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Report on the Preliminary Results of the Expert Judgment Process for the Development of a Methodology for a Generalized Flaw Size and Density Distribution for Domestic Reactor Pressure Vessels

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Executive Summary

The U.S. Nuclear Regulatory Commission (NRC) is re-evaluating the guidance and criteria in the code of federal regulations (CFR) as it relates to reactor vessel integrity, specifically pressurized thermal shock (PTS) which challenges the integrity of the reactor vessel's inner wall. The PTS rule sets forth fracture toughness requirements for protection against PTS events for pressurized water reactors (PWRs). Recent ultrasonic examinations of reactor pressure vessel (RPV) material at Pacific Northwest National Laboratory (PNNL) and industry experience with Yankee Rowe have provided the NRC with a better understanding of PTS issues. The re-evaluation of PTS will consider a risk-informed approach to the PTS rule and also provide important benefits for licensees considering license renewal. One element of this PTS re-evaluation requires an accurate estimate of fabrication flaws and this identified the need for the development of a generalized flaw distribution for domestic RPVs.

In order to develop a generalized flaw distribution (GFD) and to resolve specific technical issues for which there is scientific uncertainty, an expert judgment process was used. The expert judgment process has assisted the NRC staff in developing a GFD for domestic RPVs which is used as input into probabilistic fracture mechanics calculations.

The panel of experts, who were part of the expert judgment process, consisted of 17 individuals who had expertise in the ASME Code for vessel construction; failure analysis; forgings; metallurgy; non-destructive examination (NDE); reactor vessel fabrication; statistics; and welding. Results from the expert judgment process provided substantial quantitative and qualitative information regarding the introduction of flaws during the entire reactor vessel fabrication process, the detection of flaws through preservice inspection and the likelihood of a flaw remaining in the vessel after preservice inspection. Some conclusions based on the expert judgment process are 1) a GFD for domestic RPVs can be developed but with a wide range of uncertainty, 2) the flaw density of base metal is substantially less than that for weld metal, 3) discontinuities in the cladding may not be of concern for RPV integrity, 4) large flaws are usually caused by loss of control of the welding process and would be detected by NDE, 5) variations in weld quality are greatly affected by welder skill and inspector skill, and 6) weld processes are an important factor in the introduction of flaws. The expert judgment process was not a consensus process. Responses and data were obtained from each expert during individual elicitation sessions. The entire set of data and responses from the process will be published in an upcoming NUREG which will contain the GFD for the entire fleet of domestic reactor vessels along with uncertainty and sensitivity studies. In addition, comments and questions received by NRC related to data acquisition, methodologies and process used for the expert judgement process and development of the GFD will be addressed in the upcoming NUREG, specifically flaw depth location, PVRUF flaw sizing and characterization accuracy, flaw distribution development and destructive examination techniques.

This technical letter report will briefly discuss three topics, 1)background of PTS, 2) previous work on developing flaw distributions, 3) the fabrication process of domestic reactor pressure vessels; present the results of the expert judgment process and present the methodology for the generalized flaw distribution developed from the expert judgment process with validated and unvalidated data from PNNL. Additional work will be completed on sensitivity studies and uncertainties for the GFD.

Abbreviations and Glossary

B&W	Babcock and Wilcox
BWR	Boiling Water Reactor
CB&I	Chicago Bridge and Iron
CCDF	Complementary Cumulative Distribution Function
CE	Combustion Engineering
CFR	Code of Federal Regulations
DE	Destructive Examination
EPRI	Electric Power Research Institute
ESW	Electroslag Welding
FLAW	An unintentional discontinuity that has the potential to compromise reactor vessel integrity and is in the vessel after preservice inspection. This definition was developed for use during the expert judgment process
FLAW SIZE	Weld Metal and Cladding (through wall dimension) Small Flaw ≤ 1 bead thickness for a stated weld process Large Flaw > 1 bead thickness for a stated weld process Base Metal (through wall dimension) Small Flaw ≤1/4" Large Flaw > 1/4"
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone is that portion of the base metal whose microstructure is altered during the welding process.
JSW	Japanese Steelworks
MMCP	Median Midvalue Likelihood Factor
MT	Magnetic Particle Testing
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing
NSSS	Nuclear Steam System Supplier
PFM	Probabilistic Fracture Mechanics
PNNL	Pacific Northwest National Laboratory
PSI	Preservice Inspection
PT	Liquid Penetrant Testing
PTS	Pressurized Thermal Shock
PVRUF	Pressure Vessel Research User Facility
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessels

SAFT-UT	Synthetic Aperture Focusing Technique for Ultrasonic Testing
SAW	Submerged Arc Welding
SMAW	Shielded Metal Arc Welding
TWD	Through wall dimension
UT	Ultrasonic Testing

1.0 INTRODUCTION

In response to nuclear power plant licensees, the U.S. Nuclear Regulatory Commission (NRC) is re-evaluating the guidance and criteria in the code of federal regulations (CFR) as it relates to reactor vessel integrity, specifically 10 CFR 50.61, pressurized thermal shock (PTS). The PTS rule sets forth fracture toughness requirements for protection against PTS events for pressurized water reactors (PWRs). A PTS event or transient, in which severe overcooling concurrent with or followed by an increase in pressure in the RPV, challenges the integrity of the reactor vessel's inner wall. Recent ultrasonic examinations of considerable RPV material at Pacific Northwest National Laboratory (PNNL) (ref. 1, ref. 2) and industry experience with Yankee Rowe have provided the NRC with a better understanding of PTS issues. PTS is a significant concern as plants reach the mid-cycle of their operating license when the vessels may become more brittle. PTS re-evaluation is also a concern for licensees considering license renewal. The re-evaluation of PTS will consider a risk-informed approach to the PTS rule. One element of this re-evaluation requires development of a flaw distribution for flaws created during RPV fabrication.

In order to obtain an accurate estimate of fabrication flaws to address PTS events for all classes of domestic reactor pressure vessels a generalized flaw distribution must be developed. The NRC's Office of Research has committed to revising the PTS acceptance criteria and determined that the expert judgment process in conjunction with recent data from PNNL, experience from Yankee Rowe, and flaw simulation models provided by RR-PRODIGAL (ref. 3) is the most efficient method for determining the bases for a generalized flaw density and size distribution. The expert judgment process will be used in conjunction with empirical data from PNNL RPV studies and modeling with RR-PRODIGAL in developing the revised distribution.

Previous work on the development of flaw distributions for RPVs is documented in a report by Dr. Walter Marshall (Ref. 4) of the United Kingdom. The Marshall Distribution, developed in the late 1970's and revised in the 1980s, was based on UT examination of 44 RPVs, augmented by data from non-nuclear vessels. Detection efficiency of UT exams during that time period were not designed to detect many of the flaws that have been detected by PNNL. The current work completed by PNNL combines the effectiveness of the SAFT-UT system and the destructive validation process.

2.0 BACKGROUND

Although, pressurized thermal shock transients can lead to RPV failure, fortunately, to date these transients have not resulted in reactor pressure vessel failure. To determine the potential or probability for RPV failure from a PTS event an accurate estimate of fabrication flaws is necessary. The estimate of the number, locations and sizes of fabrication flaws in RPV welds and base metal are important inputs to probabilistic fracture mechanics computer codes such as FAVOR (ref. 5) and VISA-II (ref. 6) for predicting the failure probabilities of reactor pressure vessels. These estimates are also inputs that are believed to have the greatest levels of uncertainty. To evaluate this level of uncertainty, the NRC is supporting research to establish a better basis for estimating the distributions of flaws in RPVs.

2.1 Fracture Mechanics Calculations

As previously stated, probabilistic fracture mechanics computer codes require accurate estimates of the flaw rates to determine the likelihood of vessel rupture during a PTS event. Fracture mechanics calculations during the 1980s at Oak Ridge National Laboratory (ORNL) estimated PTS related vessel failure probabilities (ref. 7). These calculations (in support of NRC Regulatory Guide 1.154 (ref. 8)) concluded that the inputs for flaw densities and size distributions were the largest source of uncertainty in failure probability calculations. The ORNL inputs were based on results of the Marshall Committee Study (ref. 4), and involved a number of approximations and conservative assumptions such as arbitrarily placing all flaws at the inner surface of the vessel.

Given the difficulty of improving on the well-known and extensively used Marshall distribution, little research progress was made until the early 1990s. The literature shows the development of two complimentary approaches. One approach involves the statistical analysis of data from nondestructive inservice inspections of welds. Lance et al. (ref. 9) and Rosinski et al. (ref. 10) described the use of data from inservice inspections (ISI) along with statistically based software (the SAVER code) to develop flaw size and density distributions. Another approach developed by Rolls Royce and Associates in the United Kingdom simulates the population of flaws in multi-pass welds by application of an expert system model based on input from experts in the areas of welding and vessel fabrication (ref. 11, ref. 12). Both approaches have the objective of using the best available data and knowledge to estimate fabrication flaw occurrence rates.

2.2 Domestic Reactor Pressure Vessel Fabrication

Fabrication flaws rates are an important input to the PFM calculations. The fabrication process presents a number of variables or characteristics that must be considered and some have a significant bearing on the introduction of flaws into the RPV. The specific fabrication characteristics that were considered and discussed during the expert judgment process are discussed in detail in sections 4.6 and 4.7 of this paper. There were three major manufacturers of domestic reactor pressure vessels, Babcock and Wilcox, Chicago Bridge and Iron and Combustion Engineering. Combustion Engineering fabricated about 45% of the domestic RPVs, Babcock and Wilcox fabricated about 35% and Chicago Bridge and Iron about the remaining 20%. The fabrication and inspection process was different for each manufacturer although each vessel was inspected to ASME (ref. 13) standards prior to operation. The fabrication process for PWRs and BWRs is very similar but PTS is only a concern for PWRs.

Simplistically, most RPVs in the U. S. were constructed by welding together plate material and forgings. The shell courses of the RPVs were constructed by welding three sections of formed plate resulting in axial weldments or the shell courses were forged rings. Figure 2.1 shows a plate being bent to form a segment of shell course.

The shell course plates were formed into arcs and the axial weld preparations were made. The forged rings assembled as the shell contained no axial welds. The base metal materials used for most plates and forgings were A533B and A508 respectively.

The welding process used in the fabrication of the reactor vessels varied with each manufacturer. For the vast majority of PWRs three welding processes were used in assembling the reactor vessels, shielded metal arc welding (SMAW), gas metal arc welding (GMAW) and

submerged arc welding (SAW). The GMAW process was rarely used or employed but when it was used it was for cladding repairs. Both SMAW and SAW can be used for axial and circumferential welds. Electroslag is an automatic process that was mainly used for axial welds in BWR vessels. Before, during and following the welding, both surface and volumetric inspections were performed. A stainless steel cladding was applied to the inside of each shell course. The formed rings were then stacked and welded to form the cylinder (figure 2.2). These circumferential weld preparation surfaces were inspected prior to welding and the welds were subjected to inspections during and following welding. Finally, cladding was applied to the inside of the vessel to cover the newly formed circumferential weld and the clad surface was then inspected

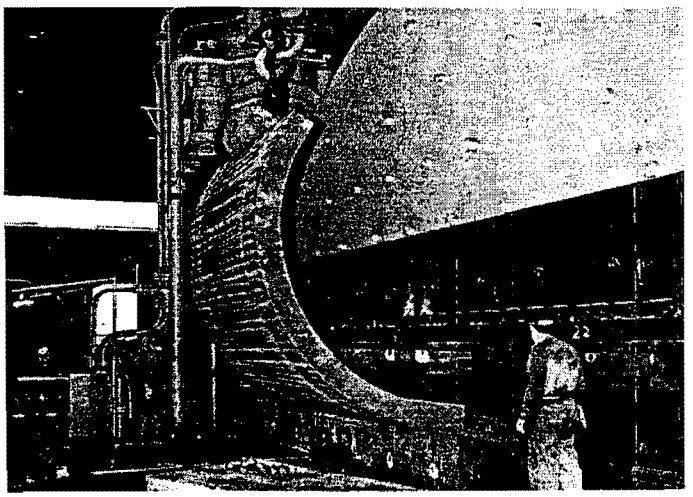

Figure 2.1 Bending of RPV plate material

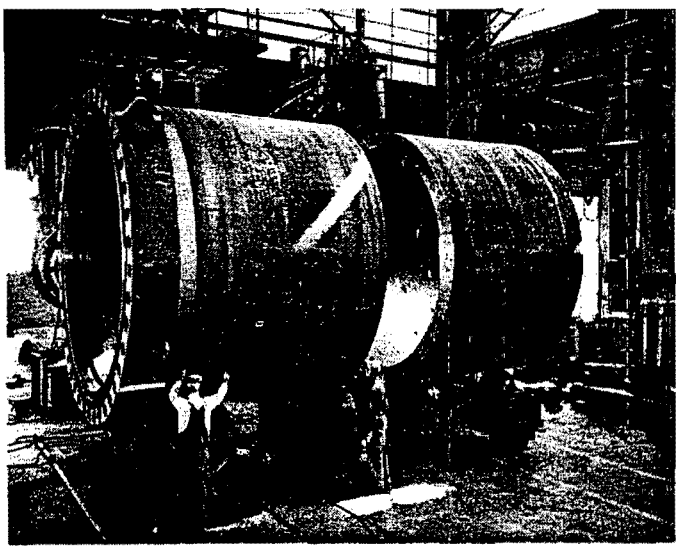

Figure 2.2 RPV rings awaiting circumferential (girth) welding

Appendix A to this report contains a compilation of weld and clad process information obtained from the experts to the best of their recollection. Domestic RPVs were fabricated between mid 1950's through the early 1980's. Data from the vessels fabricated by Rotterdam and Creusot-Lorie was not available at the time this paper was completed. Further research into the fabrication process of Rotterdam and Creusot-Lorie vessels will be published in the final NUREG on a generalized flaw distribution. This information is crucial in determining the types and sizes of flaws that are introduced.

