20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 8, Paper 2477

Fabrication Flaw Density and Distribution in Weld Repairs[1]

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Keywords: Fabrication flaws, weld repairs, reactor pressure vessels, dissimilar metal welds.

1 ABSTRACT

The Pacific Northwest National Laboratory is developing a generalized flaw distribution that may be used to describe the distribution of flaws in vessels and piping for U.S. operating nuclear power reactors. The purpose of the generalized flaw distribution is to predict component-specific flaw densities. The estimates of fabrication flaws are intended for use in fracture mechanics structural integrity assessments. Structural integrity assessments, such as estimating the frequency of loss-of-coolant accidents, are performed by computer codes that require, as input, accurate estimates of flaw densities. Welds from four different cancelled reactor pressure vessels have been studied to develop empirical estimates of fabrication flaw densities.

This paper describes the fabrication flaw distribution and characterization in the repair weld metal of vessels and piping. This work indicates that large flaws occur in these repairs that are complex in composition and sometimes include cracks on the ends of the repair cavities. Parametric analysis using an exponential fit is performed on the data.

Construction records, where available, were reviewed. It is difficult to make conclusions because of the limited number of construction records reviewed. However, the records reviewed to date show a significant change in repair frequency over the years when the components in this study were fabricated. A description of repair flaw morphology is provided with a discussion of fracture mechanics significance.

2 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) initiated research activities in 1989 at the Pacific Northwest National Laboratory (PNNL) with the major objective of estimating the density of fabrication flaws in U.S. light water reactor pressure vessels (RPVs) and piping welds (Jackson et al. 2001). PNNL's methodology for estimating the density and size distribution of fabrication flaws involves the nondestructive evaluation (NDE) of weldments from cancelled nuclear plants and the destructive validation of detected flaws. This methodology characterizes the flaws for fracture mechanics significance because the likelihood of vessel failure is sensitive to flaw location, type, size, orientation, and other flaw characterizations (Simonen and Khaleel 1995). The objective of this research is to estimate these and other relevant properties of flaws created during the fabrication of nuclear component weldments.

To meet this objective, a generalized flaw distribution approach was used because the density of fabrication flaws is expected to vary over product forms and over the years of component fabrication. To develop a generalized flaw distribution and to resolve technical issues, an expert judgment process was used. The results of this expert judgment process helped to formulate a generalized approach to fabrication flaw density and distribution (Jackson and Abramson 2000). The impaneled experts concluded that the product forms and construction processes determine the fabrication flaws in weldments. So, for the *i*th component, the number of flaws greater than size *x* can be given by a sum over product forms.

$$N_i(x) = \sum_j \rho_j(t_i) \cdot V_{ij} \cdot G_j(x) \tag{1}$$

[1] The work was sponsored by the U.S. Nuclear Regulatory Commission under U.S. Department of Energy Contract DE-AC05-76RL01830; NRC JCN Y6398; Mr. Wallace Norris, Program Monitor.

where $\rho_j(t_i)$ is the flaw density in product form j during time interval for the construction of the ith component t_i, V_{ij} is the volume (or area) of the product form in a weldment or a region of a weldment, and $G_j(x)$ is the probability that a flaw, in product form j, has a size greater than x.

PNNL data have shown that the formula:

$$G_j(x) = \alpha \exp(-\beta_j x) \quad (2)$$

provides a reasonable fit to the fabrication flaw data (Doctor and Schuster 2001).

Estimates for flaw densities are an important input to structural assessments by fracture mechanics calculations. Component failure is an issue of increasing concern as the current operating nuclear power plants reach the middle to latter portion of their license periods and have accumulated service-related degradation. Computer codes require accurate estimates of the flaw densities in the reactor component to determine the likelihood of a component failure. The majority of past work in probabilistic fracture mechanics (PFM) considered cracks to be expressed in terms of a single crack size parameter (size in the depth dimension). A two-dimensional crack is much more realistic but considerably more complex. Some PFM codes are capable of treating two-dimensional cracks and are based on the assumption that a two-dimensional crack is a semi-elliptical surface crack.

Fracture mechanics codes can provide the capability of considering more realistic and detailed flaw density information. In developing the flaw distribution models, conservative assumptions are made concerning the initial flaw size distribution, aspect ratios, and through-wall locations, because of the lack of empirical data on fabrication flaw distributions in nuclear components. Studies (Simonen et al. 1986; Simonen and Khaleel 1995) have shown that the probability of vessel rupture is sensitive to the location of the flaw in the vessel (i.e., near the inner surface versus interior of the vessel wall); the flaw type (e.g., cracks, lack of fusion, porosity, inclusions); and the flaw aspect ratio (i.e., flaw length as well as depth). Therefore, it is very useful to have flaw density estimates that are based on empirical data.

