PRESSURE VESSEL INTEGRITY AND WELD INSPECTION PROCEDURE

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SUMMARY

The primary objective of this paper is to develop a simple methodology which, when coupled with existing observations on pressure vessel behavior, provides an inter-relation between pressure vessel integrity, and the parameters of the in-service inspection program, including inspection sample size, frequency and efficiency. A modified Markov process is employed and a computer code was written to obtain numerical results.

The Markov process mathematically describes the following physical events. In a nuclear reactor pressure vessel weld, some defects may exist prior to the zeroth inspection (i.e., prior to vessel operation). During the zeroth inspection and repair processes, some of these defects are removed. During the first cycle of vessel operation, the existing defects may grow and some new defects may be generated. Those defects that are found at the first (and succeeding) inspection interval and warrant repair, are repaired. The above process continues through several operating cycles to the end of vessel life. During any inspection, only a portion of the welds may be inspected, and with less than perfect efficiency.

Defects are arbitrarily divided into four size ranges, ranging from "not requiring repair" (size A) to critical if operation continues (size D). The differential equations assumed to describe defect concentration during operation are as follows:

$$\frac{dP_A}{dt} = Q_A - \lambda_A P_A, \quad \frac{dP_B}{dt} = \lambda_A P_A - \lambda_B P_B, \quad \frac{dP_C}{dt} = \lambda_B P_B - \lambda_C P_C, \quad \frac{dP_D}{dt} = \lambda_C P_C,$$

where P_A is the probability per weld of finding a defect of size A , λ_A is the rate at which defects of size A grow to size B , Q_A is the generation rate of new defects of size A etc. Another set of equations describes the reduction in size B and C defects following each periodic inspection.

Basic input data on initial defect concentration and rate of defect development into a larger size range has been derived for non-nuclear pressure vessels from extensive British and German compilations. This input data to the model is not unique; however, except for the assumptions which influence the probability of a size D defect at time zero despite the initial inspections, the results predicted for changes in inspection are not expected to be highly sensitive to variations in derived input parameters.

Based on the British and German data, assuming 25 major welds per vessel, and applying the British non-nuclear inspection practices, the estimated probability of a critical size defect per weld at the end of weld life was about 2.5×10^{-5} . If ASME Section XI inspection requirements are applied, but other assumptions are maintained, the probability is estimated to drop to 1×10^{-5} . Inspection corresponding to four times the requirements of Section XI (infrequency or extent) reduces the probability proportionately to about 2.5×10^{-6} per weld.

An alternate set of input parameters was chosen to reflect an order of magnitude reduced probability of size D defects at end of weld life for nuclear vessels assuming British non-nuclear inspection. These parameters led to an estimated probability of 6×10^{-7} size D defects per weld at the end of weld life, if Section XI inspection was applied. Increasing the sample size or frequency beyond Section XI by a factor of say four, reduced the size "D" defect probability proportionately. A wide range of sensitivity studies were performed. Also, a simple model for economic optimization of weld inspection, given some reliability goal, was formulated.

1. Introduction

All modern pressure vessels, whether they are used in nuclear reactor applications or other applications, are composed of welded sections. Experience indicates that under most circumstances when pressure vessel integrity is lost, it is due to loss of weld integrity rather than loss of integrity of the base metal sections. As a result, this study considers the potential loss of pressure vessel integrity due to failure of one of its welds.

A pressure vessel weld is considered to fail (or to be on the verge of failure) when it contains a defect of critical size for the existing conditions. All welds, no matter how perfectly they are made, initially contain defects [1-7]. Many of these defects are small and undetectable, others are large enough to be detected but too small to require repair, and still others may be large enough to require repair. Of those defects that are large enough to require repair, not all may be detected and repaired. It has been observed that defects can develop to larger sizes as a function of time. The exact development mechanism has not been considered in this study. Instead, this study relies on empirical observations of defect development.

The initial defect sizes, the defect generation rate, and the defect development rate are derived from existing information on weld defects.