2.3 RPV Inspection

The preservice inspection (PSI) was the base line that was created for the quality of the welds prior to operation of the completed RPV. The PSI differs from the fabrication inspections (based on ASME Boiler and Pressure Vessel Section III Code) because the PSI is performed on the RPV after installation using the procedures and flaw acceptance/rejection criteria slated for inservice inspection (ASME Section XI Code). Operating RPVs received preservice inspections that have met the same requirements.

3.0 ULTRASONIC DETECTION AND DESTRUCTIVE VALIDATION OF FLAW POPULATIONS IN RPV MATERIALS

The methods used for obtaining the data for the flaw work performed at PNNL will be discussed in this section. Determining a flaw distribution is a difficult task. As previously stated until the early 1990's, little research progress has been made to update the Marshall flaw distribution and the results of the Marshall Committee Study (Ref. 4). Recent publications are available on the development of flaw distributions using the empirical data from PNNL (Ref. 1 and 2) and the simulated flaw distribution from RR-PRODIGAL Code (Ref. 3).

3.1 RPV material examined by PNNL:

PNNL obtained empirical data from RPV material fabricated by three domestic RPV manufacturers representing four different vessels. NDE inspections were performed on portions of the weldment and base metal of RPV material from Pressure Vessel Research Users Facility (PVRUF), Shoreham, River Bend Unit 2 and Hope Creek Unit 2 vessels. The very sensitive SAFT-UT(Synthetic Aperture Focusing Technique for Ultrasonic Examination) was used to detect and characterize flaws in the vessel material (ref. 1, ref. 2). The welds from the RPV material are SAW and SMAW with different weld geometries. Table 3.1 lists the RPV weld metal material that is being used for this flaw distribution work . Figure 3.1 shows the weld cross section for the PVRUF circumferential weld (girth) between the upper and intermediate shell courses. Figure 3.2 displays a micro-etch of the Shoreham axial weld. Note that the PVRUF weld geometry is a single V and Shoreham is a double U configuration. Table 3. 2 lists the base metal material that is being used in the flaw distribution work. All of the base metal material that PNNL inspected is A533 plate. Presently the empirical data does not include material from a RPV fabricated from forged rings. Midland vessel was fabricated with forged rings and was inspected using an earlier model of SAFT. Improvements to the SAFT-UT system were made after the Midland inspection to permit a more accurate characterization of small fabrication defects. Plans are being made to possibly obtain ring forging material for inspection using the improved SAFT-UT system. Additional ring forging material would allow the flaw distribution data to include all base metal material for domestic RPVs.

RPV WELD MATERIAL SELECTED FOR GENERALIZED FLAW DISTRIBUTION					
	MIDLAND*	PVRUF	SHOREHAM	RIVER BEND 2	HOPE CREEK UNIT 2
MANUFACTURER	B&W	CE	CE	CB&I	CB&I
TYPE	PWR	PWR	BWR	BWR	BWR
METERS OF WELD	4	20	24	15	3
YEARS OF CONSTRUCTION	1968-1974	1976-1981	1968-1974	1974-1978	1971-1975
FABRICATION PROCESS	Ring Forgings	Bent Plates	Bent Plates	Bent Plates	Bent Plates
WELDS INSPECTED	CIRC Welds	CIRC Welds	CIRC and Axial Welds	CIRC and Axial Welds	CIRC and Axial Welds
*Midland material is not included in the data for the Generalized Flaw Distribution					

Table 3.1. RPV WELD MATERIAL inspected for Generalized Flaw Distribution

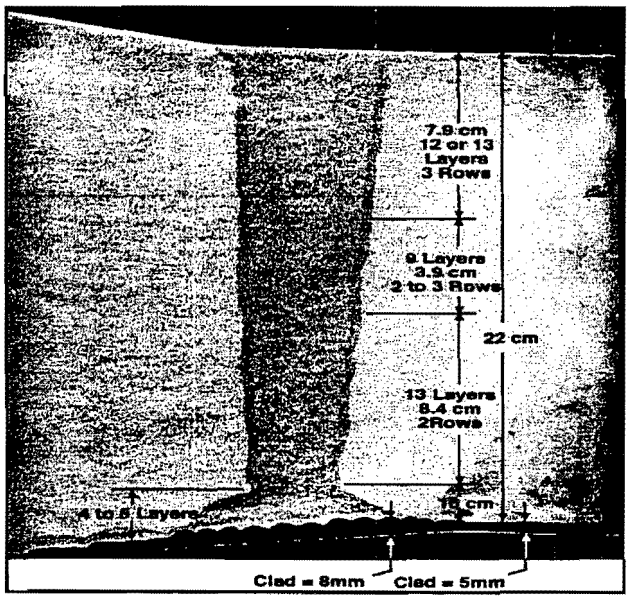

Figure 3.1. Cross Section of PVRUF Circumferential Vessel Weld

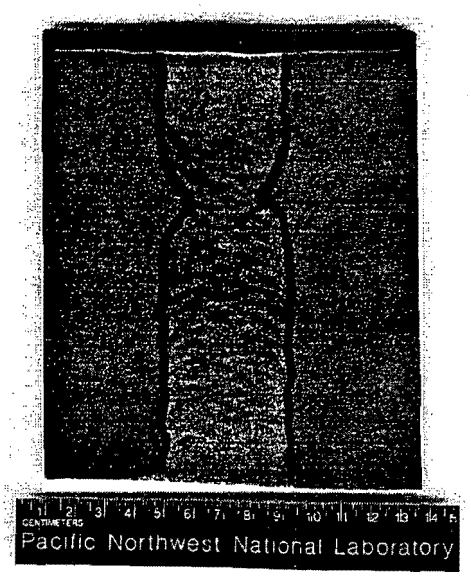

Figure 3.2 Micro-Etch of Shoreham Axial Weld

RPV BASE METAL SELECTED FOR GENERALIZED FLAW DISTRIBUTION				
	PVRUF	SHOREHAM	RIVER BEND UNIT 2	HOPE CREEK UNIT 2
MANUFACTURER	CE	CE	CB&I	CB&I
TYPE	PWR	BWR	BWR	BWR
VOLUME (M^3) OF BASE METAL	0.9	6.8	1.0	0.6
MATERIAL	A533B bent plate	A533B bent plate	A533B bent plate	A533B bent plate

Table 3. 2 RPV base metal material.

3.2 Preliminary Findings:
An extensive data base on fabrication flaws is being developed from the UT examinations of weld and base metal material. NDE of four vessels and DE of the PVRUF material has been completed. Additional work is being planned for FY 2001. In addition to the empirical data, PNNL has used the flaw simulation model of RR-PRODIGAL to estimate the number and sizes of flaws in the welds of the PVRUF and Shoreham vessels. Preliminary analysis of the data of the densities of flaw indications in base metal appear to be much less than that in weld metal. However, because there is so much more base metal in a RPV, it is therefore important to know the real flaw density and size distribution functions for base metal in order to conduct meaningful fracture mechanics structural integrity assessments.

Tables 3.3 and 3.4 show the preliminary data from all vessels on flaw indications for weld metal and base metal respectively. Tables 3.5 through 3.10 show confirmed flaw data from the PVRUF vessel. The data from the Shoreham vessel has not been validated. PNNL and EPRI are working cooperatively to examine the Shoreham vessel material. Once the NDE exams are completed the Shoreham vessel material will be destructively validated. Table 3.11 shows the distribution of simple flaw indications in the Shoreham RPV. Additional NDE will be performed on River Bend and Hope Creek material also.

Preliminary results for the four vessels show that year(s) of construction may be important. The validation research of PVRUF shows that all flaws greater than 7mm in size were associated with repaired areas. The repair flaws were complex in composition and orientation in both PVRUF and Shoreham. Complex in this work is defined as groups of more than three indications bound by proximity. Other similarities in PVRUF and Shoreham were, numerous small flaw indications were found on the fusion surfaces of the structural weld with the base metal on both PVRUF and Shoreham, and the largest flaw indications were complex in shape and related to weld repair areas. The density of flaws in the PVRUF and Shoreham vessels is significantly greater than predicted by a Marshall Distribution. The cumulative flaw rate of the Shoreham (unvalidated) vessel material is approximately three times greater than the PVRUF (validated) vessel material (figure 3.3). The Shoreham RPV material had long lack of fusion indications and the PVRUF RPV material did not.

PRELIMINARY RESULTS ON FLAW INDICATION RATES IN WELD METAL			
VESSEL	Weld Volume (m^3)	Indication Density (indications/m^3) indications ≥1.0mm	Indication Density (indications/m^3) indications ≥ 4.0mm
Shoreham	0.15	30000	1000
Hope Creek	0.004	40000	2000
River Bend	0.04	10000	300
PVRUF	0.17	9000*	600
*validated flaw rates			

Table 3.3 Preliminary results on flaw indication rates in weld metal by Vessel that PNNL has inspected to date

PRELIMINARY COMPARISON OF FLAW INDICATION RATES IN BASE METAL AND WELD METAL				
RPV	Base Metal - Inner NearSurface		Weld Metal	
	Volume Analyzed (m^3)	Indication Density (indications/m^3)	Volume Analyzed (m^3)	Indication Density (indications/m^3)
Shoreham	0.016	250	0.15	30000
Hope Creek	0.009	5000	0.004	40000
River Bend	0.024	1420	0.04	10000
PVRUF	0.014	7000	0.17	9000*
*validated flaw rates				

Table 3.4. Preliminary comparison of flaw indication rates in base metal and weld metal by vessel

	<3mm	3mm	4mm	5mm	6mm	7mm	8mm	Total ≥ 3mm
Crack, LOF	190	7	2	2				11

Table 3.5 Flaws in Weld Metal of the Inner 25mm of the PVRUF Vessel

	<3mm	3mm	4mm	5mm	6mm	7mm	8mm	Total ≥ 3mm
Crack, LOF	1200	3	1					4

Table 3.6 Flaws in Cladding and at the Clad-to-Base Metal Interface

	<3mm	3mm	4mm	5mm	6mm	7mm	8mm	Total ≥ 3mm
Indications	180	10	3					13

Table 3.7 Indications in Base Metal of the Inner 25mm of the PVRUF Vessel

	<5mm	5-6mm	7-8mm	9-10mm	11-12mm	13-14mm	Total ≥5mm
LOF, Slag	1400	19	4				23

Table 3.8 Flaws in Weld Metal Outside the Near-Surface of the PVRUF Vessel

	<5mm	5-6mm	7-8mm	9-10mm	11-12mm	Total ≥ 5mm
Laminations			1			1
Indications	360	10	1			11

Table 3.9 Indications in Base Metal Outside the Near-Surface of the PVRUF Vessel

	5-6mm	7-8mm	9-10mm	11-12mm	13-14mm	15-16mm	17-18mm	Total ≥5mm
Complex Flaws	5			1			1	7