In the work that PNNL has conducted to create an empirical database on fabrication flaws, the repairs that were made to the various product forms, produced different fabrication flaw density and distribution. This paper focuses on assembling all of the data for repairs and comparing the results with those created for the other product forms.

2.1 Repair process and frequency

Before components such as the reactor pressure vessel were declared ready for service, the manufacturing process included the detection, characterization, and repair of significant flaws. Nondestructive evaluation techniques were applied at various stages during fabrication to ensure that significant flaws were removed. This removal of fabrication flaws was accomplished by grinding out the flaws and filling the repair cavity with weld metal. This section of the report describes PNNL’s efforts to establish the number and size of repairs during the fabrication of the materials analyzed.

The vessels were manufactured using specifications in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Rules for Construction of Nuclear Pressure Vessels. All applicable Code Cases and addenda for Class A vessels that were in effect at the time of the purchase order also were applied. Later editions of the code may have been applied if agreed upon by the supplier.

For vessels like those from the Pressure Vessel Research User Facility (PVRUF) and River Bend Unit 2 (RB 2), constructed in the late 1970s, few repairs were made in contrast to what has been reported in earlier vessels. The Hope Creek Unit 2 (HC 2) RPV and the Shoreham RPV, constructed in the early 1970s, can be considered earlier vessels. Better plate material and improved welding practices reduced flaw densities. Better interpretation of NDE indications also was an important factor in reducing repair frequency.

Specifications were in place for the portions of the vessel that were to be inspected, the time(s) during manufacture for inspections to be conducted, the amount of the vessel surface preparation to be performed, and the essential variables of the test to be performed. Test and inspection results were included in the vessel’s construction records.

The construction records document the defects and repairs in the reactor pressure vessels. Complete construction records were obtained by PNNL for the RPVs from the PVRUF, RB 2, and HC 2. Partial construction records were obtained for the Shoreham RPV. These construction records included nuclear shop travelers, inspection records, rejection notices, radiographic acceptance forms, and charts of (repair) cavities. These records were analyzed as a function of location and product forms. The interested reader is referred to NUREG/CR-6945 (Schuster et al. 2008) to see the complete analysis that was conducted on these records with only a summary being presented here.

From the construction records, it is possible to extract the number of defects requiring repair. Figure 1 provides data by product form—cladding, base metal, and seam welds. Material handling is also included in the analysis. Material handling defects that required repair were typically caused by damage during temporary attachment removal. The construction records for three vessels—PVRUF, HC 2, and RB 2—were analyzed to obtain the information provided in Fig. 1. The data show that vessel-to-vessel variation in the number of defects requiring repair can be as much as a factor of 10.

Additional summary statistics are provided in Tables 1, 2, and 3. These tables show the frequency of repair in the various product forms. Repairs that originated in the removal of temporary fit-up fixtures are summarized in the handling category. Table 1 shows the repairs made from the inside surface of the vessels. Table 2 shows the frequency of repair from the outside surface. In a few cases, the construction records do not report which surface was used to make the repair and Table 3 shows this data.

