brittle fracture, such that the rarely encountered repair flaws of large sizes gave only modestly increased failure probabilities. The paper recommends the use of more discriminating ultrasonic examinations in place of RT examinations along with repair criteria based on a fitness-for-purpose approach that minimize the number of unjustified repairs.

KEY WORDS: nondestructive testing, nondestructive examination, nondestructive evaluation, fabrication flaws, pre-service examination, construction codes and standards, fracture mechanics.

INTRODUCTION

The rules of ASME Section III [1] govern the design and fabrication of nuclear vessels and piping components, and have the objective of ensuring the high levels of structural integrity needed for the safe operation of nuclear power plants. Radiographic examinations are performed to detect flaws that may be created in welds as they are fabricated. 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. The requirements in Section III are referred to as a “workmanship standard”, because they are not based on detailed structural integrity or fracture mechanics evaluations.

These are a number of considerations that should guide the development of code rules for the inspection and repair of components. The highest-level objective should be that of preventing pressure boundary failures. This requires rules that are sufficiently conservative to remove all flaws with a potential to cause structural failures, but not so conservative as to require repairs for flaws that have no potential to impact structural integrity. In addition repair procedures should minimize the possibility for the repair process to introduce structurally significant, and undetectable flaws not present in the original weld. Code rules should also recognize that small flaws are inherent even to high quality welding processes, and that flaw-free welds are not a realistic goal.

The Section III design and fabrication rules have been successfully applied since the 1960s. Operating experience has shown a high level of reliability, with service failures rarely being attributed to fabrication flaws. Nevertheless it is timely to revisit the Section III inspection and repair rules because:

1. The sensitivity of NDE methods including ultrasonic methods have significantly improved since the 1960s; these UT methods can now ensure reliable flaw detection and accurate characterization of the sizes, shapes and locations of flaws to an extent not possible with RT inspections,

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2. ASME Section XI (ASME 2001b) [2] has developed fracture mechanics approaches that allow more realistic evaluations of the significance of detected flaws on structural integrity,
3. Codes and standards used outside the nuclear power industry for the integrity of vessels and piping have been moving to flaw evaluations based on fitness-for-purpose considerations,
4. There are documented cases that show how flaws introduced by repairs into components, for which the repair flaws are more significant to structural integrity than the flaws that caused the repairs; furthermore the flaws introduced by repairs can be very difficult to detect with RT methods,
5. In addition to enhancements to structural integrity, there may be significant cost savings if difficult repairs to large components can be avoided.

The long-term objective of the present work was to identify improvements to the ASME Section III [1] code that will enhance the structural integrity of pressure vessel and piping components. In this paper, after summarizing the current rules in ASME Sections III [1] and XI [2] and in codes used in other industries, we present data from detailed laboratory examinations of welds that show in a statistical manner how repairs can increase the number and sizes of welding flaws. Results of probabilistic fracture mechanics calculations are then presented to show how the introduction of a small number of relatively large repair flaws can impact structural integrity. The paper concludes with a discussion of possible approaches to incorporate UT examinations and improved repair criteria into ASME Section III.

ASME SECTIONS III AND XI RULES

ASME Section III [1] provides rules for the design and fabrication of nuclear pressure boundary components. Under these rules all welds are inspected by radiographic methods, and repairs are required if indications exceed prescribed length dimensions. The length dimensions are based on a "workmanship standard" such that repairs must be made without an evaluation of the potential effects that the flaw indications may have on structural integrity. Section III has an added a provision for an owner to specify a preservice examination by ultrasonic (UT) methods, in which case the examination methods and acceptance of flaws are in accordance with Section XI. However, these UT examinations are in addition to and do not replace the RT examination and repair requirements of Section III. More recently Section III has developed a code case to allow the use of ultrasonic examination in lieu of radiography for weld examination (Code Case N-659 – Use of Ultrasonic Examination in Lieu of Radiography for Weld Examination, ASME Section III). However this code case does not use a fracture mechanics based evaluation for the acceptance of flaws, but continues to reference the length-based acceptance criteria of the RT examinations.