Table 3.10 Flaws in Repairs in PVRUF

Distribution of Simple Flaw Indications in the Shoreham RPV					
	<4mm	4mm	5mm	6mm	Total
Clad	59			1	60
Root	154	2			156
Weld	397	1	1		399
Fusion	3249	79	19	4	3351
Repair	45				45
Base	18				18
Total	3922	82	20	5	4029

Table 3.11 Unvalidated Shoreham NDE Data

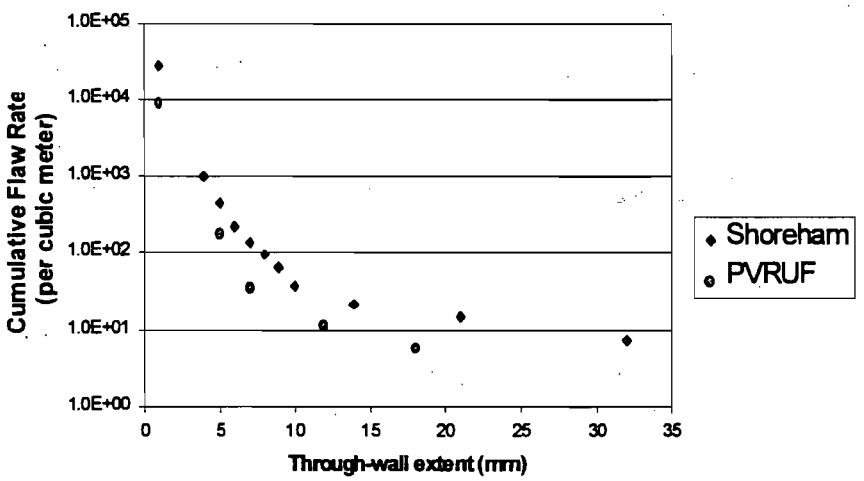

Figure 3.3
Comparison of Shoreham Cumulative Flaw Indication Rate to Validated PVRUF Results

4.0 EXPERT JUDGMENT PROCESS

The NRC's Office of Research has committed to revising the PTS acceptance criteria and determined that the expert judgment process in conjunction with recent data from PNNL, experience from Yankee Rowe, and flaw simulation models provided by RR-PRODIGAL is the most efficient method for determining the bases for a generalized flaw density and size distribution.

The formal use of expert judgment (sometimes referred to as expert opinion) has been extensively applied to a number of major studies in the nuclear probabilistic risk assessment area. Scientific inquiry and decision-making have always relied on expert judgement, but the formal use of expert judgement as a well-documented systematic process has also been used.

In the case of the development of a generalized flaw distribution for domestic RPVs, 17 experts participated as the expert panel. The panel was needed to review, interpret and supplement available information on reactor vessel fabrication processes and reactor vessel flaw distributions. The experts also reviewed the comprehensive work to date by PNNL.

The expert judgment process had eight steps. The eight steps, which form the basis for the use of expert judgment in the development of the generalized flaw distribution, are discussed in the next sections.

4.1 Selection of Issues and Experts

The selection of issues and experts was closely related. The initial selection of issues was developed by NRC staff and PNNL staff and was used to guide the selection of experts. The experts reviewed the list of issues and proposed additions, deletions, or modifications to the list. It was essential that the experts be knowledgeable about the state of the art and were chosen to represent a diversity of backgrounds, with a wide variety of viewpoints (e.g. academic, consulting, vessel fabricators, forging manufacturers, etc.). The specific areas of expertise were: ASME Code for construction; failure analysis; forgings; metallurgy; non-destructive examination (NDE); reactor vessel fabrication; statistics; and welding. The 17 experts were selected on the basis of their recognized expertise in the issue areas, such as demonstrated by their publications.

The preliminary set of issues developed by NRC and PNNL after a series of brainstorming sessions are listed below. It is important to note that responses were needed for each issue whether it is formed as a question or a statement. This list was sent to a group of individuals from which the expert panel was formed.

1. Clarification of objective, the development of a generalized flaw distribution for domestic reactor pressure vessels
2. With three fabricators and different fabrication processes, how would you determine that one distribution is sufficient?
3. What is the significance of the differences between the flaw distribution for each vessel fabricator?
4. What fabrication variables were considered?
5. Did you rank characteristics by significance?

6. What was your basis for eliminating certain characteristics?
7. Are there differences between the plate distribution and the weldment distribution?
8. What distribution was determined to be more significant and why?
9. What type/size flaws are of importance and why?
10. Were certain fabrication processes more susceptible to creating flaws?
11. Were certain welding process more susceptible to creating flaws?
12. What must be done to create a surface breaking flaw?
13. Where has industry located surface breaking flaws (nuclear and non-nuclear)?
14. Regarding the cladding process, how much is the base metal affected during the cladding process, in terms of under clad cracking and is under clad cracking more prevalent in French vessels?
15. What are the factors, variables or determinants that will have an influence on the distribution of fabrication flaws? Are there more than the list below?

    Base Metal (Plates, forged rings)
        What NDE procedure was used (sensitivity, accept/reject criteria)?
        What are the flaw specifics (type, location, size)?
        Were flaws surface connected or embedded?
        How many flaws per plate were detected?
        Was there a difference for plates in the beltline vs. nozzle shell, etc?
        What was the largest flaw detected & repaired?
        Was NDE performed on all surfaces of the plates?
        Did one surface contain more flaws than another surface?

    Welding procedure
    Welding materials
    Weld design
    Repairs (base metal, cladding, weldment)
    Cladding
        What NDE procedure was used?
        What are the flaw characteristics that required repair?
        What was the location of most flaws?
        Describe the repair process
        Pre- and Post Hatch

16. Is more data available for naval vessels than for commercial nuclear power plant (NPP) vessels?
17. What was the difference in steel used in NPP vessels and naval vessels?
18. What caused the cracking in the head of the Quad Cities vessel in the 1990s?
19. Location of vessel repairs, is there a pattern as to where the repairs are located?
20. Are NDE results of pre-Hatch vessels less reliable and are the vessels more susceptible to flaws than post-Hatch vessels? What effect did the change of NDE of vessel fabrication processes have as there were definitely more repairs? (Hatch History is discussed below)

    During 1971/1972 a major discontinuity was discovered in a Hatch vessel nozzle after delivery. Prior to the Hatch incident, no UT beyond the basic ASME Sec III was performed. During the reaction era numerous repairs were made because of the dramatic increase in UT requirements so vessels delivered between 1974 and 1977

had an increased repair rate. For vessels delivered after 1977 the repair rate was lower due to improvements in the welding and cladding processes. During the period between 1971 and 1975, reactor vessel fabricators related to the hatch incident as three separate eras, pre-Hatch era prior to 1971, reaction to Hatch era 1971-1975, and stabilizing era after 1975.

Immediate feedback was received on the list of issues prior to the formal presentation to the panel. This list of issues precipitated a wide breadth of discussions during the first meeting of the expert panel

4.2 Presentation of Issues to the Experts

In addition to providing the experts with the issues, this step provided a mechanism to discuss the state-of the art for each issue. An essential aspect of issue presentation is issue decomposition, which allowed the experts to make a series of simpler assessments rather than one overall assessment of a complex issue. This step was crucial, as the decomposition of an issue can vary by expert and thereby, significantly affect its assessment.

Upon initial review of the issues, extensive feedback was provided by the experts. This feedback was critical to NRC and PNNL staff in making revisions to the format in which the issues were presented to the experts during their individual elicitation sessions.

4.3 Elicitation Training

The purpose of the elicitation training was to help the experts learn how to encode their knowledge and beliefs into a quantitative form (Figure 4.1). Elicitation training can significantly improve the quality of the experts' assessments by avoiding psychological pitfalls that can lead to biased and/or other overconfident assessments. The training was conducted by a normative expert who is knowledgeable about decision theory and the practice of probability elicitation.

The elicitation training for the GFD was conducted as part of the initial three-day meeting of the expert panel in Atlanta, GA. In addition to elicitation training, NRC and PNNL staff gave presentations on the background of the PTS work and the empirical NDE data from RPV inspections. The definition of a flaw for use during the expert judgment process was developed. For the GFD a flaw is defined as an unintentional discontinuity that has the potential to compromise vessel integrity and is present in the vessel after pre-service inspection.

Upon completion of the elicitation training and discussions with the experts, the elicitation team developed a set of characteristics that were to be presented to each expert during the elicitation sessions.

X = Quantity to be assessed

X_L = Low value

X_H = High value

X_M = Midvalue

Chance $\{ X < X_L \} \approx 5\%$

Chance $\{ X > X_H \} \approx 5\%$

Chance $\{ X < X_M \} \approx$ Chance $\{ X > X_M \} \approx 50\%$

- (X_L , X_H) is an approximate 90% coverage interval for X

Figure 4.1. Quantitative Assessment of Knowledge and Beliefs

4.4 Preparation of Issue Analyses by the Experts

In order to perform a comprehensive issue analysis, the experts were given sufficient time and resources to analyze all of the issues before their individual elicitation sessions. If an expert's preparation required additional technical support, it was provided by NRC/PNNL staff. Each expert was given a set of documents to review which supplemented the information presented during the three-day meeting in Atlanta.

4.5 Discussion of Issue Analyses

Before the elicitation session, the experts were invited to present the results of their analyses and research. Some of the experts engaged in discussions of the characteristics prior to their individual elicitation sessions. The ensuing discussions served to ensure a common understanding of the issues and the data.

4.6 Elicitation of the Experts

The elicitation sessions were conducted by the elicitation team and were held immediately following the discussion of the issue analyses. The elicitation team met separately with each expert, to avoid pressure to conform and other group dynamic interactions that might occur if the expert judgments were elicited in a group setting. The elicitation team consisted of a normative expert, two substantive experts, and a recorder.

Tables 4.1 and 4.2 list the characteristics that were presented during the elicitation session. The experts were asked to rank each characteristic in order from highest to lowest in terms of contributing to or having a flaw after preservice inspection. They were then asked for a quantitative assessment. For example, in item 1, Product Form, the experts were asked which product form is most likely to have a flaw remaining after preservice inspection. Suppose the response was that weld metal is the most likely to have a flaw remaining following preservice inspection, followed by cladding, plate and forgings. The expert was then asked to assess the relative likelihood of a flaw in cladding, plate and forgings, each compared with the likelihood of a flaw in weld metal. For each

relative likelihood (expressed as a ratio or percent change), the expert was asked to supply low, high and midvalues, as defined in Figure 4.1. For characteristics where the ranking or quantitative assessment did not apply, such as items 4, 11, 12 and 13, the experts were asked what effect the characteristic would have on the introduction of a flaw. For example, in item 4, field vs. shop fabrication, the experts were asked to compare a field-fabricated vessel with a shop-fabricated vessel. They were asked which vessel is more likely to have a large number of flaws after preservice inspection and what elements of fabrication are most affected by field vs. shop fabrication.

As the sessions were completed it became apparent to the members of the elicitation team that the experts were not able to provide quantitative data such as ranking of the characteristics and/or pairwise comparisons for all 13 characteristics. For example, welder skill and inspector skill are dominated by human factors issues and quantitative data was not easily provided. The experts also provided the elicitation team with feedback that some of the characteristics should be further subdivided to accurately classify a particular characteristic. Flaw size and cladding process are examples of two characteristics that needed further division.

4.7 Recomposition and Summary of Results

Each expert's elicitation responses were recomposed by the normative and substantive experts to put them in a form suitable for further analysis. This was completed after each session. As stated previously, upon completion of the 17 elicitation sessions and a preliminary review of the responses, it was apparent that the characteristics had to be divided into quantitative and qualitative characteristics and there was a need to re-elicit the experts on the quantitative characteristics and obtain additional information on flaw size.

Quantitative characteristics are those characteristics for which the experts were able to provide numerical comparisons. In most cases, records and data are available to verify information for quantitative characteristics. The quantitative characteristics are product form, weld process, flaw mechanisms, repairs and flaw size.

Qualitative characteristics are those characteristics for which the experts could not provide any meaningful numerical comparisons. Records and corresponding information are not readily available. The qualitative characteristics are field vs. shop fabrication, weld procedure, weld materials, welder skill, inspection procedure, inspection skill, base metal properties, surface parameters and preparation, and flaw location.