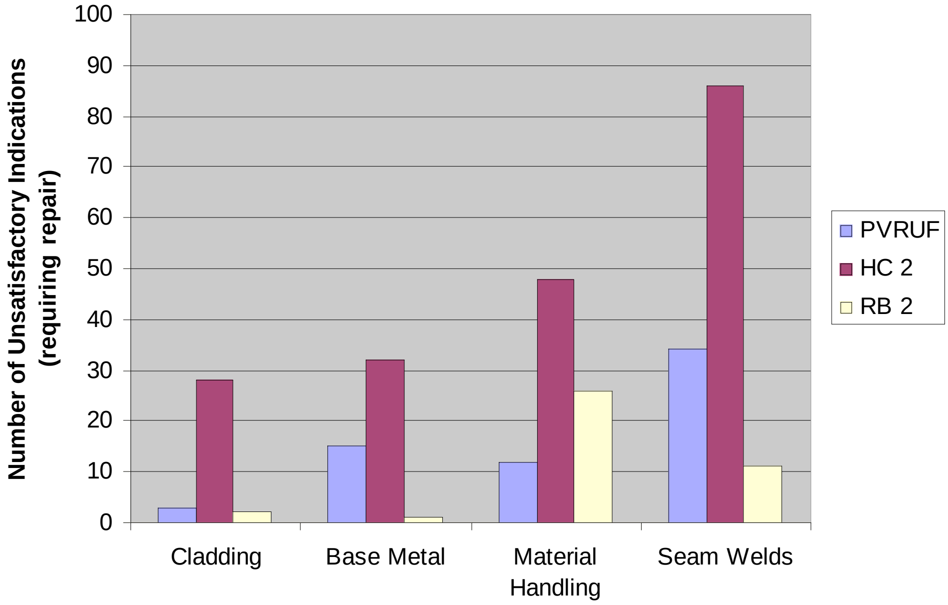

Figure 1. Summary of repair frequency for three reactor pressure vessels

Table 1. Frequency of repair from the inside surface of three reactor pressure vessels. The miscellaneous category includes repairs to the CRDM penetration seal welds.

	Cladding	Base Metal	Handling	Seams	Misc.
HC 2	28	16	4	35	6
RB 2	3	1	7	4	1
PVRUF	3			18	4

Table 2. Frequency of repair from the outside surface of three reactor pressure vessels

	Base Metal	Handling	Seams
HC 2	16	36	51
RB 2		19	7
PVRUF	11		14

Table 3. Frequency of repair where the repair surface was not specified in three reactor pressure vessels. In a few cases, the construction records did not document the repair surface.

	Base Metal	Handling	Seams
HC 2		8	
RB 2			
PVRUF	4	12	2

2.2 Reactor pressure vessel material

Materials from four different reactor pressure vessels—RB 2, HC 2, PVRUF, and Shoreham—and a collection of pipe welds were selected for study. The major component manufacturers and the major reactor designs were considered in the selection. Table 4 gives the amount of weld metal and component vintage examined in each of the categories. Table 5 lists the methods used to fabricate the welds in the reactor pressure vessels studied in this paper.

Table 4. Reactor material selected for study

Name	Manufacturer	Reactor Type	Components	Length of Weld, m (ft)	Years of Construction
Shoreham	CE[(a)]	BWR	Vessel	24 (79)	1968–1974
HC 2	CB&I[(b)]	BWR	Vessel	3 (10)	1971–1975
RB 2	CB&I	BWR	Vessel	15 (50)	1974–1978
PVRUF	CE	PWR	Vessel	20 (67)	1976–1981

(a) Combustion Engineering
(b) Chicago Bridge & Iron

Table 5. Method used to fabricate welds

Weld Type	Weld Metal
Axial Seam	Submerged metal arc
Girth Seam	Submerged metal arc with shielded metal arc for back gouge restoration
Repair to Seam	Submerged metal arc

The inspection of the welds in the PNNL specimens was conducted from a cut and machined surface. This section briefly reviews the measurements used to detect the repairs and form the initial, unvalidated flaw density and distribution within them. Then the sectioning of the weld segment to remove the repair metal is shown.

Figure 2 shows a HC 2 RPV specimen in the PNNL NDE Laboratory for ultrasonic inspection from a cut and machined surface. The surface was smoothed to better than 1.6 microns root-mean-square (RMS) to enable optimized, high-quality ultrasonic testing (UT) inspections. The PNNL staff member is seen adjusting the ultrasonic couplant system, which used heavy mineral oil in this case. The ultrasonic transducer was a 5-MHz contact probe. The HC 2 RPV specimen shown is a base metal piece. Some of the weld metal specimens can be seen in the left portion of Fig. 2.

Figure 2. Hope Creek Unit 2 base metal specimen in the NDE laboratory for ultrasonic inspection using cut and machined surface

Weld-normal ultrasonic inspections detected the repairs in the specimens. Figure 3 shows the detection and location of an undocumented repair in Shoreham Specimen C120E. The shape of the cavity is evidenced by ultrasonic reflections from small flaws on the fusion zone of the repair with the surrounding material.