The pressure vessels used in nuclear reactors are similar in design and characteristics to some of the pressure vessels used in other applications [1-10]. Although considerable information exists regarding the integrity of non-nuclear pressure vessels, rather less experience is available for nuclear pressure vessels. As a result, in order to obtain a basis for approximating nuclear reactor pressure vessel integrity, the more extensive data on non-nuclear reactor weld failure has been studied. An attempt has been made to examine data for welds of generally similar type and under similar stress to the nuclear reactor pressure vessel welds.

2. Physical Description

In this section a brief physical description of a nuclear reactor pressure vessel and its welds is given [1-11]. Generation and growth of defects in welds and eventual weld failure are discussed [12-15]. Also, a description of the inspection procedure and inspection technique is given [16-26].

2.1 Nuclear Reactor Pressure Vessel and Welds

The vessel which serves the important function of containing the highly pressurized reactor coolant water as it flows over the nuclear fuel core is usually made up of four major, welded segments. These segments include the top closure head, the nozzle course, the cylinder course, and the lower head. A typical BWR or PWR pressure vessel contains about 25 major welds. The volume of each of these welds may vary between 150 and 500 cubic inches. It was assumed [27,28] that there may exist two major groups of welds; those under low steady or cyclic load and those under moderate or high steady or cyclic load. Those welds classified as low stress welds include (1) welds whose direction of defect development is parallel to the direction of stress and (2) defects under low stress. Welds classified as moderate or high stress have a significant component of moderate or high stress that is perpendicular to the direction of defect development.

2.2 Defect Generation, Propagation, and Removal in Pressure Vessel Welds

Prior to reactor service some weld defects exist. After inspection, most of the larger defects are removed. After the reactor becomes operational, several influencing factors may cause the defects to develop. The rate of development is usually assumed proportional to the amount of stress normal to the direction of development of the defect, the frequency of cycling, and the size of the defect. The defect (if under stress), will continue to develop unless it is detected and repaired prior to becoming a critically sized defect. Critical sized defects have been observed although the detailed development process leading to this size has not been identified.

Section XI of the ASME Boiler and Pressure Vessel Code discusses the pre-service and in-service inspection of nuclear reactor pressure vessels and pressure vessel welds [25].

3. Defect Generation, Development, and Removal Model

The model assumes that the weld defects may initially be of five distinct sizes rather than assuming a continuous distribution of sizes. These five discrete sizes have been assumed because (1) the quality of the available data on defect sizes is not fine enough to distinguish between a continuous spectrum of sizes or more than five discrete sizes and (2) the mathematical model used to treat the physical process is considerably more simple for the discrete defect size.

This model uses empirical information to approximate the expected concentration of defects at a particular time rather than using a "first principal approach" or a "mechanistic approach."

The smallest sized defects are classified size "0". Defects classified size "0" are defined to be too small to detect or have less than a 50% probability of being detected even with the most sensitive equipment. These defects are assumed to have the potential to generate to defects of the next larger size (i.e., defects of size "A"), at a constant generation rate of Q_i defects per weld hour during the i th generation and development cycle, which is independent of the concentration of size "0" defects, hence the latter concentration does not enter into the analysis.

Defects of size "A" are assumed to have a minimum probability of 50% of being detected using the most sensitive equipment, but are classified too small to merit immediate repair. Defects of size "A" have the potential of developing to defects of size "B" at a rate of $\lambda_{A,i}$ during the i th generation and development cycle.

Size "B" and size "C" defects are classified arbitrarily to be defects that are large enough to merit repair if detected but small enough to be considered a non critical defect. If defects of size "B" are detected during an inspection, they are expected to be repaired to defects of either size "A" or size "0". If defects of size "B" are not detected and repaired, they have the potential of developing to the next larger size defect, (i.e., size "C" defects) at a development rate of $\lambda_{B,i}$ during the i th generation and development cycle.

Size "C" defects have the potential to grow to critical size. If size "C" defects are not corrected during the inspection and repair intervals, they will develop to size "D" defects at a rate $\lambda_{C,i}$.

Defects of size "D" are "critical" and unlike defects of size "0", "A", "B", or "C", are assumed to develop at a very rapid rate. It is assumed that a defect of size "D" will constitute a weld failure if operation continues.