The experts were re-elicited to obtain responses regarding:

- -flaw size - density of large flaws vs. small flaws
- -flaw density in cladding vs. weldmetal
- -flaw density in base metal vs. weld metal
- -repaired vs. non-repaired weld metal and base metal for small and large flaws
- -underclad cracking
- -flaw density of SAW and ESW vs. SMAW
- -flaw density of three cladding processes (strip, multi wire and single wire) vs. SMAW

A partial analysis of the quantitative results is presented in Appendix B. The characteristics include flaw size, product form, non-repair vs. repair, underclad cracking

Characteristic	Rank	LMH Value	Flaw Size/Fabricator
7. Weld Materials			
Axial Welds			
Girth Welds			
Repairs			
Cladding			
8. Welder Skill			
Axial Welds			
Girth Welds			
Repairs			
Cladding			
9. Inspection Procedure			
Forgings			
Plate			
Weld metal			
Repairs			
Cladding			
10. Inspector Skill			
Forgings			
Plate			
Weld metal			
Cladding			
Repairs			
11. Base Metal Properties			
12. Surface Prep and Parameters			
13. Flaw Location			

Table 4.2 Characteristics presented to experts (page 2)

4.8.1 Quantitative Characteristics

Technical rationales for the responses from each expert were recorded during the elicitation sessions. Information on the quantitative characteristics can also be obtained from construction and QA records for most vessels. Many experts provided similar or identical rationales to justify their assessments. The technical rationales for the quantitative characteristics are as follows:

1. Flaw Size
    1. Expect more small flaws than large flaws by a large ratio because of the fabrication processes of base metal and weld metal
    2. Large flaws should be detected by NDE
    3. Large flaws are usually caused by loss of control of the welding process
    4. Small flaws can be missed due to sensitivity and recording levels of NDE equipment
    5. Small flaws are created as a result of the weld process, e.g., laying of beads of weld metal
    6. Small flaws are less likely to affect vessel integrity

2. Product Form - Base Metal Ring Forgings
    a. No as-forged surfaces remain on the finished product
    b. The ID and OD of the forgings were machined for weld preparation
    c. Due to the forging process the inside of the forging is more likely to have flaws.
    d. 100% UT of one surface and MT on ID and OD was completed at the manufacturer prior to being shipped to the vessel fabricator

3. Product Form - Base Metal Plate
    a. Laminations and non-metallic inclusions were the most prominent problems
    b. Base metal was rolled to required size and flat surfaces were descaled
    c. Vanadium content presented problems with strip cladding and was modified
    d. Due to the fabrication process of plates, it is more likely to have flaws in the center of the plate

4. Product Form - Cladding
    a. No volumetric NDE on cladding
    b. Discontinuities in the cladding maybe of no concern to RPV integrity
5. Product Form - Weld metal
    a. Most likely to have flaws as compared to other product forms due to the welding process (starts and stops, flux)
    b. The introduction of flaws is dependent on the weld process
    c. The placement of weld metal is strongly affected by human factors; therefore more likely to have flaws than other product forms

6. Repairs to Weld metal
    a. The vast majority of repairs were performed using SMAW
    b. A repaired weld will likely have an improved level of integrity relative to the flawed weld prior to repair

c. A repaired weld is more likely to have flaws that an unrepaired weld because repairs are completed by the SMAW process
d. The flaw state in a repaired weld is the same as repaired base metal
e. In-process removal of slag, etc. were not considered as a weld repair

7. Repairs to Base Metal
   a. Due to the fabrication process there are fewer structurally significant flaws in the base metal that in welds or cladding
   b. The flaw state in repaired base metal is the same as repaired weld metal. Repair to a weld prep region prior to welding is classified as a repair to the base metal
   c. During fabrication, repairs to weld joint preparations were common
   e. Most repairs to base metal were to edge prep laminations or other flaws extending to the weld groove and would be detected via MT or PT.

8. Repairs to Cladding
   a. Manual welding process was used to repair cladding
   b. Good access to cladding eliminated difficult repairs geometries

9. Weld Process - SMAW
   a. Flaw size is usually smaller than flaws created by other weld processes due to the smaller bead size
   b. Strongly affected by human element; more so than SAW and ESW
   c. SMAW is more likely to have a flaw as compared to SAW and ESW due to stop and start during the process to change electrodes

10. Weld Process - SAW
    a. Incorrect equipment setup could result in a large number of flaws
    b. An out-of-control SAW process could produce more large flaws than SMAW
    c. Can have larger flaws than SMAW due to the larger bead size

11. Weld Process - ESW (mainly used in BWRs but information was provided by experts)
    a. Most likely to produce very large flaws due to the large pass size of ESW process
    b. Large flaws produced by ESW would be detected by NDE

12. Weld Process - Cladding
    a. Most circumferential welds were manually clad
    b. Control of the single wire process is superior to multi-wire
    c. Multi-wire cladding is superior to single wire because there are fewer interconnections and there are fewer passes to cover a given area with multi wire than with single wire
    d. Strip wire cladding problems are readily visible due to the smooth surface
    e. Strip wire cladding is superior to multi-wire

13. Flaw Location - (Most common areas for flaws)
    a. Weld metal
       repairs
       start/stop locations

back gouge areas
root pass

b. Base metal
heat affected zone
forgings at the inside surface
plates at the top and center

4.8.2 Qualitative Characteristics:

As stated in Section 4.7 for qualitative characteristics it is not possible to quantify the effect the characteristic will have on the introduction of a fabrication flaw and there are no records readily available to document information on these characteristics. However, qualitative knowledge can help guide application of existing data to other vessels. The technical rationales for the qualitative characteristics are as follows:

1. Field vs. Shop Fabrication
    a. Most field fabricated vessels were partially assembled in the shop
    b. Welder skill may have more effect on field-fabricated vessels because some or even most of the welders have been relocated from their home bases.
    c. Better positioning equipment was available for shop fabricated vessels
    d. Easier to control post weld heat treatment in the shop
    e. Field and shop vessels were accredited by ASME to same standards
    f. All field welds were SMAW in 2G position vs. shop weld being automated and in 1G position

2. Weld Procedure
    a. All weld procedures were qualified to meet ASME requirements
    b. If the weld procedure was properly qualified and demonstrated prior to use, it should not significantly affect the introduction of flaws

3. Weld Materials
    a. All weld materials were ASME-qualified
    b. In terms of introducing a flaw, weld flux is more important than weld wire
    c. Improvements of weld materials were made over the years of RPV fabrication
    d. Storage, handling, contamination, etc. are important for all weld materials

4. Welder Skill
    a. Welder skill is important for all weld processes
    b. Manual processes are strongly affected by human factors
    c. All welders must meet the same minimum requirements
    d. Welding is an art as well as a science
    e. Poor welder skill is recognized early
    f. Records will not provide data on welder skill on a vessel specific basis

5. Inspection Procedure
    a. NSSS contract inspection requirements varied for each vendor as stated by the client
    b. Minimum requirements for the inspection procedures were stated by ASME
    c. UT was relatively new during early fabrication and has evolved extensively

d. No significant improvements in RT with the exception of digitized radiographs
e. Inspection procedures may have been one possible cause of the Hatch incident
f. Fabricators performed independent tests to enhance/improve fabrication process

6. Inspector Skill
    a. Interpretation of NDE information is an important inspector skill
    b. Inspector skills have changed over the years due to experience, equipment improvements and automation of certain NDE techniques

7. Base Metal Properties
    a. Variability of base metal properties should have little or no effect on flaw occurrence
    b. Base metal chemistry can influence under clad cracking

8. Surface Preparation and Parameters
    a. Surface treatment such as sandblasting and grinding can seal a crack or other flaw from dye penetrant
    b. Cleanliness/removal of machining oil is extremely important
    c. Joints that were prepared by arc/flame cutting may be more susceptible to flaws due to surface contamination

5.0 GENERALIZED FLAW DISTRIBUTION

This section consists of two parts. The first part presents a general methodology for constructing a generalized flaw distribution (GFD) which is applicable to any RPV. The methodology separates out vessel-specific properties of the RPV (volumes and areas of material) from general properties of flaws (densities and crack depth distributions). This separation allows us to combine observed data from different RPVs to estimate the general properties. The second part applies the general methodology to the PVRUF pressure vessel. Because the PVRUF and other analyses are still ongoing, the results should be considered preliminary and are subject to revision as more data becomes available.

5.1 Methodology

A GFD describes the number of flaws whose depths exceed x mm. The present approach is based on two GFDs, one for small TWD flaws and one for large TWD flaws. For weld metal, the size for welds separating small and large flaws depends on the bead thickness (b), and for base metal size it is determined by a fixed dimension, with one-quarter inch and less is considered a small flaw in this case (also denoted by b). For weld metal, a small flaw is one whose crack depth does not exceed the bead thickness ($x \leq b$) and a large flaw is one whose crack depth exceeds the bead thickness ($x > b$). Because bead thickness can vary from weld to weld, the range of x for small and large flaws may vary from weld to weld or for different welding processes used for a single weld.

Each GFD is composed of three parts: (i) flaw densities; (ii) volumes (for weld metal) or areas (for base metal) of material; and (iii) the distribution of crack depth, given a flaw. The densities together with the volumes or areas determine the total number of flaws and depend on flaw size, product form, weld process and repair state. The crack depth distributions depend only on flaw size and do not depend on product form, weld process or repair state. (This assumption will be checked as more data becomes available.) The separation of the crack depth distributions from the number of flaws allows crack depth data from different flaws to be combined to estimate the distributions.

The GFDs are given by $N_S(x)$ and $N_L(x)$, where x = crack depth and

$N_S(x)$ = number of small flaws > x, for $x \leq b$

$N_L(x)$ = number of large flaws > x, for $x > b$.

Product form, weld process and repair state are denoted as follows, together with the values they can take:

PF = Product Form (Weld Metal, Cladding, Plate, Ring Forgings)

WP = Weld Process (SMAW, SAW, ESW; Strip, Single & Multi Wire)

R = Repair State (Unrepaired, Repaired).

Flaw densities and amount of material are denoted by:

ρ_S(PF, WP, R) = density of small flaws per unit volume or area

$\rho_L(PF, WP, R)$ = density of large flaws per unit volume or area

$V(PF, WP, R)$ = volume or area of material.

For any RPV, let N_S and N_L be the total number of small and large flaws, respectively. Then

$$N_s = \sum \rho_S(PF, WP, R) \bullet V(PF, WP, R)$$

$$N_L = \sum \rho_L(PF, WP, R) \bullet V(PF, WP, R),$$

where the summations are taken over all values taken by PF, WP and R.

Each crack depth distribution is expressed as a complementary cumulative distribution function (ccdf), as follows:

$G_S(x)$ = ccdf for small flaws = Prob {crack depth > x}, where $x \leq b$

$G_L(x)$ = ccdf for large flaws = Prob {crack depth > x}, where $x > b$.

Each GFD is the product of the number of flaws and the corresponding crack depth distribution, as follows:

$$N_s(x) = N_S \bullet G_S(x) = [\sum \rho_S(PF, WP, R) \bullet V(PF, WP, R)] \bullet G_S(x)$$

$$N_L(x) = N_L \bullet G_L(x) = [\sum \rho_L(PF, WP, R) \bullet V(PF, WP, R)] \bullet G_L(x).$$

5.2 Application to the PVRUF Pressure Vessel

In this section, data from the PVRUF pressure vessel and the PNNL inspection and destructive evaluation results will be combined with results from the expert judgment process to estimate flaw distributions for the PVRUF vessel. Because they are based only on the observed data and on median values from the expert judgment process, these estimates do not reflect uncertainties in the flaw distributions. Furthermore, because the PVRUF and other analyses on which the estimated flaw distributions are based are still ongoing, the results in this section should be considered preliminary.

Volumes and areas of weld metal, base material and cladding for the PVRUF vessel, along with the applicable weld processes and repair status are listed in Table 5.1. These are taken from Ref. 14. Also in Table 5.1 are estimates of the flaw densities for both small and large flaws. The numbers of small and large flaws for each case are calculated by multiplying the volume or area by the corresponding density.

The flaw densities are based on the PNNL results where applicable and on the expert judgment results where data was not available, as explained in the notes for each case. The expert judgment results were used for the plate and cladding densities. As PNNL gathers additional plate and cladding data, it may be possible to base these densities on data.