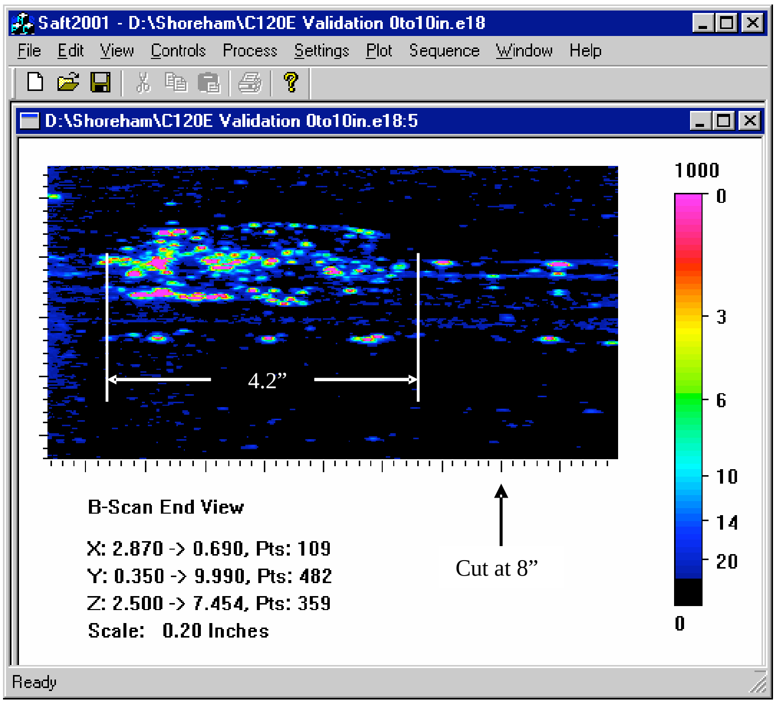

Figure 3. Location of an undocumented repair in Shoreham specimen C120E. The units in this figure are shown in inches because the Synthetic Aperture Focusing Technique (SAFT)-UT system is programmed to do so. To convert to centimeters, multiply by 2.54.

PNNL developed a systematic process to detect and characterize fabrication flaws in these materials. The interested reader can obtain additional information on PNNL's validation methodology in Doctor and Schuster (2001).

3 MORPHOLOGY OF REPAIR FLAWS

The flaws detected in the weld normal inspections were then sized and reviewed. All critical flaws that impacted the density and distributions were sectioned into 25-mm-thick plates, inspected by radiography (RT) and re-examined with high-resolution SAFT-UT at either 5 or 10 MHz. These data were then reviewed and specific flaws were selected for further analysis that first required them being cut out into a 25-mm cube. RT and SAFT-UT from all surfaces were then repeated to further refine the size and the type of flaws. Based on the data, selected flaws were subjected to destructive testing to validate the flaw size and type. It is not possible to present much information in this paper and the interested reader should see NUREG/CR-6945 (Schuster et al.). Some representative examples of the data obtained in this process are shown in Figs. 4, 5, and 6.

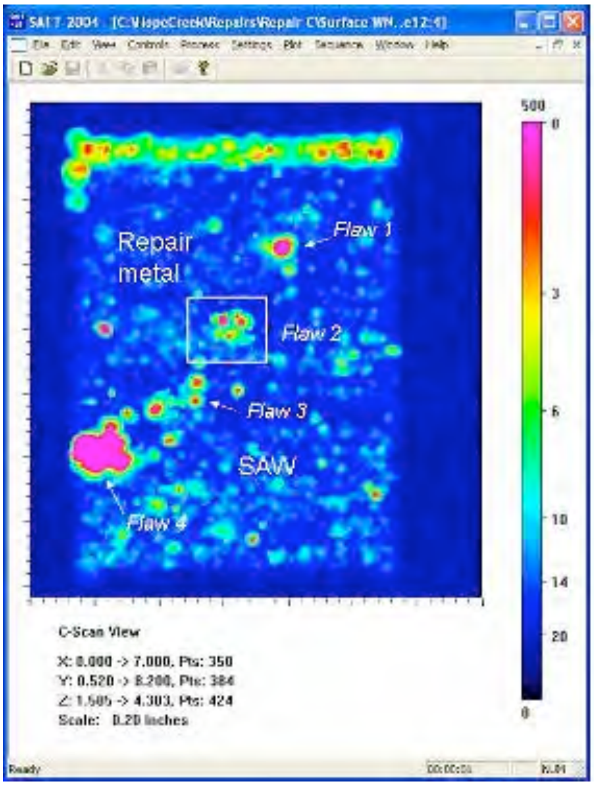

Figure 4. Weld-normal UT C-scan image of flaw in fusion zone and on end of repair cavity C in Hope Creek Unit 2 reactor pressure vessel. To convert to centimeters, multiply by 2.54.