ASME Section XI [2] has rules for inspections performed on a periodic basis after a component is placed into service. Section XI volumetric inspections primarily use UT rather than RT methods because the radiation environment and access conditions of nuclear power plants. These UT examinations may detect fabrication flaws that were not detected by the Section III RT examinations or they may detect service induced flaws. Section XI then requires repairs on the basis of structural integrity evaluations, which take into account the measured sizes and the locations of detected flaws. One evaluation approach uses tables listing acceptable flaw sizes, which were developed on the basis of structural integrity calculations that assumed stresses equal to the full code stress allowables. Because actual stresses are seldom equal to the code stress limits at the location of a detected flaw, detailed fracture mechanics evaluations can also be performed to show that flaws are acceptable without repair. These acceptable flaws can be substantially larger than the bounding flaw sizes listed in the Section XI tables.

It should be recognized that the differing inspection and repair criteria of Sections III and XI were developed at different times, for different purposes, and were based on different philosophies. As a result 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 will not be detected by the other method. In addition, from the standpoint of the ability to fully characterize flaw dimensions and locations, UT methods offer significant advantages over RT examinations. RT examinations only provide measurements of flaw lengths, and no information on through-wall dimensions and radial locations of flaws relative to the vessel surfaces. On the other hand, such information, which is critical as inputs to structural integrity evaluations, is provided by the measurements obtained from UT examinations.

INSPECTION/REPAIR PRACTICES IN OTHER INDUSTRIES

Inspection methods and repair criteria for components with flaws have evolved in other industries, as they have evolved in the nuclear power industry. For example, Code Case 2235 (Rana et al. 2000) [3] was approved in 1996 to allow for ultrasonic examinations in lieu of RT examinations of ASME Section VIII Division 1 and Division 2 vessels with wall thickness of 4 inch or greater. The code case requires state-of-the-art inspections including automated computer data acquisition and the certification of personnel, and includes flaw acceptance criteria that are based on the criteria of ASME Section XI. The applicability of the code case has since been extended down to wall thicknesses of 0.5 inch. Yoemans and Davidson (2001) [4] report on the first code compliant inspection performed in accordance with the provisions of this code case.

FLAWS CAUSED BY REPAIRS

The present paper was motivated in large measure by results from a research program performed at Pacific Northwest National Laboratory (PNNL) for the U. S. Nuclear Regulatory Commission (NRC) and previously reported (Doctor et. al. 1999) [5]. The objective of this research was to develop density and distribution functions for fabrication flaws created during the manufacture of reactor pressure vessel welds.

Weld Examinations

Welds taken from reactor pressure vessels of cancelled nuclear power plants were examined in detail both by high sensitivity nondestructive and by destructive methods to detect, classify, locate, measure and validate the sizes of fabrication flaws in the welds and in base metal regions of vessels (Schuster et al. 1998 [6], 1999 [7], 2000 [8]; Jackson et al. 2001) [9]. The examined vessels were fabricated from the middle 1960s to the early 1980s and as such were typical of vessels currently in use at nuclear power plants in the United States.

The data on fabrication flaws provided insights into the flaw origins. Very sensitive examinations showed a large numbers of small flaws in all of the examined welds, with most of these small flaws being too small to impact the integrity of the vessel. It was concluded that high-quality nuclear welds should be expected to have such small flaws. Repairs for such flaws would be ill advised because the repaired material would have similar flaws. It was also found that about 95% of the flaws created by welding were located along the weld fusion lines. None of these flaws were surface connected. Most significantly, the largest flaws were located in areas where repairs had been conducted, and in all cases these flaws were complex and consisted of inclusions, slag, porosity, and lack of fusion (Figure 1). These large repair flaws were generally located at the ends of repair cavities and were three dimensional in the sense that they extended around the end of the repair cavity.