The top part of Table 5.1 deals with flaws in weld metal and plate and the bottom part with flaws in cladding. The natural unit for the density of flaws in weld metal or plate is flaws per unit

volume and for flaws in cladding is flaws per unit area. Another reason for the division in Table 5.1 is that large flaws in cladding can have crack depths no larger than the cladding thickness, which is 6-8 mm. Because much of the data on which they are based is accurate to no more than one significant figure, most of the entries in Table 5.1 have been rounded to two significant figures (or three when the leading digit is 1) to avoid round-off error. However, the results should generally be considered accurate to no more than one significant figure. Although some material combinations were not present in the PVRUF pressure vessel, the corresponding densities are included in Table 5.1 for completeness and for possible application to other RPVs.

From Table 5.1, the estimated number of small flaws is N_S = 22,400, of which 18% are in the weld metal, 59% are in the plate and 23% are in the cladding. The estimated number of large flaws is N_L = 222, of which 26% are in the weld metal, 4% are in the plate and 70% are in the cladding. As explained in Note 10, large flaws in cladding can have crack depths no larger than 6-8 mm.

It remains to estimate the crack depth distributions. From Tables 4.1-4.6 in Ref. 15, there were 19 validated large flaws in the examined PVRUF material and from Tables 6.1-6.10 in Ref 2, there were 46 large flaws in the examined Shoreham material. These 65 large flaws are listed in Table 5.2. The flaw sizes are assumed to be the bin centers as listed in the PVRUF and Shoreham tables. In those cases where the bead thickness fell within the bin range, the flaw sizes were assumed to be uniformly distributed across the bin in order to determine how many of the flaws should be classified as small and how many as large. Although the PVRUF data is validated while the Shoreham data has not yet been validated, the two data sets were combined to estimate $G_L(x)$, the ccdf for large flaws (see Figure 5.1). Note that this ccdf may change when the validated Shoreham data is used.

The crack depth distribution for large flaws in the PVRUF vessel can be estimated by multiplying the ccdf for large flaws by the estimated number of large flaws in the PVRUF weld metal and plate. (Possible large flaws in the cladding are ignored because they cannot exceed 6-8 mm in crack depth; no large flaws were found in the examined PVRUF cladding.) From Table 5.1, the estimated number of such large flaws is 66. The corresponding crack depth distribution is given by Figure 5.2 as the number of flaws exceeding a specified crack depth.

From Table 3.1 in Ref. 15, there were 43 radiographic indications of small flaws. The measured through-wall sizes listed in Table 3.1 are plotted in Figure 5.3 as an estimate of $G_S(x)$, the ccdf for small flaws. The relatively large jumps in the graph at x = 1.0 and 1.5 are due to rounding in the measured values. Because of this and other sources of uncertainty in the data, no smoothing of the ccdf was done; a smoothed curve would not necessarily be a better estimate of $G_S(x)$ than the unsmoothed curve.

The crack depth distribution for small flaws in the PVRUF vessel can be estimated by multiplying the ccdf for small flaws by the estimated number of small flaws in the PVRUF weld metal, plate and cladding. From Table 5.1, the estimated number of small flaws in the weld metal and plate is 17,200 and in the cladding is 5,200. The corresponding crack depth distributions are given by Figures 5.4a and 5.4b as the number of flaws exceeding a specified crack depth.

Product Form/ Weld Process/Repair State	PVRUF Volume (m^3)	Density of Flaws		No. of Flaws		Notes
		Small/m^3	Large/m^3	Small	Large	
Weld Metal/SMAW/NR	0.025	14,000	290	350	7	[1]
Weld Metal/SAW/NR	0.45	7,900	22	3,600	10	[2]
Plate/NR	16.7	790*	0.55*	13,200	9	[3]
Weld Metal/SMAW/R	0.007	9,800	5,700	70	40	[4]
Plate/SMAW/R	0	9,800	5,700	0	0	[5]
Total Weld Metal & Plate				17,200	66	
	PVRUF Area(m^2)	Small/m^2	Large/m^2	Small	Large	
Cladding/SMAW/NR	2.9	57	1.7*	165	5	[6]
Cladding/Strip/NR	72	69	2.1*	5,000	151	[7]
Cladding/MultiWire/NR	0	173*	5.2*	0	0	[8]
Cladding/SMAW/R	TBD	114*	5.7*	TBD	TBD	[9]
Total Cladding				5,200	156	[10]
TOTAL				22,400	222	

Table 5.1. PVRUF Flaw Distribution

* Based on expert judgment results

Notes for Table 5.1 The volumes and areas of material in the PVRUF vessel are for the middle portion of the vessel, as this is the only portion considered relevant to PTS issues. See Table 5.2 for a compilation of large flaws found in PVRUF and associated bead thicknesses.

[1] Volume: Ref. 14, Table 4. Densities: From Ref. 15, Table 4.1, there were 197 small and 4 large flaws in the inspected material. From Ref. 15, Table 2.1, .014 m^3 of material was inspected in the near-surface zone.

[2] Volume: Ref. 14, Table 4. Densities: From Ref. 15, Table 4.4, there were 1419 small and 4 large flaws in the inspected material. From Ref. 15, Table 2.1, 0.18 m^3 of material was inspected outside the near-surface zone.

[3] Volume: From Ref. 14, the total volume of the intermediate and lower shell = 8.37 + 8.37 = 16.74 m^3. Densities: From Table B.3, the median midvalue likelihood factor (MMLF) for plate vs. weld metal (SAW) is 0.1 for small flaws and 0.025 for large flaws. The corresponding densities for Weld Metal/SAW/NR are multiplied by these values.

[4] Volume: Ref. 14, Table 4. Densities: From Ref. 14, Table 2, 12 small and 7 large flaws were found in repaired weld metal. From Table 1, Note 7, the reported dimensions of the inspected repair differ from the dimensions of the SAFT-UT image. Using the averages of these dimensions, the repaired volume inspected is (.2215)•(.045)•(.165)•(.75) = 0.00123 m^3, where the factor of 0.75 accounts for the taper in the cavity. Hence the small flaw density is 12/0.00123 = 9800/m^3 and the large flaw density is 7/0.00123 = 5700/m^3.

[5] Volume: No repairs were made to plate in the PVRUF vessel. Densities: Because repairs to plate are made in the same way as repairs to weld metal, the flaw densities for plate are the same as the flaw densities for weld metal.

[6] Area: Ref. 14, Table 4. Densities: From Ref. 14, Table 2, 80 small and no large flaws were found in SMAW cladding. From Table 1, the area inspected was 1.4 m^2. Hence the small flaw density is 80/1.4 = 57/m^2. Because no large flaws were found in the PVRUF cladding, the expert elicitation results are used. From Table B.1, the MMLF for large vs. small flaws in unrepaired SMAW cladding is 0.03. Hence the large flaw density is (0.03)•(57) = 1.7/m^2.

[7] Area: Ref. 14, Table 4. Densities: From Ref. 14, Table 2, 180 small and no large flaws were found in strip-wire cladding. From Table 1, the area inspected was 2.6 m^2. Hence the small flaw density is 180/2.6 = 69/m^2. Because no large flaws were found in the PVRUF cladding, the expert elicitation results are used. From Table B.1, the MMLF for large vs. small flaws in unrepaired SMAW cladding is 0.03. Because the likelihood factor for strip-wire cladding is expected to be less than for SMAW cladding, a conservative estimate of the large flaw density is (0.03)•(69) = 2.1/m^2.

[8] Area: There is no multi-wire cladding in the mid-portion of the PVRUF vessel. The PVRUF multi-wire cladding was located only along the transition zone from one vessel wall thickness to a larger one. Accordingly, there was a significant misalignment between the multi-wire deposition weld and the RPV. This is not typical of the multi-wire process used in the belt line region of a vessel shell course. Densities: From Table B.9, The likelihood factors for both strip-wire and multi-wire vs. SMAW cladding are less than 1. However, for small flaws in strip-wire cladding, this result is at variance with the data-based likelihood factor of 69/57 = 1.2. Accordingly, direct application of the MMLF of 0.25 for multi-wire vs. SMAW cladding is not used. Instead, a derived likelihood factor for multi-wire vs. strip-wire is used. The ratio of the respective MMLFs is 0.25/0.1 = 2.5. This multiplier is applied to the small flaw density for strip-wire cladding to obtain a small flaw density of (2.5)•(69) = 173/m^2. From Table B.1, the MMLF for large vs. small flaws in unrepaired SMAW cladding is 0.03. Because the likelihood factor for multi-wire cladding is expected to be less than for SMAW cladding, a conservative estimate of the large flaw density is (0.03)•(173) = 5.2/m^2.

[9] Area: PNNL will review construction records to determine if any restoration cladding was made to the PVRUF vessel. Densities: From Table B.5, the MMLF for non-repaired vs. repaired SMAW cladding is 0.5 for small flaws. Hence the small flaw density for repaired cladding is 57/0.5 = 114/m^2. From Table B.6, the corresponding MMLF for large flaws is 0.3. Hence the large flaw density for repaired cladding is 1.7/0.3 = 5.7/m^2.

[10] Because flaws in cladding can have crack depths no larger than the cladding thickness, large cladding flaws can have crack depths no larger than 6-8 mm.

Flaw Size (mm)										BT (mm)	PVRUF (Ref. ~~10~~ 15
4	5	5-6	6	7	7-8	8	9	10	>10		
2	2									3.5	Tbl 4.1 (W,SMAW)
					4					6.5	Tbl 4.4 (W,SAW)
		2**			2					6	Tbl 4.5 (BM, NV)
		5							11.5, 17.5	3.5	Tbl 4.6 (W,R)
2	2	7			6				11.5, 17.5	#=19	Total PVRUF
Flaw Size (mm)										BT (mm)	Shoreham (NV) (Ref. ~~11~~ 2
4	5	5-6	6	7	7-8	8	9	10	>10		
			4							5	Tbl 6.1-6.3(W,SAW)
	10*									5	Tbl 6.1-6.3(W,R)
				1					21, 32 R	5	Tbl 6.4-6.5 (W, ~~SAW~~) R
								1		6	Tbl 6.5 (BM)
				1					14	5	Tbl 6.6 (W, R)
	1*		1	1		2	3			5	Tbl 6.7-6.8 (W,SAW)
	4*		7	3		2	1	1		5	Tbl 6.9-6.10 (W,SAW, SMAW)
	15		12	6		4	4	2	14, 21, 32	#=46	Total Shoreham
2	17	7	12	6	6	4	4	2	11.5, 14, 17.5, 21,32	#=65	Total

Table 5.2 Large Flaws in the PVRUF and Shoreham Vessels

Notes for Table 5.2

BT: Bead thickness
W: Weld metal
BM: Base metal
NV: Not validated
R: Repaired

* 50% of tabular value (BT = center of bin)
** 25% of tabular value (bin range = 4.5 - 6.5 mm and BT = 6 mm)