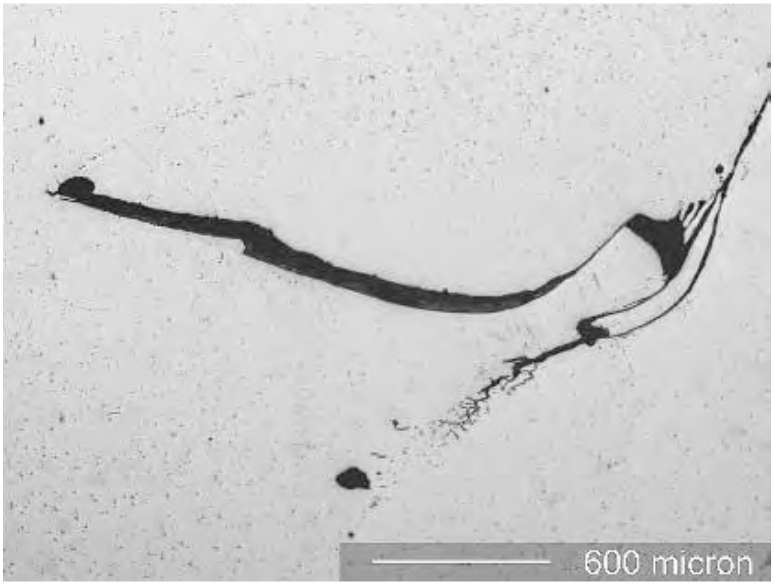

Figure 5. Micrograph, as machined, of portion of crack in Hope Creek Unit 2 RPV Specimen C2CC

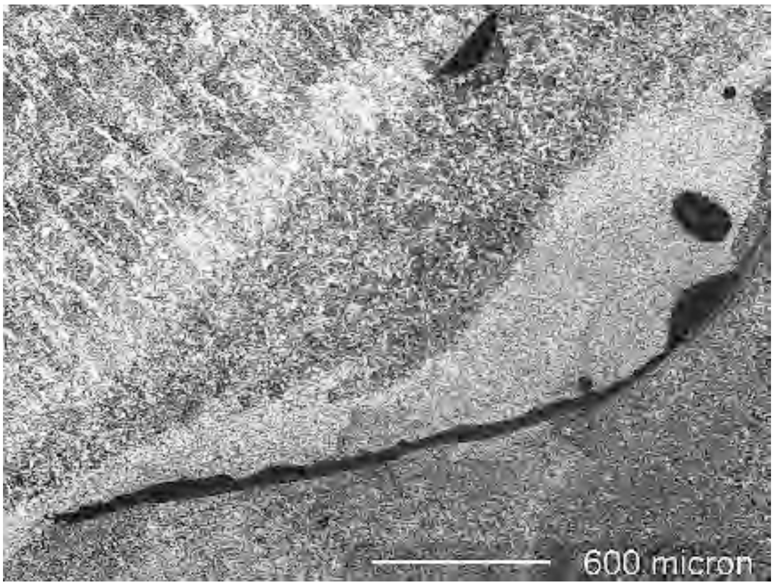

Figure 6. Micrograph, as polished and etched, of portion of crack in Hope Creek Unit 2 RPV Specimen C2CC

4 SUMMARY

Conclusions can be drawn from the data extracted from the construction records and from the validated flaw density and distribution in the repair metal that was studied. Construction records contain the repair locations and cavity dimensions. PNNL data on repair flaw morphology showed complex composition including cracks as part of a larger flaw. Separate size distributions can be estimated for individual vessel repairs, and those distributions are highly variable.

The defects reported in the construction records were found by documented NDE procedures or were visually apparent. Penetrant testing found defects, mostly slag defects, sometimes through the cladding thickness. A difference of a factor of 10 in defect density was found between the HC 2 vessel (manufactured in the early 1970s) and that of RB 2 (manufactured in the late 1970s). The PVRUF vessel, a late-vintage vessel, had a defect density more like that of the RB 2 RPV. RT and UT found defects of various kinds in the seam welds. Most of the reported defects—80% in HC 2—were found by RT. For defects greater than 3.5 cm in length, there is a difference of a factor of 10 between the early versus late fabricated vessels. This indicates that the welding process improved and fewer defects were being created in the newer vessels.

PNNL analyzed the fabrication flaw density and distribution in the repairs found in a HC 2 RPV specimen. A greater flaw density was observed in the weld preparation surface repairs when compared to seam weld repairs. The weld preparation surface repairs are embedded while the structural seam weld repairs connect to either the inside diameter or the outside diameter of the vessel. Cracking was observed in the metallography.