The five discrete sizes, "D", "A", "B", "C", and "D" are selected for convenience. Admittedly, it may be very difficult to distinguish between size "B" and size "C" defects since both of these sizes include defects that are large enough to merit repair but yet small enough to be considered an unfailed weld. Two discrete sizes in this repairable range were selected to reflect the fact that a rather wide range of repairable size defects exist.

During the time interval $0 < T < \delta'_0$ the zeroth inspection takes place where $W_0\%$ of the weld is inspected. Defects of size "A" are detected with an efficiency of $H_0^A(j)$ percent using the j th inspection technique, defects of size "B" are detected with an efficiency of $H_0^B(j)$ percent using the j th inspection technique, etc.

At $t = \delta_0 > \delta'_0$, (immediately following the zeroth repair), the expected concentration of defects of size "A", size "B", size "C", and size "D" assumed present are $P_A(\delta_0)$, $P_B(\delta_0)$, $P_C(\delta_0)$, respectively.

From $\delta_0 < t < T_1$, (during the first generation and development cycle), the rate of change in the expected concentration of size "A" defects is equal to the generation rate per weld hour of size "A" defects minus the rate of change in concentration of defects that grow out of size "A"; the rate of change in the expected concentration of defects of size "B" is equal to the rate of change in the concentration of defects that develop into size "B" from size "A" minus the rate of change in the concentration that develop out of size "B" to size "C", etc. The expected concentration of defects of size "D" defects is equal to the sum of defects that develop out of size "C" to "D". Mathematically, during the first cycle:

$$\frac{dP_A(t)}{dt} = Q_1 - \lambda_{A,1}P_A(t), \quad (1)$$

$$\frac{dP_B(t)}{dt} = \lambda_{A,1}P_A(t) - \lambda_{B,1}P_B(t), \quad (2)$$

$$\frac{dP_C(t)}{dt} = \lambda_{B,1}P_B(t) - \lambda_{C,1}P_C(t), \text{ and} \quad (3)$$

$$\frac{dP_D(t)}{dt} = \lambda_{C,1}P_C(t). \quad (4)$$

The subscript 1 on the generation and development rates corresponds to the first generation and development cycle.

The solutions [27,28] to the simultaneous equations (1) to (4) during the first generation and development cycle are respectively:

$$P_A(\delta_0 < t \leq T_1) = \frac{Q_1}{\lambda_{A,1}} (1 - e^{-\lambda_{A,1}t}) + P_A(t=\delta_0)e^{-\lambda_{A,1}t} \quad (5)$$

$$\begin{aligned} P_B(\delta_0 < t \leq T_1) &= \lambda_{A,1}Q_1 \left[\frac{1 - e^{-\lambda_{A,1}t}}{\lambda_{A,1}(\lambda_{B,1} - \lambda_{A,1})} + \frac{1 - e^{-\lambda_{B,1}t}}{\lambda_{B,1}(\lambda_{A,1} - \lambda_{B,1})} \right] \\ &+ \frac{\lambda_{A,1}P_A(t=\delta_0)}{\lambda_{B,1} - \lambda_{A,1}} \left[\frac{e^{-\lambda_{A,1}t}}{\lambda_{A,1}} - \frac{e^{-\lambda_{B,1}t}}{\lambda_{B,1}} \right] \\ &+ P_B(t=\delta_0)e^{-\lambda_{B,1}t}, \end{aligned} \quad (6)$$