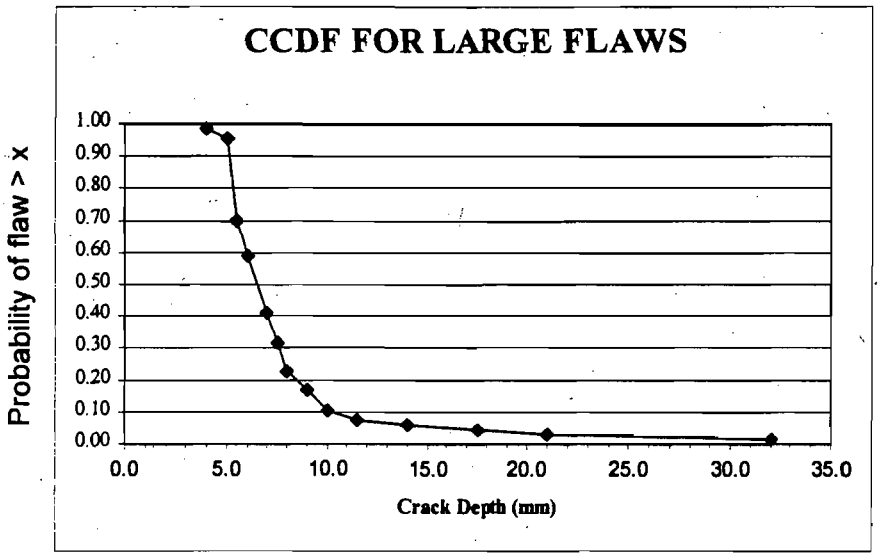

Figure 5.1 CCDF for Large Flaws

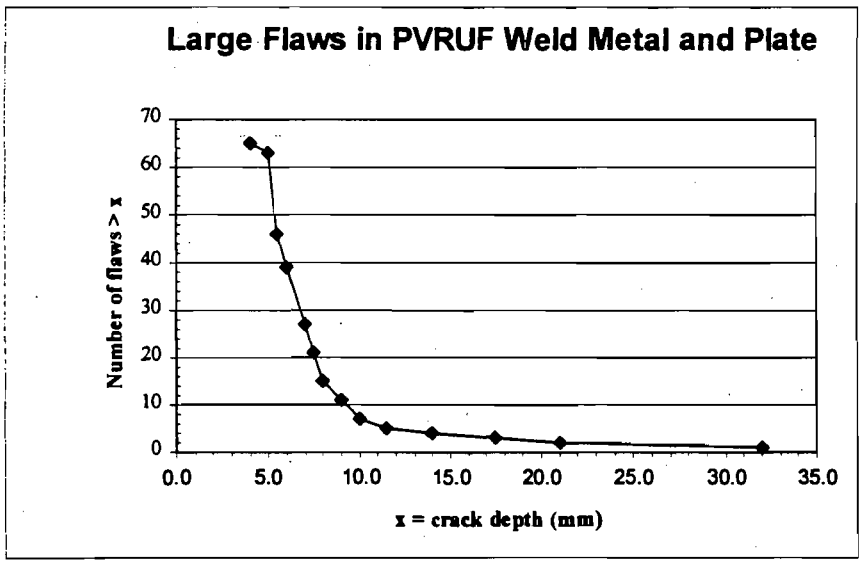

Figure 5.2 Large Flaws in PVRUF Weld Metal and Plate

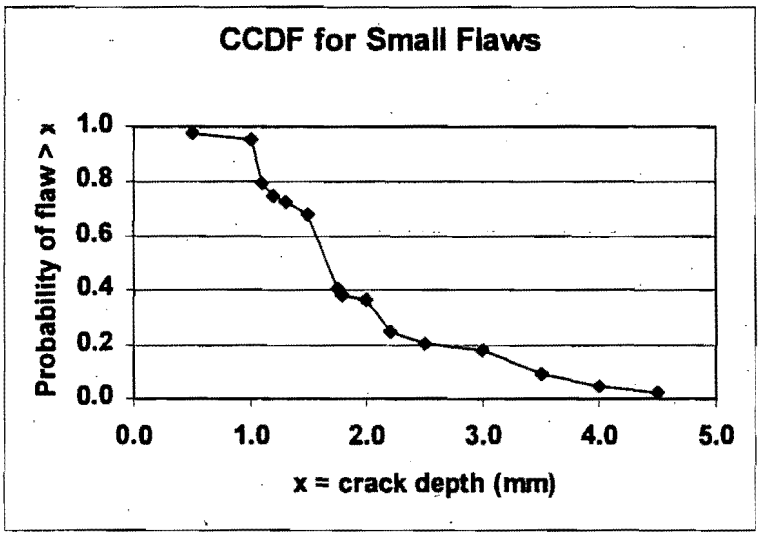

Figure 5.3. CCDF for Small Flaws

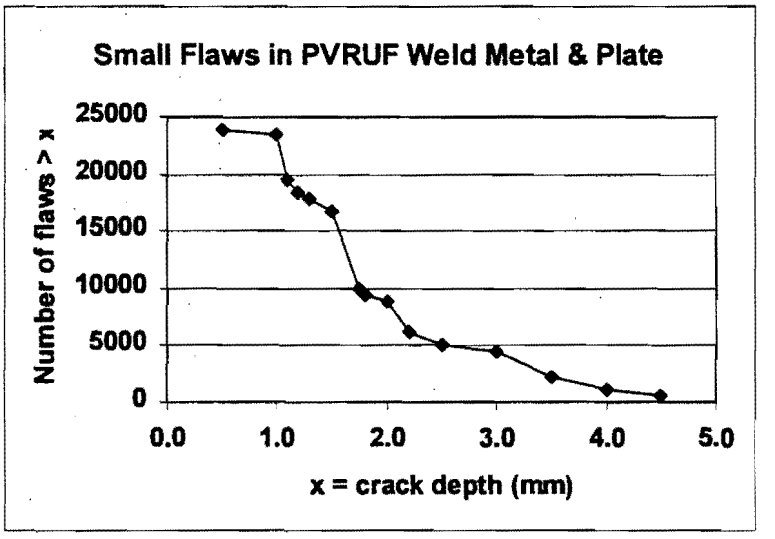

Figure 5.4a. Crack Size Distribution for Small Flaws in PVRUF Weld Metal and Plate

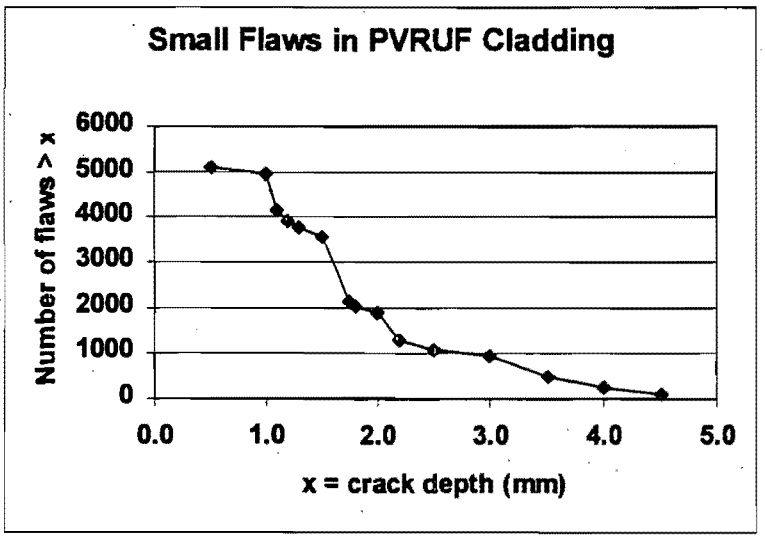

Figure 5.4b. Crack Size Distribution for Small Flaws in PVRUF Cladding

6.0 EXTENSION OF THE EMPIRICAL DATA TO THE FLEET OF RPVS AND FUTURE WORK

The empirical studies were performed at PNNL to obtain inclusive data for a database of fabrication flaws in RPVs. The database can be augmented through several different strategies to expand the amount of inspected RPV material.

The use of the RR-PRODIGAL code shows much promise as a tool to be used to extend the empirical database to the remainder of the RPV fleet. The agreement of the SAFT-UT data with the predictions by the RR-PRODIGAL expert system model indicates that the number and sizes of flaws in the PVRUF vessel are consistent with estimates made by welding experts based on their extensive knowledge and experience gained from the manufacture of a large number of welds similar to those in the PVRUF vessel. Further work is planned to validate the use of PRODIGAL for the Shoreham, River Bend and Hope Creek RPVs.

With the latest flaw density data obtained from the NDE of PVRUF and Shoreham RPV material and the development of RR-PRODIGAL, it is apparent that the Marshall flaw distribution can be replaced with an updated flaw distribution.

The results presented in this report are based only on the observed data from PVRUF and Shoreham and on median values from the expert judgment process. As such, they do not reflect the uncertainties in the data and especially in the expert judgments. Future work will assess these uncertainties as they affect the vessel failure probabilities in a two-stage approach. First, a sensitivity study will identify those combinations of product form, weld process, repair state and flaw size which dominate vessel failure probability. Second, an uncertainty analysis will assess the uncertainty in vessel failure probability as a function of the uncertainties in the

components of the dominant combinations identified in the sensitivity study. Statistical techniques will be used to assess the uncertainties in the observed data. The high and low values of the likelihood factors from the expert judgment process, as well as the full distribution of the midvalues, will be used to assess the uncertainties in the likelihood factors elicited from the expert panel. The data and expert judgment uncertainties will be combined to yield uncertainties in the generalized flaw distributions. These will then be propagated through the failure probability calculations to yield uncertainties in the vessel failure probabilities.

7.0 CONCLUSIONS

The commitment by the NRC's Office of Research to develop a generalized flaw size and density distribution for reactor pressure vessels has been positively received by industry and the NRC's Advisory Committee on Reactor Safeguards (ACRS). The development of a generalized flaw distribution will be a step forward in possibly reducing a source of uncertainty in the fracture mechanics calculations for reactor vessel failure and may result in justification for removal of some of the conservative assumptions regarding reactor pressure vessel integrity guidance in the CFR. The expert judgment process is complex. The recent NDE data on RPV material proves that NDE has played and continues to play a very important role in the assessment of the integrity of RPVs and will be a significant topic during the development of the generalized flaw distribution.

The expert judgment process was not a consensus process. Responses and data were obtained from each expert during individual elicitation sessions. The entire set of data and responses from the process will be published in an upcoming NUREG which will contain the GFD for the entire fleet of domestic reactor vessels along with uncertainty and sensitivity studies. In addition, comments and questions received by NRC related to data acquisition, methodologies and process used for the expert judgement process and development of the GFD will be addressed in the upcoming NUREG, specifically flaw depth location, PVRUF flaw sizing and characterization accuracy, flaw distribution development and destructive examination techniques

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Appendix A

Welding and Cladding Processes for Domestic Reactor Pressure Vessels

WELDING AND CLADDING PROCESSES FOR
DOMESTIC REACTOR PRESSURE VESSELS

PLANT NAME	RPV WELDS				CLADDING	NSSS
	AXIAL	PROCESS	CIRC	PROCESS		
Arkansas 1	B&W	SAW	B&W	SMAW/SAW	single or multi wire	B&W
Arkansas 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE
~~Beaver Valley 1~~	~~CE~~	~~SAW~~	CE	SMAW/SAW	multi wire/SMAW	W
~~Beaver Valley 2~~	~~CE~~	~~SAW~~	CE	SMAW/SAW	~~multi wire/SMAW~~	W
Braidwood 1	F-1	--	B&W	SAW	single wire	W
Braidwood 2	F-1	--	B&W	SAW	single wire	W
Byron 1	F-2	--	B&W	SAW	single wire	W
Byron 2	F-1	--	B&W	SAW	single wire	W
Callaway 1	CE	SAW	CE	SMAW/SAW	strip	W
Calvert Cliffs 1	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE
Calvert Cliffs 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE
Catawba 1	F-3	--	Rott.			W
Catawba 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Comanche Peak 1	CE	SAW	CE	SMAW/SAW	strip	W
Comanche Peak 2	CE	SAW	CE	SMAW/SAW	strip	W
Cook 1	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Cook 2	CB&I	SAW	CB&I	SMAW	Series Arc	W
Crystal River 3	B&W	SAW	B&W	SAW	single or multi wire	B&W
Davis-Besse	F-2	--	B&W	SAW	single or multi wire	B&W
Diablo Canyon 1	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Diablo Canyon 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Farley 1	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Farley 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Fort Calhoun	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE
Ginna	F-4	--	B&W	SAW	single wire	W
Indian Point 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Indian Point 3	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Kewaunee	F-4	--	CE	SAW	multi wire/SMAW	W
McGuire 1	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
McGuire 2	F-3	--	Rott.			W
Millstone 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE

PLANT NAME	RPV WELDS				CLADDING	NSSS
	AXIAL	PROCESS	CIRC	PROCESS		
Millstone 3	CE	SAW	CE	SMAW/SAW	strip	W
North Anna 1	F-3	--	Rott.			W
North Anna 2	F-3	--	Rott.			W
Oconee 1	B&W	SAW	B&W	SAW	single or multi wire	B&W
Oconee 2	F-2	--	B&W	SAW	single or multi wire	B&W
Oconee 3	F-2	--	B&W	SAW	single or multi wire	B&W
Palisades	CE	SAW	CE	SMAW/SAW	multi-wire/SMAW	CE
Palo Verde 1	CE	SAW	CE	SMAW/SAW	strip	CE
Palo Verde 2	CE	SAW	CE	SMAW/SAW	strip	CE
Palo Verde 3	CE	SAW	CE	SMAW/SAW	strip	CE
Point Beach 1	B&W	SAW	B&W	SAW	single or multi wire	W
Point Beach 2	F-4					W
Prairie Island 1	F-5	--	Cr-Lo			W
Prairie Island 2	F-5	--	Cr-Lo			W
Robinson	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Salem 1	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Salem 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
San Onofre 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE
San Onofre 3	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE
Seabrook 1	CE	SAW	CE	SMAW/SAW	strip	W
Sequoyah 1	F-3	--	Rott.			W
Sequoyah 2	F-3	--	Rott.			W
Shearon Harris 1	CB&I	SMAW	CB&I	SMAW/SAW	Series Arc	W
South Texas 1	CE	SAW	CE	SMAW/SAW	strip	W
South Texas 2	CE	SAW	CE	SMAW/SAW	strip	W
St. Lucie 1	CE	SAW	CE	SMAW/SAW	multi-wire/SMAW	CE
St. Lucie 2	CE	SAW	CE	SMAW/SAW	strip	CE
Summer	CB&I	SMAW	CB&I	SMAW	Series Arc	W
Surry 1						W
Surry 2						W
TMI-1	B&W		B&W		single or multi wire	B&W
Turkey Point 3	F-4	--	B&W		single wire	W
Turkey Point 4	F-4	--	B&W		single wire	W