The repair flaws were found to be complex. Metallographic analysis of repair flaw specimens shows that the fabrication flaws are composed of a mixture of cracks, lack of fusion, contamination, and porosity. The repair flaws can repeat on the next weld pass. This phenomenon is of known interest to the modelling of welding flaws (Chapman and Simonen 1998).

PNNL's laboratory data acquired on repairs in weld segments was analyzed to determine the fabrication flaw density and size distribution. Weld segments from three reactor pressure vessels and one dissimilar metal weld piping section were found to contain weld repairs. The NDE inspections detected many fabrication flaws in the repairs, and the data were analyzed for density and distribution. An estimate of flaw density and distribution was made for five cases.

The results for through-wall size distribution are given in Fig. 7. A parametric fit is made to the cumulative flaw size distribution, and the parameters are given in Table 6. The through-wall dimensions of repair flaws span a range extending from 2 mm to 17 mm. For the five flaw distributions shown in Fig. 7, significant differences can be seen—a factor of 10 difference in some cases. The distributions of flaws for the seam weld repairs from three vessels (the PVRUF, Shoreham, and HC 2 repairs) should have similar slopes; the variability can be attributed to the small number of repairs examined. In Fig. 7, the distribution of flaws for weld preparation surface repairs is shown to be higher than that of flaws in weld seam repairs. This is to be expected because the repair metal in this case contacts the mid-wall segregates in the base metal. For comparison, the distribution of flaws found in three piping repairs span a limited range, from 2 mm to 4 mm.

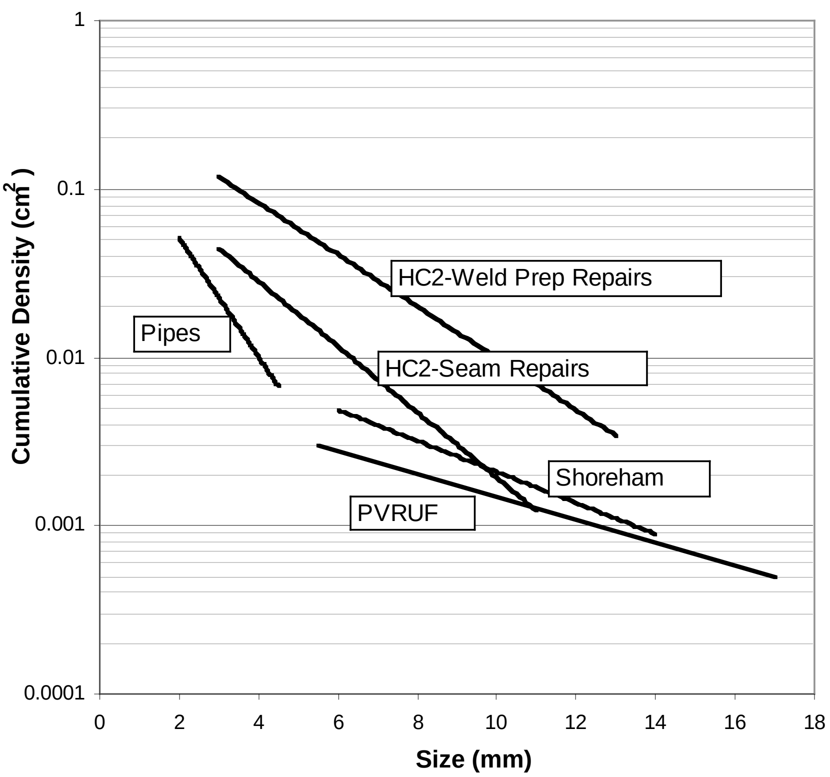

Figure 7. Comparison of flaw density and through-wall size distributions for repair flaws in three reactor pressure vessels and in dissimilar metal welds of piping

Table 6. Exponential fit results for through-wall size

	α	
HC 2 – Weld Preparation Repairs	0.34 cm^{-2}	0.35 mm^{-1}
HC 2 – Weld Preparation Repairs	0.15 cm^{-2}	0.44 mm^{-1}
Shoreham – Seam Weld Repairs	0.017 cm^{-2}	0.21 mm^{-1}
PVRUF – Seam Weld Repairs	0.0077 cm^{-2}	0.16 mm^{-1}
Pipes – Dissimilar Metal Weld Repairs	0.37 cm^{-2}	0.22 mm^{-1}

Acknowledgments

The author thanks George J. Schuster for his efforts and outstanding contributions. Mr. Schuster, who is now retired, was the key PNNL staff person that oversaw the conduct of the work reported in this paper.

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