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Background

Continued operation of the aging fleet of BWRs worldwide requires gradually increasing expenditures for inspection, maintenance, and repair. An initiative to proactively address material aging issues in BWR reactor vessels and internals was initiated in the USA in 1994 to lead the industry toward a proactive, generic resolution of vessel and internals material condition issues and the development of cost-effective, remedial strategies [2]. Among the most critical reactor aging mechanisms, corrosion damage in the coolant circuits is known to be a reason for an estimated 80% of unscheduled shutdowns of commercial Light Water Reactors (LWRs) and results in significant financial losses to the plant owners [1]. IGSCC in austenitic stainless steel piping was accepted as a major issue for BWRs in the 1980s, at which time susceptibility of reactor internals to IGSCC was also recognized [2,3]. Shroud cracking, which was identified in 1993-1994, confirmed that IGSCC of internals is a significant issue for BWRs.

IGSCC is a time-dependent material degradation process that is known to be caused and accelerated by the presence of residual and operating stresses, material sensitization, irradiation, cold work, elevated temperature, and corrosive environments (Figure 1). Many internal components inside BWR vessels are made of materials that are susceptible to IGSCC, including austenitic stainless steels, Alloy 600, Alloy X750, and Alloy 182 weld metal.

IGSCC is a commonly observed phenomenon in BWR core shrouds [4]. It was first observed in 1990 at the Mtihleberg site in Switzerland [5]. As of 2013, the surface cracks being monitored in the core shroud of Mtihleberg ranged from few centimeters to over half a meter in length and had depths exceeding two centimeters. In response to this finding, the original equipment manufacturer (OEM) issued an information letter to all owners of BWRs designed by the OEM, recommending a visual examination of the shroud circumferential welds [6]. The NRC responded to the early observations of cracking at several plants by issuing Generic Letter 94-03 to request that all licensees inspect their BWR core shrouds no later than the next scheduled refueling outage [7]. By the mid-1990s, the cracking had progressed to the point that several plants had installed tie rods to bolster the integrity of the core shroud, in the presence of circumferential cracks [5, 6]. By the late 1990s, a significant percentage of operating BWRs had installed tie rods [8, 9].

The tie rods rely on the integrity of the vertical welds of the shroud to perform their key function, but by 1993, cracking had been observed in the vertical welds, as well [9]. Multiple visual and ultrasonic examinations were conducted after this observation, and these cracks have been observed to progress slowly. Inspection and evaluation guidelines for the BWR core shroud were developed and documented in BWRVIP-76-A [10], which was submitted to the NRC for review, and Revision 1 received a safety evaluation in 2014 [11]. This supported the establishment of a re-inspection interval that can be up to ten years for these welds. To date, plants have been able to continue operation with the observed flaws, despite increases in the number and size of the flaws.

As these inspections progressed, the number of flaws observed has increased and flaw dimensions have changed. Figure 2 illustrates the various types of cracking that have been observed . Cracks oriented in the heat-affected zones along the welds have been commonly observed and were the primary concern related to core shroud integrity when SCC was first identified in the early 1990s. More recently, "off-axis" cracking (i.e., cracks that propagate approximately perpendicular to the associated weld, see Figure 2) has become more of a concern as inspections have revealed changes over time to the off-axis cracks along with new or deeper than expected cracks. These changes observed during inspections could be due to improvements in inspection techniques and equipment, rather than additional crack growth or initiation [8]. Analyses of BWR core shrouds indicate that the off-axis flaws are likely to grow through-wall, but are not likely to grow into long cracks due to the stress distribution predicted around the weld [12]. These analytical results are consistent with the majority of the reported off-axis flaws.

Correlation studies have shown that off-axis cracking is most strongly related to plant design, neutron fluence, and shroud fabrication [8]. The location of most of the reported off-axis cracks has been the core shroud beltline region spanning beltline welds H3 and H6a (Figure 3). Factors introduced during construction, such as cold work due to manipulation of the shroud during fit-up or local material changes due to the welding and subsequent removal of construction support and alignment lugs on the core shroud could have contributed to the cracking. The correlation with neutron fluence is driven by the location of the cracking in beltline region welds (Figure 3). Some of these correlated factors could be confounded with fabricator or design differences. The cause of this off-axis cracking remains under active investigation, but analytical results indicate that off-axis cracks are expected to remain short and do not have a significant impact on core shroud structural integrity [12]. To date, this has been confirmed by the results of field inspections.