$$P_C(\delta_0 < t \leq T_1) = \lambda_{A,1} \lambda_{B,1} Q_1 \left[\frac{1 - e^{-\lambda_{A,1} t}}{\lambda_{A,1} (\lambda_{B,1} - \lambda_{A,1}) (\lambda_{C,1} - \lambda_{A,1})} + \frac{1 - e^{-\lambda_{B,1} t}}{\lambda_{B,1} (\lambda_{A,1} - \lambda_{B,1}) (\lambda_{C,1} - \lambda_{B,1})} \right. \\ \left. + \frac{1 - e^{-\lambda_{C,1} t}}{\lambda_{C,1} (\lambda_{A,1} - \lambda_{C,1}) (\lambda_{B,1} - \lambda_{C,1})} \right] + \lambda_{A,1} \lambda_{B,1} P_A(\delta_0) \left[\frac{e^{-\lambda_{A,1} t}}{(\lambda_{B,1} - \lambda_{A,1}) (\lambda_{C,1} - \lambda_{A,1})} \right. \\ \left. + \frac{e^{-\lambda_{B,1} t}}{(\lambda_{A,1} - \lambda_{B,1}) (\lambda_{C,1} - \lambda_{B,1})} + \frac{e^{-\lambda_{C,1} t}}{(\lambda_{A,1} - \lambda_{C,1}) (\lambda_{B,1} - \lambda_{C,1})} \right] \\ + P_C(t = \delta_0) e^{-\lambda_{C,1} t} + \lambda_{B,1} P_B(\delta_0) \left[\frac{e^{-\lambda_{B,1} t}}{(\lambda_{C,1} - \lambda_{B,1})} + \frac{e^{-\lambda_{C,1} t}}{(\lambda_{B,1} - \lambda_{C,1})} \right], \quad (7)$$

$$P_C(\delta_0 < t \leq T_1) = \lambda_{A,1} \lambda_{B,1} \lambda_{C,1} Q_1 \left[\frac{t - \frac{1}{\lambda_{A,1}} (1 - e^{-\lambda_{A,1} t})}{\lambda_{A,1} (\lambda_{B,1} - \lambda_{A,1}) (\lambda_{C,1} - \lambda_{A,1})} + \frac{t - \frac{1}{\lambda_{B,1}} (1 - e^{-\lambda_{B,1} t})}{\lambda_{B,1} (\lambda_{A,1} - \lambda_{B,1}) (\lambda_{C,1} - \lambda_{B,1})} \right. \\ \left. + \frac{t - \frac{1}{\lambda_{C,1}} (1 - e^{-\lambda_{C,1} t})}{\lambda_{C,1} (\lambda_{A,1} - \lambda_{C,1}) (\lambda_{B,1} - \lambda_{C,1})} \right] + \lambda_{A,1} \lambda_{B,1} \lambda_{C,1} P_A(\delta_0) \cdot \\ \cdot \left[\frac{\frac{1}{\lambda_{A,1}} (1 - e^{-\lambda_{A,1} t})}{(\lambda_{B,1} - \lambda_{A,1}) (\lambda_{C,1} - \lambda_{A,1})} + \frac{\frac{1}{\lambda_{B,1}} (1 - e^{-\lambda_{B,1} t})}{(\lambda_{A,1} - \lambda_{B,1}) (\lambda_{C,1} - \lambda_{B,1})} + \frac{\frac{1}{\lambda_{C,1}} (1 - e^{-\lambda_{C,1} t})}{(\lambda_{A,1} - \lambda_{C,1}) (\lambda_{B,1} - \lambda_{C,1})} \right] \\ + P_C(t = \delta_0) (1 - e^{-\lambda_{C,1} t}) + \lambda_{B,1} \lambda_{C,1} P_B(\delta_0) \left[\frac{(\frac{1}{\lambda_{B,1}}) (1 - e^{-\lambda_{B,1} t})}{(\lambda_{C,1} - \lambda_{B,1})} \right. \\ \left. + \frac{(\frac{1}{\lambda_{C,1}}) (1 - e^{-\lambda_{C,1} t})}{(\lambda_{B,1} - \lambda_{C,1})} \right] + P_D(t = \delta_0). \quad (8)$$

At $t = T_1 + \delta_1$, (immediately after the first inspection and repair interval), the expected number of defects per weld of size "A" is equal to the number of defects per weld that were added to "A" from repair of defects of size "B" and size "C". On the other hand, the expected number of defects per weld of size "D" at $t = T_1 + \delta_1$ is essentially equal to the number of size "D" defects per weld at $t = T_1$ since repair of size "D" defects is not allowed in the model.