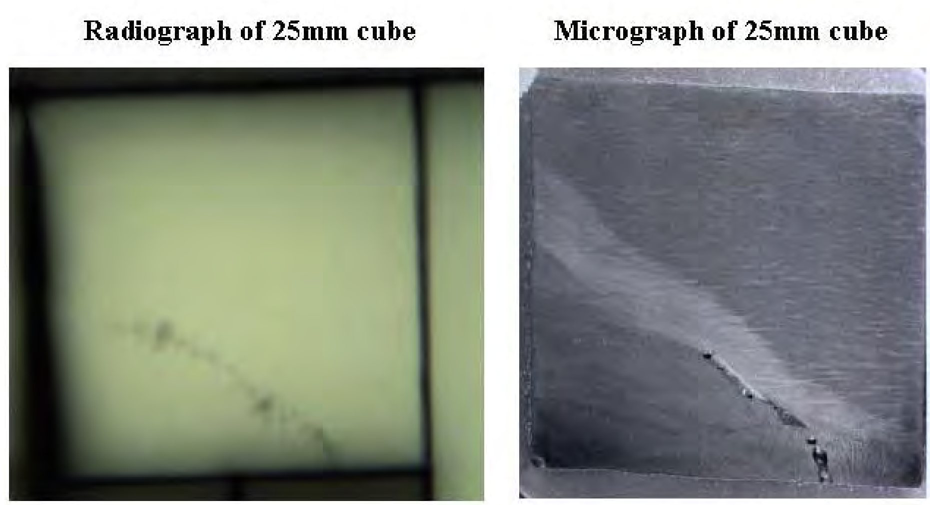

Fig. 1 Validated Complex Repair Flaw in Beltline Weld of PVRUF

Flaw Distributions for Probabilistic Fracture Calculations

A previous paper (Simonen et al. 2002) [10] described a methodology that applied the measured data from the vessel examinations to estimate statistical distributions that describe the number and sizes of flaws in a vessel welds. Figure 2 is a cumulative distribution for the number of flaws exceeding each depth dimension for the case of a three-foot length of weld that was assumed to have been repaired over its entire length. The vessel wall thickness was 8.63 inch and the weld repair was assumed to consist of an excavation from the inner surface to a maximum depth of 50 percent of the wall thickness. As described previously (Simonen et al. 2002) the flaw distribution parameters were based on data from the Shoreham vessel. Two curves are indicated in Figure 2. For one curve the large flaws found in repair welds were included and for the other curve such flaws were neglected.

Both curves of Figure 2 give about the same number and sizes of smaller flaws (depths less than 2 to 3 percent of the wall thickness). There were a total of 72 flaws in the three-foot length of the repaired region with most of the flaws having depth dimensions of 2-mm or less. Significant differences are seen in the tails of the two flaw depth distribution curves, which is largely a function of the assumed amount of repair welded material. It is important to note that Figure 2 describes a small length of weld that has been repaired, whereas for an entire vessel only a small fractional length of the seam welds would actually be repaired. Therefore the curves of Figure 2 exaggerate the relative contribution of weld repairs to the overall population of flaws if viewed from the standpoint of an entire vessel.

The curves of Figure 2 were truncated and predict no flaws of an extreme depth that would significantly exceed the largest flaws detected in the vessel examinations. The truncation level was at about 11 percent of the wall thickness for flaws in the original seam welded material. The truncation was at about 23 percent of the wall thickness for flaws in material deposited during a repair process.

The curves of Figure 2 were used as statistical inputs to probabilistic fracture mechanics calculations. Other details of the flaw distribution inputs are described in another paper (Simonen et al. 2002) [10]. All flaws were assumed to be buried within the thickness of the vessel wall, with their locations having an equal probability of occurring at any location relative to the vessel inner surface. For the sensitivity calculations described below all flaws were assumed to have an aspect ratio of 6:1 (ratio of the total flaw length to the flaw depth dimension).

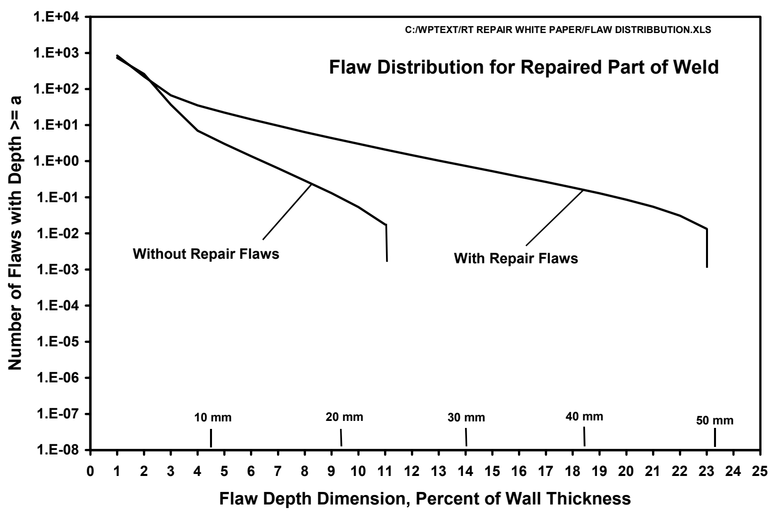

Fig. 2 Reactor Pressure Vessel Flaw Distributions With and Without Presence of Repair Related Flaws