Many other BWR internal components have also shown evidence of environmental cracking; though the cracking in core shrouds is one of the most widespread [5]. The experience summarized above shows that stainless steel welds operating in BWR environments are highly susceptible to stress corrosion cracking. Neutron irradiation appears to increase this susceptibility, and this phenomenon has become known as “Irradiation Assisted Stress Corrosion Cracking (IASCC)”. The experience of the BWR core shrouds provides evidence that much of the cracking initiated early in BWR plant life due to fabrication factors and the initial exposure to the oxidizing, Normal Water Chemistry (NWC) environment is important.

A reliable, predictive model is required for proactively resolving vessel and core internal material condition issues with generic, cost-effective strategies. A completely successful model must account for all of the phenomenological correlations that exist between IGSCC susceptibility and crack velocity and various environmental, electrochemical, and mechanical independent variables, as summarized above. To date, models have been developed that appear to account for the effects of electrochemical potential, loading waveform, and stress intensity on crack velocity, at least qualitatively, but only one, the Coupled Environment Fracture Model (described below), has succeeded in providing a comprehensive theoretical account of IGSCC in sensitized Type 304 SS. The empirical model developed by Ford and coworkers [13-18] perhaps came closest to this goal before the development of deterministic models. The Ford, et.al. model [13-18] does not account for the influence of the external environment on crack growth in an analytical (as opposed to empirical) manner. This latter aspect is particularly important, because the conductivity of the recirculating fluid in an operating BWR may vary significantly if upset chemistry conditions are experienced, resulting in enhanced crack growth rate. Extensive laboratory and in-plant studies indicate that impurity concentration (and hence conductivity) is one of the most important parameters in determining the rate of propagation of intergranular cracks [19-27]. In short, contemporary models for IGSCC, except the Coupled Environment Fracture Model (CEFM) [28-35], fail to invoke charge conservation explicitly and hence fail to account for processes that occur in the environment external to the crack in an analytical manner. The principal shortcoming in this regard is the failure to describe the cathodic reactions that must occur on the external surfaces to consume the current leaving the crack. Indeed, simple charge conservation considerations show that the internal and external environments must be strongly coupled, and this coupling is most likely responsible for the influence of solution conductivity, corrosion potential (ECP), and flow velocity on crack velocity. The CEFM was developed by Macdonald and co-workers to couple the internal and external environments in an analytical manner and to invoke charge conservation as a necessary condition for any deterministic treatment of crack growth [28-35]. Importantly, invocation of charge conservation leads to specification of the electrostatic potential in the solution at the crack mouth, which in turn allows calculation of the coupling current and hence the crack growth rate via Faraday's law. The main advantage of deterministic models for predicting corrosion damage in the coolant circuits of water-cooled nuclear power reactors is that their output is constrained to physical reality by the natural laws and the impact of all independent variables can be captured if correctly identified and included in the model.

Deterministic Modeling of Environment, Crack Propagation and Component's Lifetime

The typical deterministic modeling process for the evolution of SCC damage in the primary coolant circuit of a water-cooled nuclear power reactors involves three steps (Figure 4):

1. Calculation of concentrations of reducing and oxidizing species in the reactor coolant based on known reactor operating parameters and the principles of water radiolysis and chemical kinetics;
2. Estimation of Electrochemical Corrosion Potential (ECP) from interfacial charge conservation based on calculated species concentrations, hydrodynamic conditions, and electrochemical parameters of the structural materials in reactor Heat Transport Circuit (HTC);
3. Estimation of Crack Growth Rates (CGR) and crack depth in HTC components based on known species concentrations, ECP, material degradation parameters, mechanical stress (stress intensity factor), and reactor operating history.

As may be seen from Figure 4, such modeling requires the following five types of input data:

1. Reactor operating data that include neutron and gamma dose profiles, coolant temperatures and flow velocities, certain geometrical dimensions of the HTC "flow channels" and data on impurities and additions of chemicals, such as hydrogen over the reactor operating history. All these data usually are available from plant engineering personnel.