Mathematically,

$$P_A(t = T_1 + \delta_1) = P_A(t = T_1) + H_1 \overset{B \rightarrow A}{(\Sigma)} W_1 P_B(t = T_1) + H_1 \overset{C \rightarrow A}{(\Sigma)} W_1 P_C(t = T_1) \quad (9)$$

$$\cong P_A(t = T_1) \quad (10)$$

$$\text{because } H_1(\Sigma) W_1 P_B(t=T_1) + H_1(\Sigma) W_1 P_C(t=T_1) < P_A(t=T_1), \quad (11)$$

$$P_B(t=T_1+\delta_1) = P_B(t=T_1) - (H_1(\Sigma) + H_1(\Sigma)) W_1 P_B(t=T_1), \quad (12)$$

$$P_C(t=T_1+\delta_1) = P_C(t=T_1) - (H_1(\Sigma) - H_1(\Sigma)) W_1 P_C(t=T_1), \text{ and} \quad (13)$$

$$P_D(t=T_1+\delta_1) = P_D(t=T_1). \quad (14)$$

During $T_1+\delta_1 \leq t \leq T_1+T_2$, (during the second generation and development cycle), the expected number of defects per weld can be easily calculated since $P_A(t=T+\delta_1)$, $P_B(t=T_1+\delta_1)$, $P_C(t=T_1+\delta_1)$, and $P_D(t=T_1+\delta_1)$ were calculated in equations (10), (11), (12), and (13) respectively and the generation and development of equations (5), (6), (7), and (8) may be adjusted to reflect new initial conditions at $t = T_1+\delta_1$. This technique can be continued through subsequent generation, development and removal cycles. [27,28]

4. Results

Because of the rather limited nuclear pressure vessel experience and the relatively extensive experience in non-nuclear pressure vessels, much of the information obtained on weld defect generation, development, and removal has been inferred from the latter source.

Table 1 [10-13] is a summary of the number of defects found during the zeroth inspection in British, German, and American pressure vessel welds. Based on the assumed percent of weld inspected and repaired [8,10,11,15,16,17,19,21], (see Table 2), and the range of assumed inspection and repair efficiencies [8,10-16,18,20], (see Table 2), the range in the number of defects per weld expected to be present immediately after the zeroth inspection and repair (but prior to vessel operation) is estimated in Table 1. For example, it can be seen in Table 1 that prior to vessel operation, the British located 2 defects in high stress welds. For the purpose of this study, these defects were assumed to belong to size D classification of weld defects. Using the assumed British non-nuclear pressure vessel inspection standards [8,10,11,17,27,28] and the range in assumed British inspection and repair efficiencies [8,10-16,18,21,27,28], the model estimates that there will be between 9×10^{-7} and 15×10^{-7} D size defects per high stress, British non-nuclear pressure vessel weld after the zeroth inspection and repair process, (i.e., at times $t = \delta_0$; immediately prior to vessel operation). In a similar manner, the number of defects of sizes A, B, C, and D expected present immediately after the zeroth inspection and repair but prior to vessel operation, (i.e., $P_A(\delta_0)$, $P_B(\delta_0)$, $P_C(\delta_0)$, and $P_D(\delta_0)$ respectively) are estimated for the British, German, and American pressure vessel welds. Using the estimated value of $P_A(\delta_0)$, $P_B(\delta_0)$, $P_C(\delta_0)$, and $P_D(\delta_0)$ for the British non-nuclear pressure vessel welds along with the British non-nuclear pressure vessel inspection standards [8,10,11,17] the estimated British weld defect generation and development rates* [27,28], and the inspection efficiencies, the estimated number of size "D"

* The defect generation and development rates are estimated from the three defects assumed (for the purpose of this study) to be of size D that were found in 120,000 high stress British welds during 8.8×10^9 high stress weld hours and the British inservice inspection standards.

defects per high stress British non nuclear vessel weld at the end of vessel life is predicted to be 2.5×10^{-5} , (case 1 of Table 3).