FRACTURE MECHANICS CALCULATION

Probabilistic fracture mechanics calculations were performed to simulate the effects of repair flaws on the probability of failure for reactor pressure vessels.

Reactor Pressure Vessel

The significance of repair flaws as described by Figure 2 were evaluated by performing probabilistic fracture mechanics calculations with the VISA-II computer code (Simonen et al. 1986) [11]. Sensitivity calculations predicted failure probabilities for a neutron embrittled vessel having an inner diameter of 180 inches and a wall thickness of 9 inches. Evaluations addressed only the contribution to vessel failure from a 3-foot repaired length of an axial weld. Fabrication flaws were treated as buried at random locations within the thickness of the vessel wall, which resulted in only a small fraction of the flaws being located at or near the highly embrittled vessel inner surface.

Calculations addressed a pressurized thermal shock (PTS) transient consisting of a constant pressure of 2000 psi and an exponential cooling transient from 550 F to 150 F as defined by the equation $T = \Delta T \exp(\beta t)$, where t = time (minutes) and $\beta = 0.15$ (min^{-1}). The initial ductile-brittle transition temperature (RT_{NDT}) of the weld was taken to be 20 ^{o}F. Embrittlement was predicted using the Regulatory Guide Revision 2 correlation for copper and nickel contents (weight percent) of 0.30 and 0.75 respectively.

Figure 3 presents calculated probabilities of failure (through-wall crack) predicated on the occurrence of the PTS transient. Failure probabilities increased as a function of time as the neutron fluence and the embrittlement increased. A base case assumed no flaws or residual stresses associated with repairs. The second case included an increased number of large flaws from repairs as described by Figure 2. The third case also included a 10 ksi tensile residual stress caused by the repair welding. Figure 3 indicates that repair flaws can increase calculated failure probabilities by a factor of about 2-5. With the 10 ksi residual stress also included, the calculated increases in failure probability are by a factor of about 5-20. The increases in failure probabilities are relatively small, because a single large flaw in a vessel will usually not occur in the most embrittled vessel region, whereas there will usually be one or more of the smaller flaws in the embrittled region that are sufficiently large to cause vessel failure.

Figure 4 shows results from a second set of sensitivity calculations that postulated a low-temperature over-pressure transient (LTOP event). This calculation assumed the occurrence of a maximum pressure of 2000 psi with the vessel wall at 100 ^{o}F. The relative increases in failure probabilities (factor of 10 to 100) caused by the repair flaws were greater for the LTOP event than the increases for the PTS transient, which indicates an enhanced role of larger repair flaws for pressure-dominated transients (LTOP) as compared to thermal stress transients (PTS).

The results of Figures 3 and 4 tend to exaggerate the increases in failure probabilities associated with repair flaws, because the calculations addressed only a limited part of the vessel that is repaired, and not the entire vessel. Because only a small fraction of a vessel volume will actually be repaired, the overall increases in failure probabilities from the standpoint of the entire vessel will be quite small.

The vessel calculations show that both small and large flaws can cause vessel failures and that the flaws must be relatively close to the embrittled and flaw-sensitive inner surface, which is also the region subjected to the highest levels of thermal stress. Figure 5 shows that a relatively small flaw (5 percent of the wall) is almost as likely to cause a vessel failure as a much larger flaw (25 percent of the wall). On the other hand, the larger flaws have much lower frequencies of occurrence than the smaller flaws. The net result as indicated by Figure 5 is that small flaws would most often cause failures of embrittled vessels, because the vessel region with the most extreme level of embrittlement is likely to have at least one small flaw that is capable of fracturing of the vessel.