2. Radiolytic yields (or G-values) of species generated via neutron and gamma radiation of water at high temperatures. For gamma radiolysis, the G-values are well known at ambient temperature. Even for radiolysis with fast neutrons, the G-values at ambient temperature are known. The G-values for both gamma radiation and fast neutrons have been determined in recent years in experiments as a function of temperature by several groups, so that a moderately comprehensive database for these parameters is now available.
3. Reaction rate constants for water radiolysis reactions at reactor operating temperatures. Rate constants at ambient temperature are generally well known. In normal cases, rate constants at high temperature have been calculated from the rate constants at ambient temperature and the (often-assumed) activation energies. Exceptions to this rule are required for certain reactions. For diffusion-controlled reactions, activation energy of 12 kJ/mole is assumed. For slower reactions, higher activation energies are commonly assumed, but are not always verified experimentally.
4. Electrochemical parameters of structural materials and major reducing and oxidizing species. Over the past thirty years, researchers and power plant operators alike have come to realize that corrosion damage in coolant circuits, including most, if not all, forms of general corrosion and localized corrosion, including pitting, stress corrosion cracking, corrosion fatigue, erosion-corrosion, hydrogen-induced cracking, and crevice corrosion, are primarily electrochemical phenomena that involve charge transfer at metal/coolant interfaces. As with any electrochemical charge transfer process, the rate at which charge transfer occurs (the current and hence the rate of accumulation of damage) depends upon the voltage that exists across the metal/environment interface. This potential difference, when measured under free corrosion conditions with respect to a suitable reference electrode, is referred to as the ECP. The corrosion potential, or the "ECP", as it is commonly known in the nuclear power technology arena, is accounted for by mixed potential theory and can be calculated using mixed potential models (MPM) [29,34], provided that the required thermodynamic, kinetic, and mass transport parameters are known
5. Materials degradation modeling parameters, including mechanical, chemical and electrochemical parameters required for the estimation of initiation and propagation of localized damage (cracks) in LWR components [35], including stress intensity factor (K_I).

This paper compares deterministic and empirical predictions of IGSCC rates in sensitized austenitic stainless steel, in order to calculate the accumulated damage (crack depth versus time) in BWR in-vessel components and estimate component lifetimes for given operating conditions. Our extensive crack growth rate modeling work predicts that the crack growth rate should decrease with increasing crack depth; a relationship that is generally not gleaned from experimental data obtained from fracture mechanics specimens of fixed design. In this case, the electrochemical crack depth (shortest distance from the crack front to the external surface) is constant and independent of the mechanical crack depth. The impact that increasing electrochemical crack depth has on the CGR is a sensitive function of water conductivity, ECP, flow rate (especially for a high aspect ratio crack), and stress intensity factor. Accordingly, the predicted accumulated damage becomes a non-linear function of time and hence the operating history of the plant, which can be captured accurately only by deterministic models.

The accumulated damage is the expected crack depth, L, which is calculated on a component-by-component basis as a function of time, T, for an envisioned future operating protocol:

$$L = \int_0^T \frac{\partial L}{\partial t} dt \tag{1}$$

Crack growth rates at each state point t of reactor operation, $\frac{\partial L}{\partial t}$, are calculated by the Coupled Environment Fracture Model [28-35] as:

$$\frac{\partial L}{\partial t} = f[power(t), chemistry(t), L(t)] \tag{2}$$

The evolution of crack depth, L, over the anticipated service time of a component, T, is obtained by an accumulation of crack advances over N periods of time (state point duration) $\Delta t_1, ..., \Delta t_i, ...\Delta t_N$.

$$L_i = L_{i-1} + \left(\frac{\partial L}{\partial t}\right)_i \Delta t_i \tag{3}$$

$$T = \sum_{i=1}^{N} \Delta t_i \tag{4}$$

The crack growth rate is assumed to be time-independent for each interval, Δt_i, in that it depends on the crack depth (due to dependence of K_I on crack depth and because of changes in the current and potential distributions in the crack internal and external environments). The initial crack depth, L_0, corresponds to the depth of a pre-existing crack (as may have been detected during an inspection or assumed for a safety analysis scenario) or the length of the crevice at an initiation site.