If ASME Section XI [25] nuclear pressure vessel inspection standards were applied to the British non nuclear welds instead of the assumed British inspection standards, then, based on the model the estimated number of D size defects expected at the end of vessel life in high stress welds is reduced to 5.0×10^{-6} (case 2 of Table 3). That is to say, by applying ASME nuclear vessel inspection standard instead of the assumed British non nuclear inspection standards, there is a five fold reduction in the expected number of size D defects at the end of vessel life (for welds under high stress).

If it were postulated that nuclear vessel welds have ten times the integrity of non nuclear vessel welds [9] and if British non nuclear vessel inspection standards were applied to these welds of higher integrity, then the expected number of D size defects at the end of high stress weld life would be estimated to be 2.5×10^{-6} , (case 3 of Table 3). If, on the other hand, ASME Section XI were applied, then this number would be reduced to approximately 5×10^{-7} , (case 4 of Table 3).

Assuming for the purpose of this study that the higher integrity weld figures are representative of nuclear pressure vessels, the results of Figure 1 can be obtained using so called "base" parameters for nuclear pressure vessel welds. Sensitivity studies are given in Figures 2 and 3; the input parameters for these studies are given in Table 2. Figure 2 shows the effect of having a variable initial concentration of size A defects. Figure 3 illustrates the effect of variable generation and development rates.

The value of $P_D(t=350,000 \text{ hours})$ is most sensitive to the initial concentration of size "C" defects and less sensitive to the initial concentration of size "A" defects. The value $P_D(t=350,000 \text{ hours})$ is particularly sensitive to the generation and development rates of size C flaws. Increasing the generation and development rates by a factor of 10 over the base case for high stress welds results in $P_D(t=350,000 \text{ hours}) = 9.3 \times 10^{-7}$ defects/weld. When the number of equally spaced inspections is doubled from 12 to 24, the value of $P_D(t=350,000 \text{ hours}) = 2.5 \times 10^{-7}$ defects/weld or about one-half of the value for $P_D(t=350,000 \text{ hours})$ for the base run using high stress weld data [27,28]. When zero defects are initially present and there are no subsequent inspections, then $P_D(t=350,000 \text{ hours}) = 1.0 \times 10^{-4}$ defects/weld [27,28].

The value of $P_D(t=350,000 \text{ hours})$ varies between 2.1×10^{-4} and 4.3×10^{-8} as the percent of weld inspected per inspection (i.e., W), varies between 0% and 100%. The value of $P_D(t=350,000 \text{ hours})$ is especially sensitive to changes in W for small values of W. The value of W is more influential in changing the value of $P_D(t=350,000 \text{ hours})$ for high stress welds than for low stress welds.

Increasing the efficiency of detecting size "A", "B", "C", and "D" defects by 20%, 10%, 5%, and 0.1%, respectively, reduces the value of $P_D(t=350,000 \text{ hours})$ by less than 40%.

An exact quantitative study considering inspection cost constraints is beyond the scope of this study because many of the required input parameters are difficult to estimate. However, based on a variety of simplifying assumptions [30,31], the total inspection cost over the weld lifetime can be written parametrically [30,31] in terms of cost per inspection, cost of additional down time required, and so on. Based on this parametric expression, the total cost of inspection over weld lifetime can be minimized (in principle) using convex programming [27,28].

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Table 1. Number of Defects Found and Number Assumed Present at Startup