In summary, the presented calculations show that larger repair flaws increase failure probabilities for embrittled vessels but only to a modest extent. Another study (Simonen and Dickson 2003) [12] has applied the FAVOR code (Dickson 1994) [13] to address the effects of repair flaws, and these results also show an insensitivity of vessel failure probabilities to the repair flaws.

Potential Code Changes

Rather than proposing specific code changes, several options are suggested. Options range from no code changes to a requirement for fitness-for-purpose evaluations to ensure that repairs have a positive rather than a negative impact on structural integrity.

Good experience with the current code, with few if any field failures because of damage caused by repairs, would argue against code changes. However, this approach would ignore progress made in the areas of improved NDE inspections and in the ability to better evaluate the effects of flaws on structural integrity. In this regard improved NDE methods can now detect flaws that might not be detected by past methods. Therefore more realistic criteria for decisions regarding repairs would be a strong incentive to adopt improved NDE methods as they are developed.

A first step could be a code case or non-mandatory appendix to avoid ill-advised repairs by performing a fitness-for-purpose evaluation for every flaw detected. Section III now allows no option other than to repair, even for flaws that can be demonstrated to have no effects on structural integrity. Rather difficult repairs may be required, which could introduce significant structural damage in the form of new flaws, adverse residual stresses, degraded material properties or undesirable material microstructures, and add substantial costs to a component.

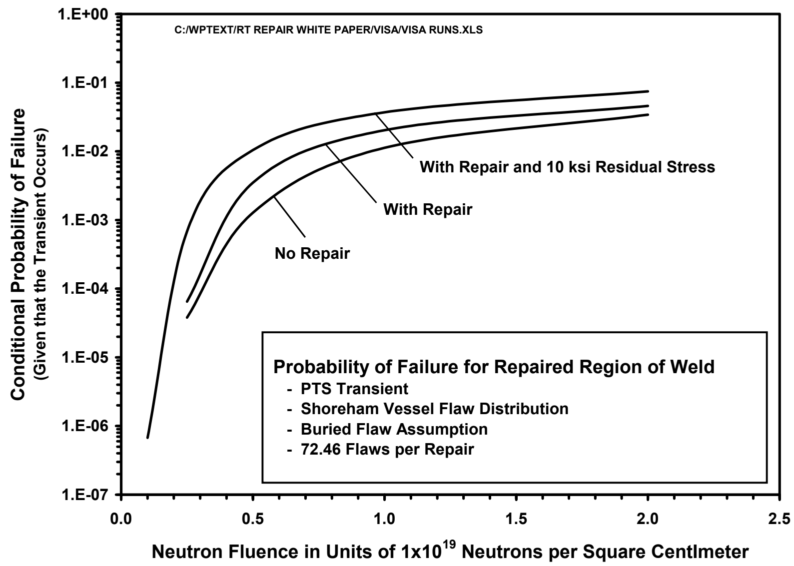

Fig. 3 Calculated Vessel Failure Probability for PTS Transient

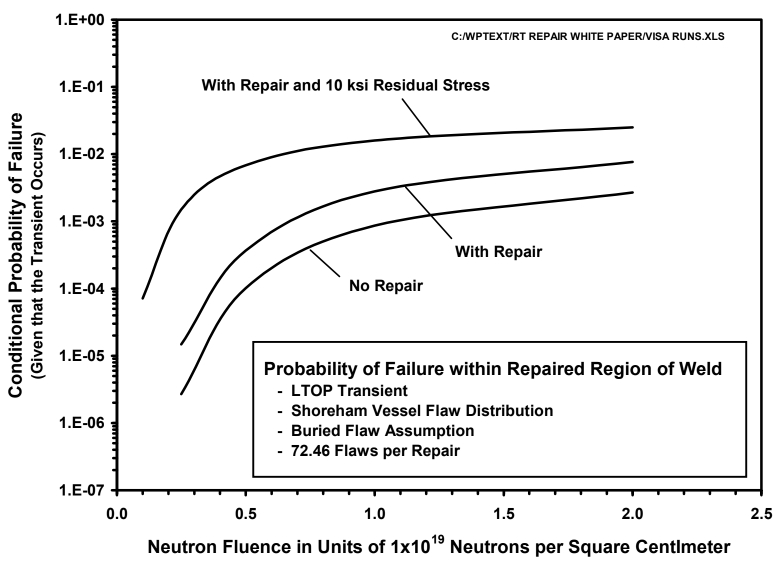

Fig. 4 Calculated Vessel Failure Probability for LTOP Transient

Longer-term code changes could provide guidance on when repairs should be made or should be avoided when radiographic indications are found to exceed current code limits. The guidance would specify the need for further examinations (ultrasonics) to better characterize the locations and sizes of flaws associated with RT indications. Other guidance would describe structural integrity evaluations for the potential impact of detected flaws on the integrity of components.