A computer code REMAIN [36] has been developed for performing calculations for each step shown in Figure 4. This code performs the calculations for each state point during BWR operation history of 40 – 60 or more years within an hour on a desktop PC. Recently updated codes (PWR MASTER and BWR MASTER) with generic kinetics algorithm and advanced MPM and CEFM models for MAC and PC are described elsewhere [37-39]. The remaining service life of the core shroud was estimated using the BWR MASTER code based on safety criteria (which require crack depth to be less than half the wall thickness) for the H6a weld.

Modeling of Stress

The BWR MASTER code has no Finite Element Modeling (FEM) module for calculating stresses in in-vessel components. The code only calculates the stress intensity factor (K_I in $MPa\sqrt{m}$) of a pre-existing crack based on K_I at the previous state point and an empirical correction factor for CT specimens assuming a constant stress but correcting for increased crack length:

$$f_{CT} = \frac{(2+L)(0.886 + 4.64L - 13.32L^2 + 14.72L^3 - 5.6L^4}{(1-L)^{3/2}} \tag{5}$$

Values of K_I at the beginning of the operating period are obtained from plant engineers.

There are codes, such as ABAQUS [40], Grizzly [41,42] and number of others capable of finite element method (FEM) analysis to obtain stresses and fracture mechanics parameters, such as K_I in 3-D structures like the components of nuclear reactors. FEM is a direct modeling based on first principles and no empirical correlations, such as in Eq. (5), are required. The downside of the FEM modeling is the long input preparation and computation time that is frequently required in localized modeling of a component.

FEM modeling of the relationship between K_I and L for propagating crack in the H6a weld of a BWR core shroud (Figure 3) was reported [43] as an attempt to estimate remaining life of shroud. First, a 2-D model of the H6a weld (Figure 5) for the weld's residual stresses was created. The redistribution of the stress field in the vicinity of the weld, which initially consists of welding residual stresses but is later affected by SCC propagation was simulated and, in combination with the J-integral method, the evolution of the stress intensity factor K_I at the cracking tip was calculated.

Empirical Modeling of Crack Propagation and Component's Lifetime

The estimated SCC growth rate was calculated in [43] using empirical relations between K_I and the SCC propagation rate $\frac{dL}{dt}$ that can be summarized as follows [44]:

$$\frac{dL}{dt} = 2 \cdot 10^{-9} mm/s, K_I \leq 6.7 MPa\sqrt{m} \tag{6}$$

$$\frac{dL}{dt} = 3.33 \cdot 10^{-11} K_I^{2.161} mm/s, 6.7 MPa\sqrt{m} \leq K_I \leq 59 MPa\sqrt{m} \tag{7}$$

$$\frac{dL}{dt} = 2 \cdot 01^{-7} mm/s, K_I \geq 59 MPa\sqrt{m} \tag{8}$$

The relations between the K_I and SCC crack growth rate are obtained under normal water conditions at 288 °C for 316L stainless steel and are given by the Nuclear and Industrial Safety Agency in [44]. As suggested in [44], the SCC crack growth rate, while referring to "normal water" conditions, does not include the effect of various oxidizing conditions in the HTC regions under normal water chemistry on SCC and ignores SCC crack growth rate variations during temperature transients. There are several radiolytically produced reducing and oxidizing species, such as H_2, O_2 and H_2O_2, with concentrations varying significantly in the HTC regions and establishing various level of ECP and SCC crack growth rate. For example, concentrations of H_2, O_2 and H_2O_2, and resulting ECP and crack growth rate in core bypass and recirculation line vary significantly under normal water chemistry conditions. As a result, using the type correlations specified in [44] leads to large negative and positive biases, depending on HTC region. The remaining service life of the core shroud was estimated based on safety criteria (requiring the crack depth to be less than half the wall thickness) for the H6a weld [43]. Of perhaps greater concern is that Equations (6) to (8) appear to have been established using crack growth rate data that are not purely "mechanical" in nature, but contain significant contributions from environmental effects. If so, the CGR data employed in [43,44] inadvertently contain environmental effects.