Source of Information	# of Defects Actually Found at Zeroth Inspection ($\pm \delta_0^i$)				# of welds inspected	# of Defects Per Weld Expected Present After Zeroth Inspection and Repair ($\pm \delta_0^i$)			
	$\#_A(\delta_0^i)$	$\#_B(\delta_0^i)$	$\#_C(\delta_0^i)$	$\#_D(\delta_0^i)$		$\#_A(\delta_0^i) \times 10^{-4}$	$\#_B(\delta_0^i) \times 10^{-6}$	$\#_C(\delta_0^i) \times 10^{-6}$	$\#_D(\delta_0^i) \times 10^{-7}$
U.K. (P, 64,) ⁽³⁴⁾	33	¹² 2 ¹	¹² 2 ¹	2	120,000	3.9 ± 5.9	1.3 ± 3.4	1.3 ± 3.4	9 ± 15
High Low Stress	39	¹² 1.5 ¹	¹² 1.5 ¹	1	181,050	3.0 ± 4.3	0.4 ± 1.3	0.4 ± 1.3	2 ± 6
FRG (K, 68,) ⁽³⁵⁻³⁸⁾	—	24	5	2	4,700,000	—	2.7 ± 5.3	0.51 ± 0.96	0.31 ± 0.63
High Low Stress	—	26	5	1	7,400,000	—	1.9 ± 3.5	0.25 ± 0.45	0.07 ± 0.21
U.S. (non-nuclear) ⁽³³⁾	—	5	2	0	330,000	—	1.6 ± 4.8	0.53 ± 0.98	—
1962 ± 1971 High Low Stress	—	6	1	0	410,000	—	1.2 ± 3.6	0.26 ± 0.49	—
1952 ± 1961 High Low Stress	—	5	1	0	270,000	—	2.1 ± 6.5	0.49 ± 0.94	—
1942 ± 1951 High Low Stress	—	3	2	1	120,000	—	1.6 ± 5.1	0.98 ± 1.4	4.1 ± 8.6
U.S. (nuclear) ⁽³³⁾	3	1	0	0	1,200	3.6 ± 5.3	—	—	—
High Low Stress	4	1	0	0	1,800	3.1 ± 4.4	—	—	—

Table 2. Assumed Set of Input Parameters

Case # (See Figure)	NUMBER OF DEFECTS PER WELD INITIALLY PRESENT				EFFICIENCY OF INSPECTION				PERCENT OF WELD INSPECTED $\bar{W}_1$	GENERATION RATE q_i $\times 10^{-8}$	DEVELOPMENT RATE			NUMBER OF INSPECTIONS IN 350,000 WELD HOURS	COMMENTS Valid for
	$\#_A(0)$ $\times 10^{-4}$	$\#_B(0)$ $\times 10^{-6}$	$\#_C(0)$ $\times 10^{-6}$	$\#_D(0)$ $\times 10^{-6}$	$H_A^0(1)$ PERCENT	$H_B^0(1)$ PERCENT	$H_C^0(1)$ PERCENT	$H_D^0(1)$ PERCENT			$\lambda_{A,1}$ $\times 10^{-10}$	$\lambda_{B,1}$ $\times 10^{-9}$	$\lambda_{C,1}$ $\times 10^{-8}$		
1	6.0	6.0	6.0	0	60.0	90.0	95.0	99.9	33.3%	6.0	6.0	6.0	6.0	12	≤ 12
2	*	6.0	6.0	0	60.0	90.0	95.0	99.9	33.3%	6.0	6.0	6.0	6.0	12	≤ 12
3	6.0	6.0	6.0	0	60.0	90.0	95.0	99.9	33.3%	*	*	*	*	12	≤ 12

*Variable input parameter
**Base Run

Table 3. Comparison in the Predicted Number of Size D Defects per Weld* Expected at the End of Weld Life

Assuming	Estimated Number of Defects Per High Stress Weld at the End of Vessel Life
Case 1: British non nuclear data on weld integrity and non nuclear inspection standards	2.5×10^{-6}
Case 2: British non nuclear data on weld integrity and ASME XI inspection standards	5.0×10^{-6}
Case 3: Nuclear (high integrity) data and ASME XI inspection standards	5×10^{-7}

*For high stress welds

Figure 1. The Expected Number of Defects per Weld of Sizes "A", "B", "C", and "D" as a Function of Time. Base Run for High Stress Welds.

Figure 2. The Number of Defects of Size "D" per Weld at $t = 350,000$ hours as a function of the Number of Size "A" Defects per Weld Initially Generated. Other Parameters are Fixed as for Base Run, High Stress Welds.

Figure 3. The Number of Defects of Size "D" per Weld at $t = 350,000$ hours as a function of the Number of Size "A" Defects per Weld Initially Generated. Other Parameters are Fixed as for Base Run, High Stress Welds.