PLANT NAME	RPV WELDS				CLADDING	NSSS
	AXIAL	PROCESS	CIRC	PROCESS		
Vogtle 1	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Vogtle 2	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	W
Waterford 3	CE	SAW	CE	SMAW/SAW	multi wire/SMAW	CE
Watts Bar 1	F-3	--	Rott.			W
Wolf Creek	CE	SAW	CE	SMAW/SAW	strip	W

F-1 = Forging by Japan Steel Works
F-2 = Forging by Ladish
F-3 = Forging by Rotterdam Dockyards
F-4 = Forging by Bethlehem Steel
F-5 = Forging by Creusot-Loire

** One is CE and one is B&W.
*** One is Rotterdam and one is B&W.

Appendix B

Box Plots for the Results of the Expert Judgment Process

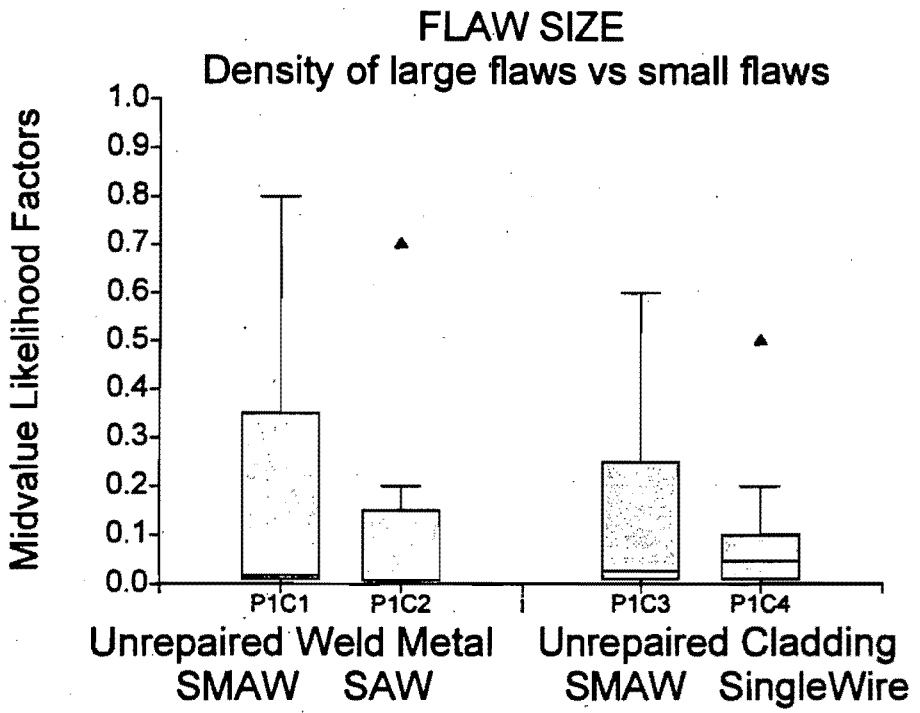

Figure B.1

	Unrepaired Weldmetal		Unrepaired Cladding	
	SMAW	SAW	SMAW	Single Wire
MIN	.001	.001	.001	.001
LQ	.01	.01	.01	.01
MED	.02	.01	.03	.05
UQ	.35	.15	.25	.1
MAX	.8	.7	.6	.5

Table B.1

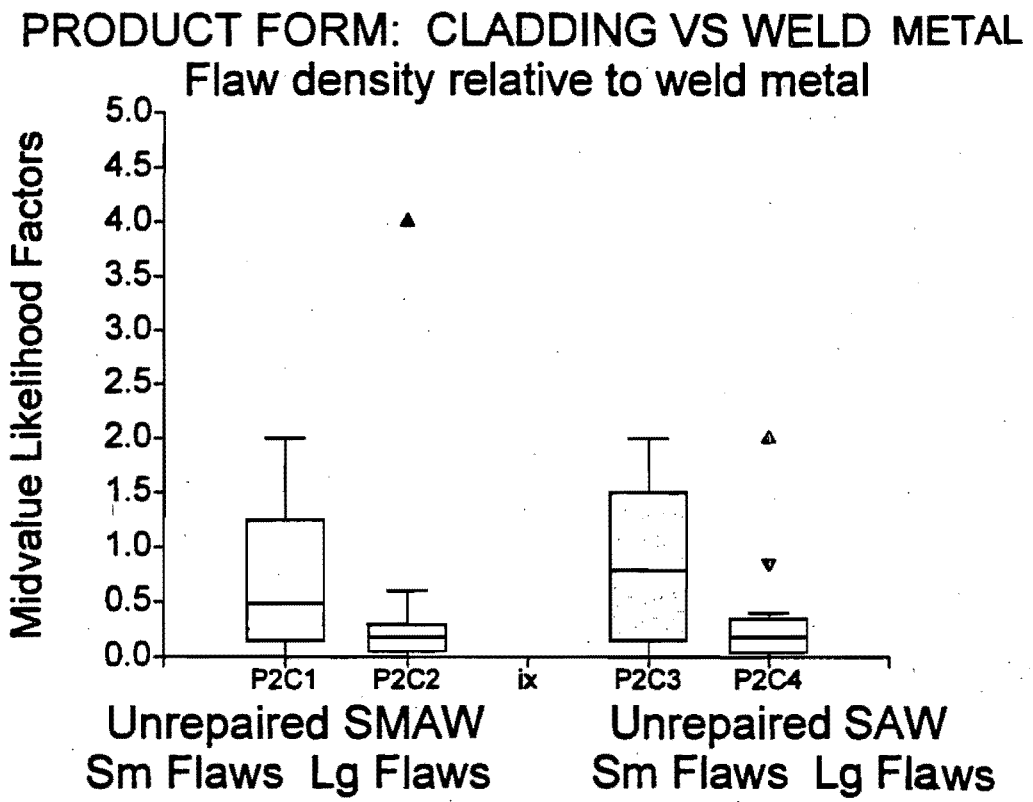

Figure B.2

Cladding vs. Weldmetal				
	Unrepaired SMAW		Unrepaired SAW	
	Small Flaws	Large Flaws	Small Flaws	Large Flaws
MIN	.002	0	.001	0
LQ	.15	.05	.15	.04
MED	.5	.2	.8	.2
UQ	1.3	.3	1.5	.35
MAX	2.0	4.0	2.0	2.0

Table B.2

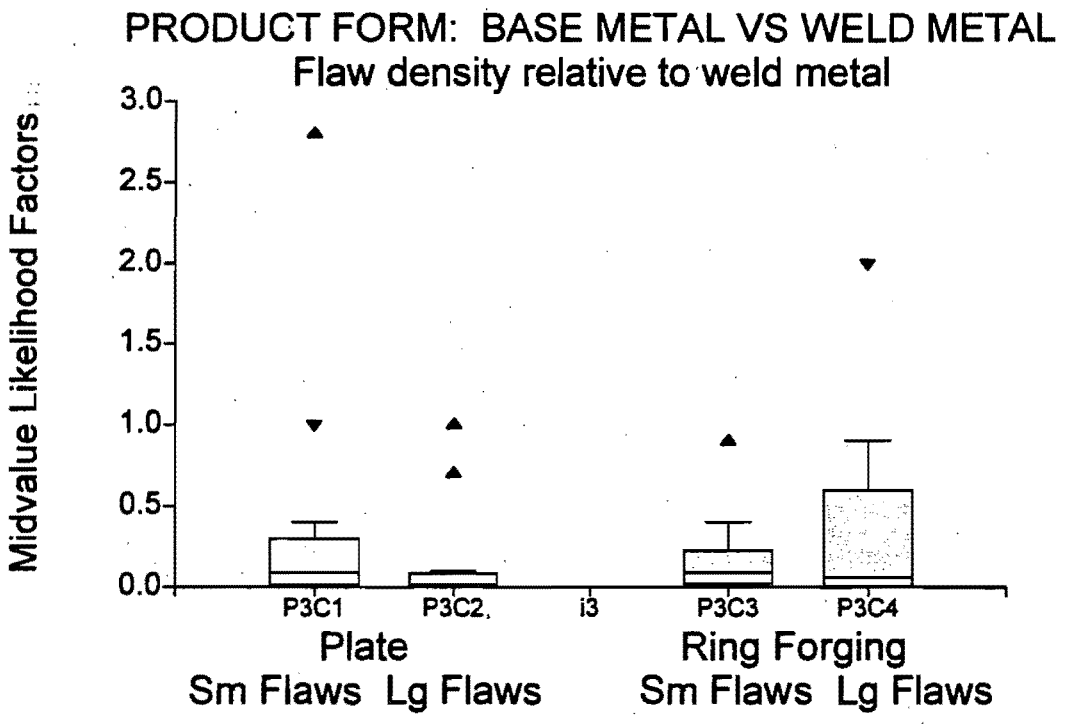

Figure B.3

	Base Metal vs. Weldmetal			
	Plate vs. Welds		Ring Forgings vs. Welds	
	Small Flaws	Large Flaws	Small Flaws	Large Flaws
MIN	.0004	.001	.001	.002
LQ	.015	.01	.02	.007
MED	.1	.025	.1	.07
UQ	.3	.09	.2	.6
MAX	12.0	1.0	.9	2.0

Table B.3

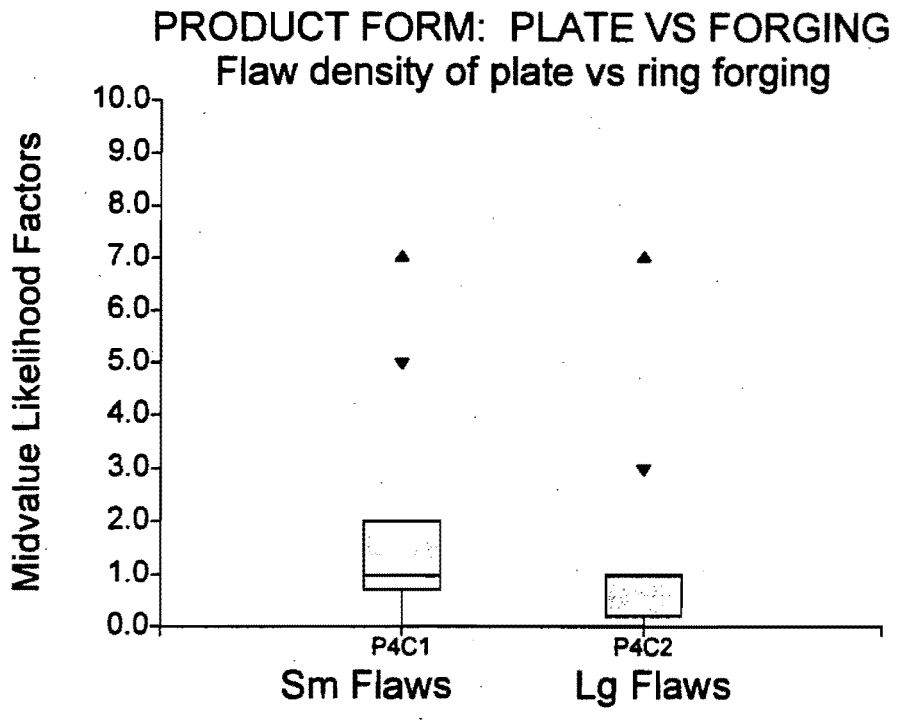

Figure B.4

	Small Flaws	Large Flaws
MIN	.002	.004
LQ	.7	.2
MED	1.0	1.0
UQ	2.0	1.0
MAX	20.0	20.0