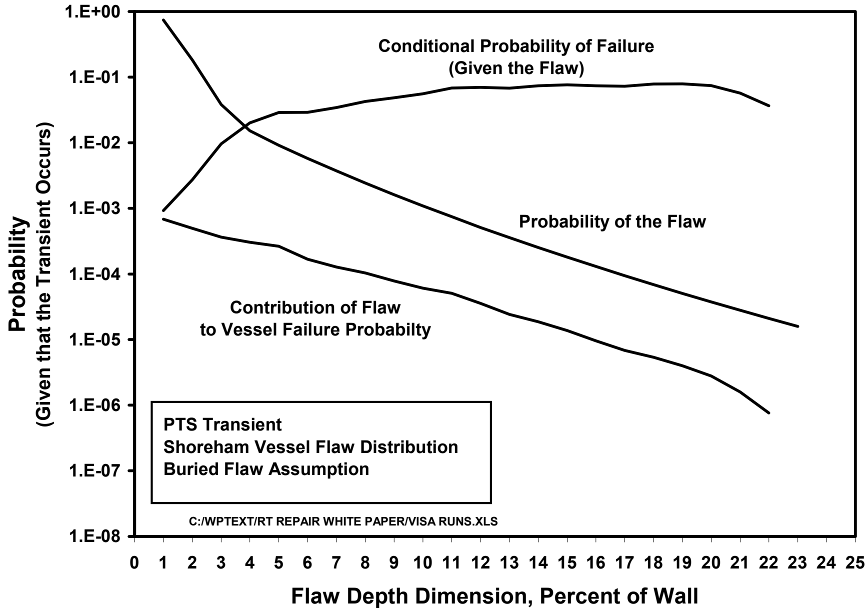

Fig. 5 Details of Probabilistic Fracture Mechanics Results That Show Why Large Repair Flaws Make Only a Relatively Small Contribution to Overall Vessel Failure Probability

SUMMARY AND CONCLUSIONS

This paper has addressed concerns that repairs made to welds to correct conditions associated with RT indications can be the source of large flaws and that repair procedures can reduce rather than increase the structural integrity. The following summarizes the conclusions of the study described above:

1. Examinations of welds from reactor pressure vessel welds have shown that the largest flaws were associated with repairs made to the welds to correct RT indications exceeding the allowable lengths of the ASME Section III construction code. The original flaws associated with the RT indications are believed to have been smaller and less structurally significant than the flaws introduced by the repair process.
2. Sufficient data on flaws in seam weld processes and from repair welding are available to allow the development of statistical distributions needed to describe the number and sizes of flaws in welds for use as inputs to probabilistic fracture mechanics calculations.
3. Probabilistic fracture mechanics calculations show that repair flaws can increase failure probabilities of embrittled vessels for conditions of pressurized thermal shock and for low temperature over-pressure events. The predicted increases in failure probabilities are relatively small because the effects of the large number of small flaws located in the embrittled inner region of the vessel are important to structural integrity, which decreases the relative significance of a few large repair flaws.
4. Changes to ASME Section III requirements for the examination and repair of welds appear to be warranted, because current procedures have the potential to decrease rather than increase structural integrity. Improved procedures should use ultrasonic examinations to better characterize the sizes and locations of flaws, and should use fracture mechanics methods to minimize repairs that are not justified on the basis of fitness-for-purpose considerations.
5. UT technology has evolved so that fabrication flaws important to component structural integrity can be reliably detected, sized and located so that meaningful assessments can be made of their structural significance.
6. Work is in progress to develop density and distribution functions for fabrication flaws in piping weldments to understand if there are similar trends as to those found in reactor pressure vessel materials.

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