Comparison of Stress Intensity Factors

According to the model for K_I at the crack tip given in Equation (5) and used by the BWR MASTER code (Figure 6, solid bold line), there is a linear increase of K_I from 28 $MPa\sqrt{m}$ to 62 $MPa\sqrt{m}$ as the crack depth increases from 1 mm (assumed depth of a pre-existing crack) to 25 mm. The variation of K_I is within the allowed range for the CEFM, which is from 10 $MPa\sqrt{m}$ to 80 $MPa\sqrt{m}$.

In [43], an average J-integral from a FEM analysis was used to calculate K_I. The solid symbols in Figure 6 show the results of that analysis, which are fit to a polynomial shown by the black thin curve in that Figure. The K_I increases with the cracking depth at the beginning stage and reaches a maximum value (54.98 $MPa\sqrt{m}$) at a cracking depth of 12.0 mm. As the SCC continues to propagate through the wall, K_I eventually decreases with crack depth, because of the stress relief that occurs due to the loss of constraint caused by the crack and the movement of the crack tip away from the region of maximum residual stress. When K_I reaches zero, the SCC stops propagating, as K_I halls below K_{ISCC} [43].

While the results of the K_I calculations using the two approaches are drastically different, both of them are within the 10 – 60 $MPa\sqrt{m}$ range. The effect of using the FEM based K_I instead of the CT based K_I on SCC crack growth rate and component lifetime in deterministic modeling using the BWR MASTER code is explored in the next sections.

Comparison of Crack Growth Rates

Simulation of SCC crack propagation rate using the BWR MASTER code has been performed for two cases: (1) using the original relationship between K_I and crack depth based on Equation (5); and (2) using the FEM based relationship between K_I and crack depth represented by a polynomial approximation of results from [43] shown as a solid line and a small dotted line respectively in Figure 7. In both cases, a 1 mm deep preexisting crack was an input parameter, corresponding to field observed situation when multiple cracks from fabrication have been missed with existing detection techniques. While a crack initiation model has been developed, field data indicate that majority of the observed cracks have been grown from pre-existing cracks created during components fabrication and installation process. The crack growth rate decreases from $8x10^{-8}$ mm/s to $1x10^{-8}$ mm/s with crack propagation, as predicted by CEFM. Substitution of the "simplified" relationship between K_I and crack depth based on Equation (5) (solid line in Figure 7) with the "more accurate" FEM based relationship (small dots line in Figure 7) did not result in significant changes in CEFM-predicted crack growth rates. This fact demonstrates the low sensitivity of crack growth rates to variations in K_I in deterministic modeling based on CEFM, because over the K_I range of interest the crack growth rate is dominated by electrochemical factors (i.e., it is in the Stage II region of CGR vs K_I). These results agree well with the Artificial Neural Network based sensitivity analysis result for Type 304 stainless steel [45], in which the K_I comes out as the fourth most important parameter in determining the CGR after temperature, conductivity, and ECP, suggesting that the SCC in sensitized Type 304SS in high temperature aqueous environments is primarily electrochemical in character. Such low sensitivity of crack growth rate to K_I opens an opportunity to avoid the use of time-consuming FEM calculations and to use simplified approaches such as Equation (5) instead.

In the FEM analysis in [43], the crack was permitted to propagate by releasing nodes until the crack tip was no longer in tension, which occurred at a crack depth of 29.6 mm (indicated by the point where the crack growth rate shown by the bold dotted line in Figure 7 goes to zero). However, the SCC propagation rates are obtained using the relation between K_I and the SCC propagation rate calculated using the empirically-derived Equations (6)–(8), which are continuously calculated during the simulation and the effect of environment (water chemistry) is ignored.

In BWR MASTER, modeling crack propagation is driven, according to CEFM [36], by electrochemical dissolution of bare metal after rupture of surface oxide film caused by stress and by the injection of hydrogen into the matrix ahead of the crack tip. In order for such dissolution to occur, the internal environment of the crack and external (surface) environment must be coupled: i. e. an IR drop between the internal and external environments has to be low enough for current to flow from the crack tip to the external surface where it is annihilated by cathodic reactions, such as oxygen reduction and hydrogen evolution. In other words, crack growth rate should slow down as crack grows, because crack tip becomes more electrochemically isolated (IR drop increases) from the external surface, resulting in a lower voltage being available across the external interface to drive the cathodic reactions. Theory shows that the crack can grow no faster that the coupling current can be consumed on the external surfaces; that is, the crack is driven by a large cathode, which is an outcome of differential aeration hypothesis that is the basis of all localized corrosion processes, including SCC. The resulting dependence of SCC rate on crack depth predicted by BWR MASTER is shown in Figure 7 as solid and small dots lines.