Table B.4

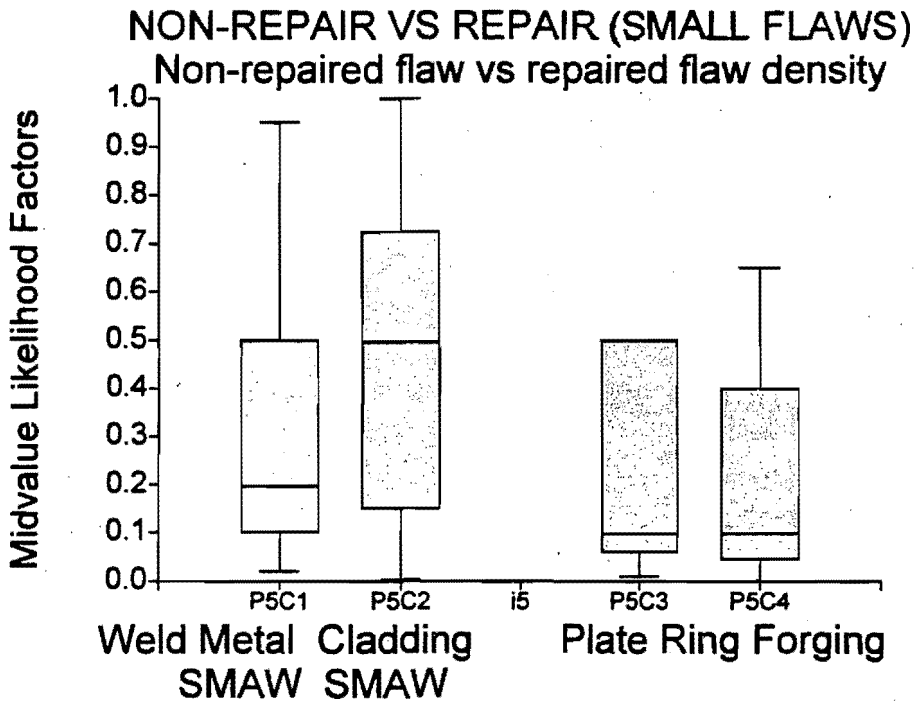

Figure B.5

	Weldmetal SMAW	Cladding SMAW	Base Metal Plate	Base Metal Forging
MIN	.02	.004	.01	.002
LQ	.1	.15	.06	.04
MED	.2	.5	.1	.1
UQ	.5	.7	.5	.4
MAX	.95	1.0	.5	.65

Table B.5

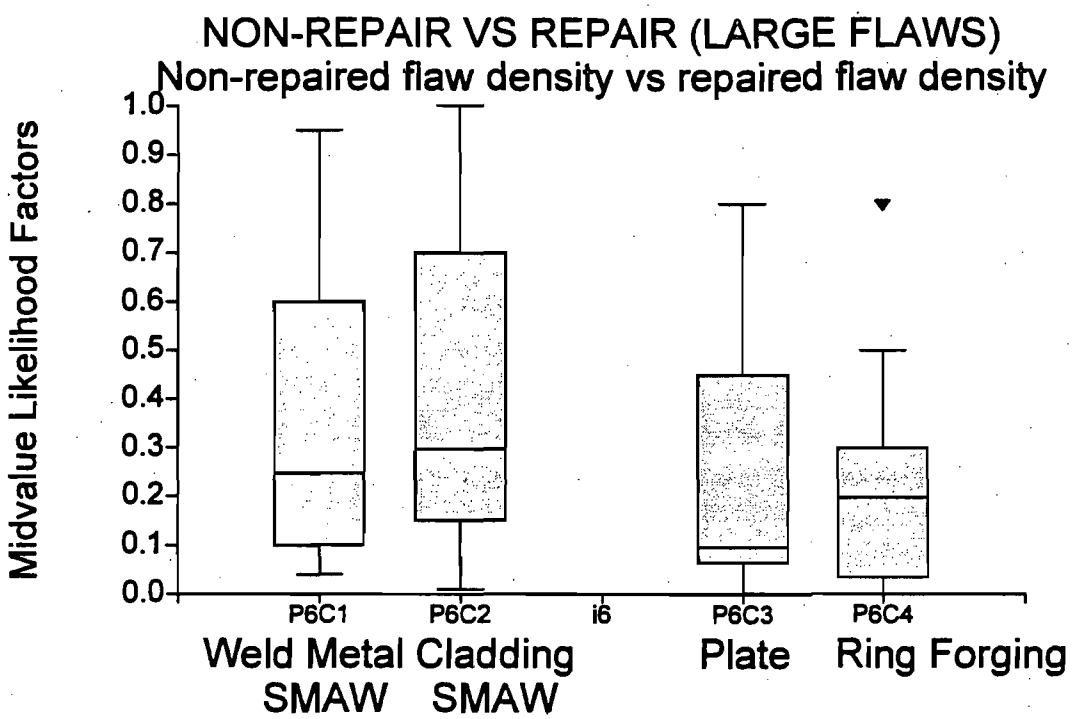

Figure B.6

	Weldmetal SMAW	Cladding SMAW	Base Metal Plate	Base Metal Forging
MIN	.04	.01	.002	.0004
LQ	.1	.15	.06	.03
MED	.25	.3	.1	.2
UQ	.6	.7	.5	.3
MAX	.95	1.0	.8	.8

Table B.6

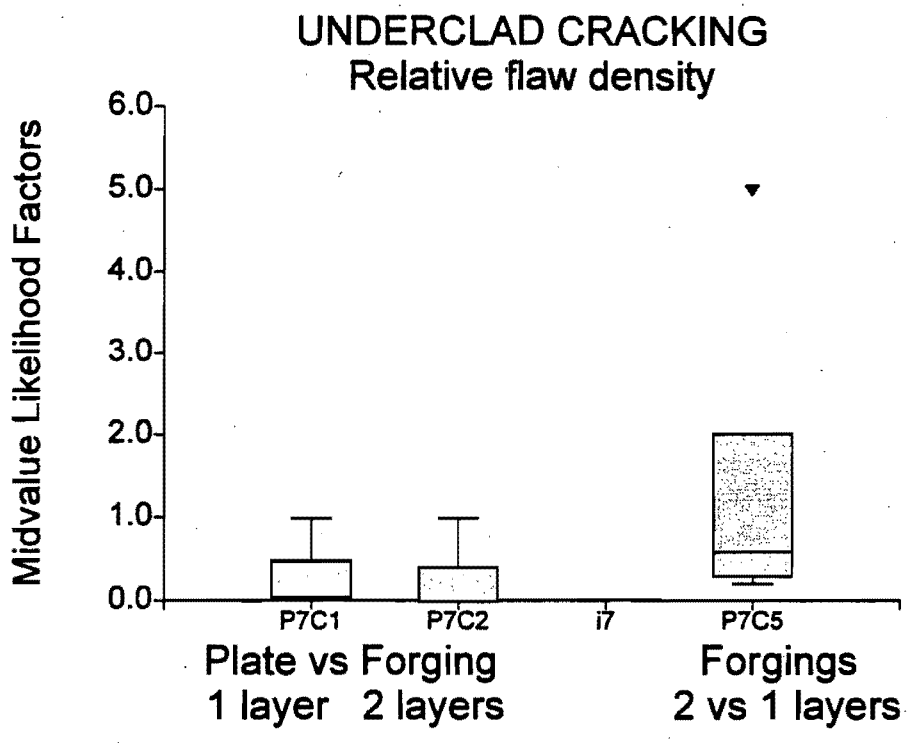

Figure B.7

	Plate vs. Ring Forgings		Ring Forgings
	Relative to Ring Forgings		Two Layers vs. One Layer
	One Layer	Two Layers	Relative to One Layer
MIN	0	0	.2
LQ	0	0	.3
MED	.05	.001	.6
UQ	.4	.4	2.0
MAX	.98	.98	50.0

Table B.7

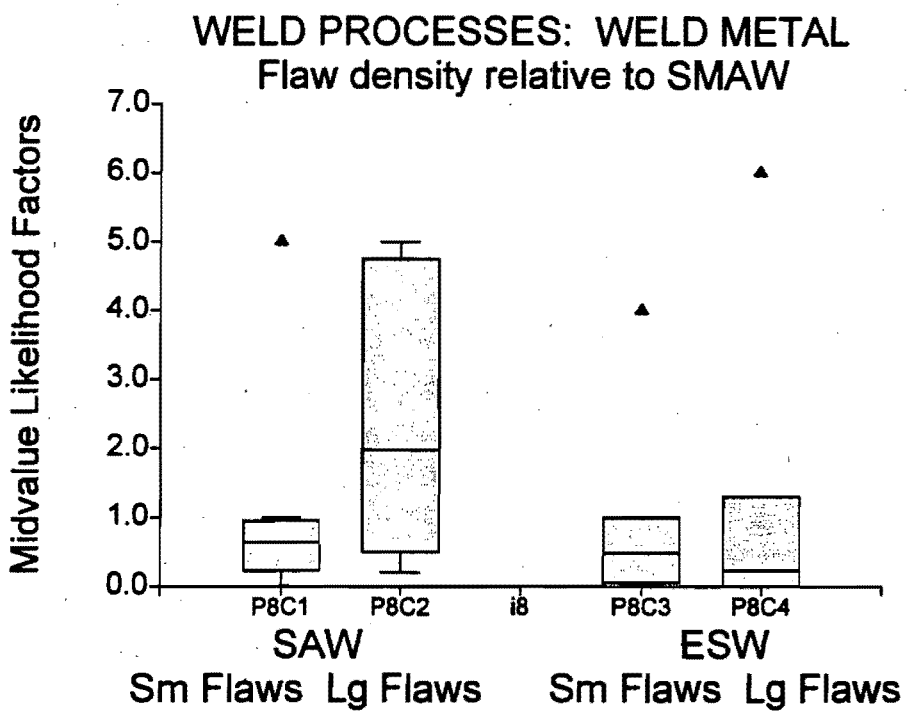

Figure B.8

	SAW: Small Flaws	SAW: Large Flaws
MIN	.01	.2
LQ	.25	.5
MED	.65	2.0
UQ	.9	4.5
MAX	5.0	5.0
	ESW: Small Flaws	ESW: Large Flaws
MIN	.002	0
LQ	.05	.001
MED	.5	.25
UQ	1.0	1.3
MAX	4.0	6.0

Figure B.8

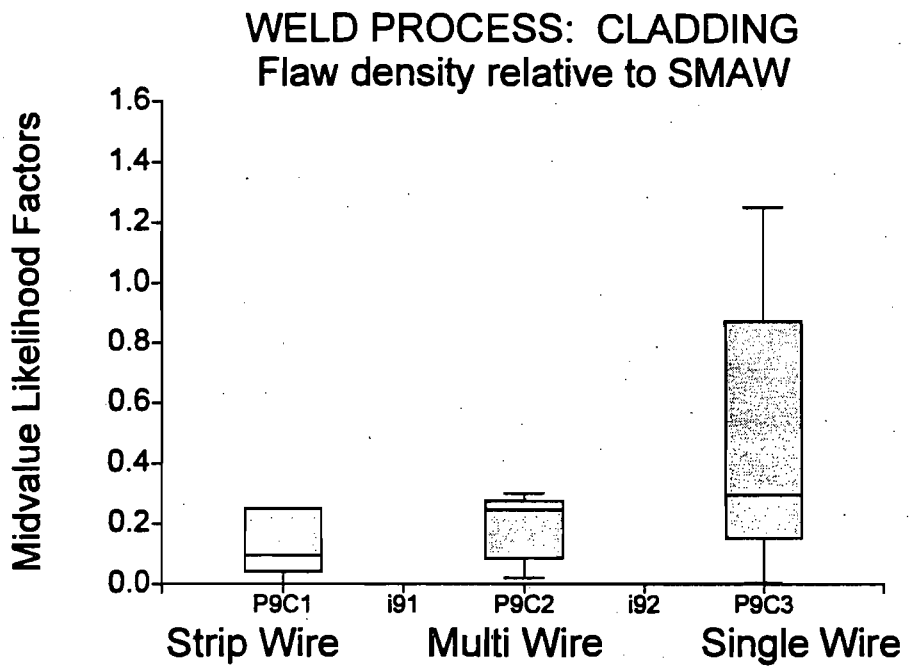

Figure B.9

	Strip Wire	Multi Wire	Single Wire
MIN	<.01	.02	.004
LQ	.04	.08	.15
MED	.1	.25	.3
UQ	.25	.3	.9
MAX	.25	.3	1.25

Table B.9