Parenthetically, it may be noticed that, when both BWR MASTER and FM modeling are used to predict crack advance into the base alloy, BWR MASTER predicts a higher CGR than does FEM initially (up to 5 years), because of additional positive impact of oxidizing chemistry conditions in the former. Thus, such a comparison for higher crack depth is not appropriate: BWR MASTER takes into account the decrease of the electrochemical activity at the crack tip (decrease of the CGR) as the crack grows in depth, while the FEM model recognizes no dependence of CGR on crack depth and postulates a much stronger dependence on K_I within the range 10 – 60 $MPa\sqrt{m}$ [i.e., Equation (7)]. The practical implication of this difference is discussed below in the next section.

The SCC propagation rate increase to a maximum value of $1.84\text{x}10^{-7}$ mm/s at a cracking depth of 9.0 mm and decreases to 2 $\text{x}10^{-9}$ mm/s at 26.5 mm and remains relatively constant to a depth of 27.4 mm. The behavior of the FEM-based K_I contradicts the CEFM-prediction that the CGR decreases as the crack depth increases, because the former is a purely mechanical model that does not consider electrochemistry, whereas the decrease of the crack growth rate with increasing crack length (for constant K_I) is an electrochemical phenomenon related to the IR potential drop down the crack brought on by the coupling current.

While the predictions of crack growth rate from these two methods are drastically different, the effect of using a FEM based K_I instead of a CT based K_I on a component's lifetime in deterministic modeling using the BWR MASTER code and a comparison of these results with the results of empirical modeling [43] are explored in the next section.

Comparison of Predicted Component Lifetime

A component's lifetime is defined by a safety criterion, which limits crack penetration to the half of the wall thickness. This criterion corresponds to a crack depth of 25 mm in the H6a BWR core shroud weld. There are two major differences between empirical approaches of estimating component's life time, as described in [43], and the deterministic approach implemented in the BWR MASTER code:

1. Deterministic modeling using the BWR MASTER code includes all three components that drive the SCC process as shown in Figure 1: (1) environment (i.e. BWR heat transport coolant chemistry and electrochemistry), (2) stress (in a simplified way) and (3) material microstructure. Empirical modeling as presented in [43] ignores the effect of the environment. This is problematic, as there is extensive plant, laboratory, and modeling evidence of the importance of water chemistry in SCC.
2. BWR MASTER calculates an accumulated crack depth [i.e. the crack advancement process is modeled according to Equation (1)] and BWR operating protocol, which includes periods of operating at full power and transients, such as startups and shutdowns. Operating protocol represents a stepwise function of time with reactor thermal power and temperature are constant over time (a state point). Duration of a state point may be one hour or less during startup and shutdown to over a month long during full power operation. Simulating 60 years of operating history comprises 1,200 state points, in this case. The modeling presented in [43] assumes that the reactor operates at full power 100% of the time. This is another significant simplification as there is extensive plant and modeling evidence of the importance of operating transients on the progression of SCC.

A comparison of the component's lifetime predicted by [43] and by BWR MASTER for a simplified case of operation at full power for 100% of the time is presented in Figure 8. Ignoring the water chemistry (environment) effect on SCC in [43] results in estimated lifetime of about 9 years (bold squares in Figure 8). BWR MASTER predicts about 40 years of lifetime regardless of the type of model used for estimating K_I used: a "simplified" one based on Equation (5), which is shown as a solid line in Figure 8 or an "accurate" one based on FEM modeling and Equations (6) – (8), which is shown as a small dotted line in Figure 8. Thus, in the case of the H6a weld, ignoring the effects of chemistry of the BWR coolant and the electrochemistry at the metal/coolant interface on SCC propagation rate leads to underestimating component's lifetime by a factor of four. The apparent paradox that a model that incorporates environmental effects (i.e., BWR MASTER) should predict a longer life that one that explicitly does not (i.e., that described in [43]) needs to be resolved, but probably arises from the fact that the empirical model proposed in [43] may contain environmental effects inadvertently by being calibrated on SCC data rather than on data for purely mechanical cracking (creep) and because the model does not recognize a dependence of the CGR on crack length for constant K_I.

An assumption of full power operation during 100% of time is also unrealistic, and leads to significant underestimation of component lifetime, thereby rendering the value of such predictions marginal for safety analysis. Modeling of SCC crack propagation, with power transients taken into account, indicates that a significant fraction of the SCC damage is accumulated during short transients. Additional modeling has been performed using BWR MASTER to illustrate this claim. Reactor operation was modeled over 60+ years with 12 months fuel cycles with refueling outages. Each outage includes 50 hours long shutdown, one month of a standby at zero thermal power and 50 hours long startup. Results of the accumulated crack depth are shown in Figure 8 as solid gray line. Lifetime of the BWR core shroud under these conditions (i.e., time to produce a 25 mm crack) was estimated as 28 years. At the same time, ignoring transients in BWR MASTER modeling results in ten years longer lifetime of about 40 years. These results indicate, that including transients into [43] modeling would reduce estimated component's lifetime also by a factor of 28/40 = 0.7, i. e. from 9 years to 6.3 years. This estimation is four times lower than deterministic one of 28 years obtained from BWR MASTER. Based on this analysis, it was concluded that typical SCC modeling, which ignores water chemistry and electrochemistry and does not take into account the actual operating history, would underestimate component's lifetime by a factor of four. Again, this difference can be attributed to the much higher dependence of CGR on K_I and the lack of a dependence on crack length. Finally, modeling like that in Ref. [43] is controversial, because, on the one hand, it overestimates SCC damage, even though it ignores water chemistry and electrochemistry and on the other hand it underestimates SCC damage by ignoring reactor operating transients during refueling outages.

Summary and Conclusions

A comparison of deterministic and empirical predictions of IGSCC in sensitized austenitic stainless steel, in order to calculate the accumulated damage (crack depth versus time) in a BWR in-vessel component and estimate component's lifetime for given operating conditions is described. Counterintuitively, it was found that substitution of a "simplified" relationship between K_I and crack depth based on Equation (5) with a "more accurate" FEM based relationship, which gives significantly lower values of K_I for higher crack depths, did not result in significant changes in the CEFM-predicted crack growth rates. This is due to the fact that the crack growth rate in the CEFM has a relatively low sensitivity to K_I. This low sensitivity of crack growth rate to K_I opens an opportunity of avoiding the use of time-consuming FEM calculations and to use simplified models such as Equation (5) instead. Based on the performed modeling, it was concluded that typical SCC modeling, which ignores water chemistry and electrochemistry and does not take into account the actual operating history would underestimate component's lifetime by a factor of 4. Finally, modeling like that in Ref. [43] is controversial, because, it overestimates SCC damage by using empirical fracture mechanical models that do not correspond to the actual mechanical condition of the core shroud. On the other hand, it underestimates SCC damage by ignoring water chemistry and reactor operating transients during refueling outages. Involving operating transients is particularly important, as during start-up and shut-down the change in the stress field around the crack increases the crack tip strain rate which, as a consequence, increases the fracture frequency and the exposure of the bare metal to the environment, which results in a higher CGR.

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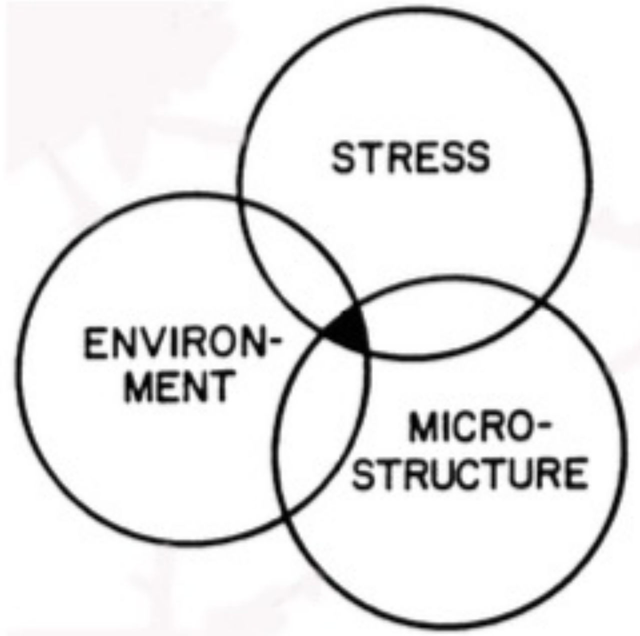

Figure 1 Synergy of Driving Forces for the Stress Corrosion Cracking Phenomenon

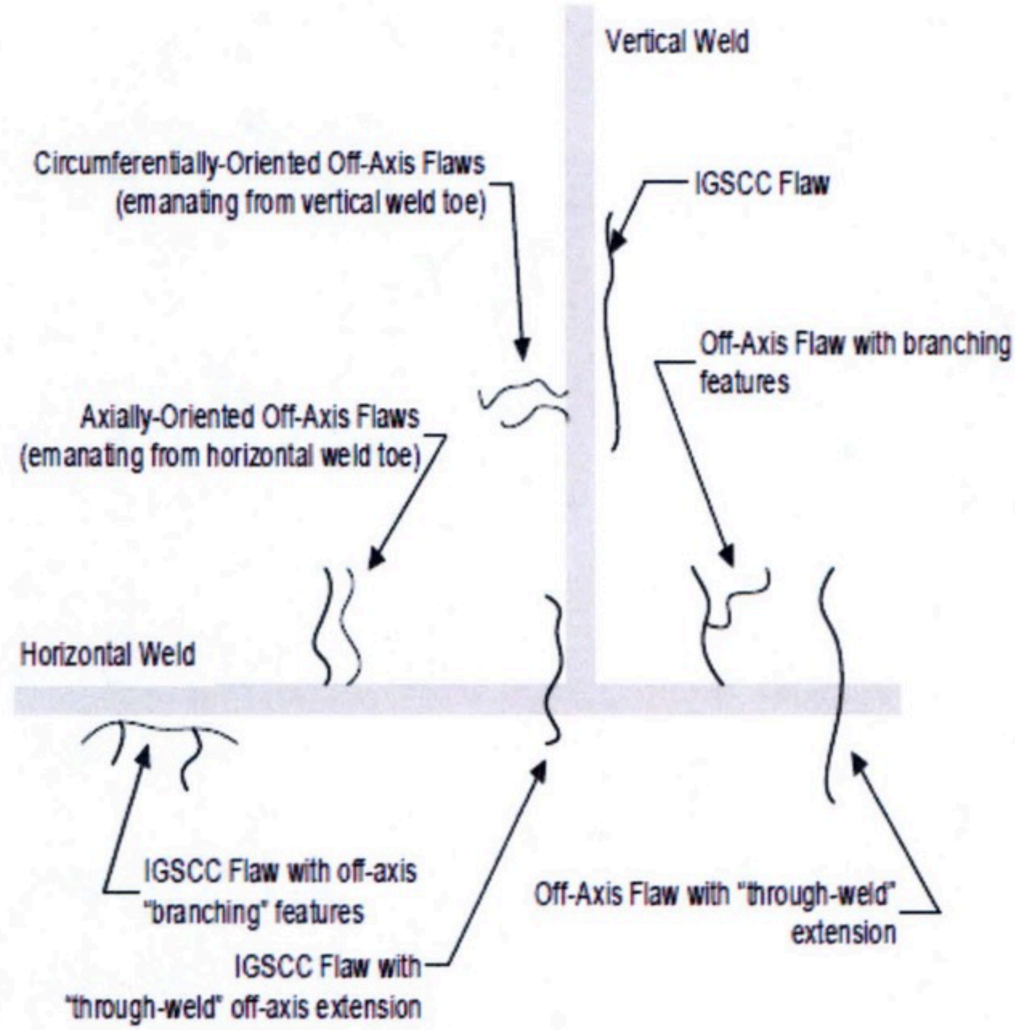

Figure 2 Locations and Orientations of BWR Shroud Cracking [8]

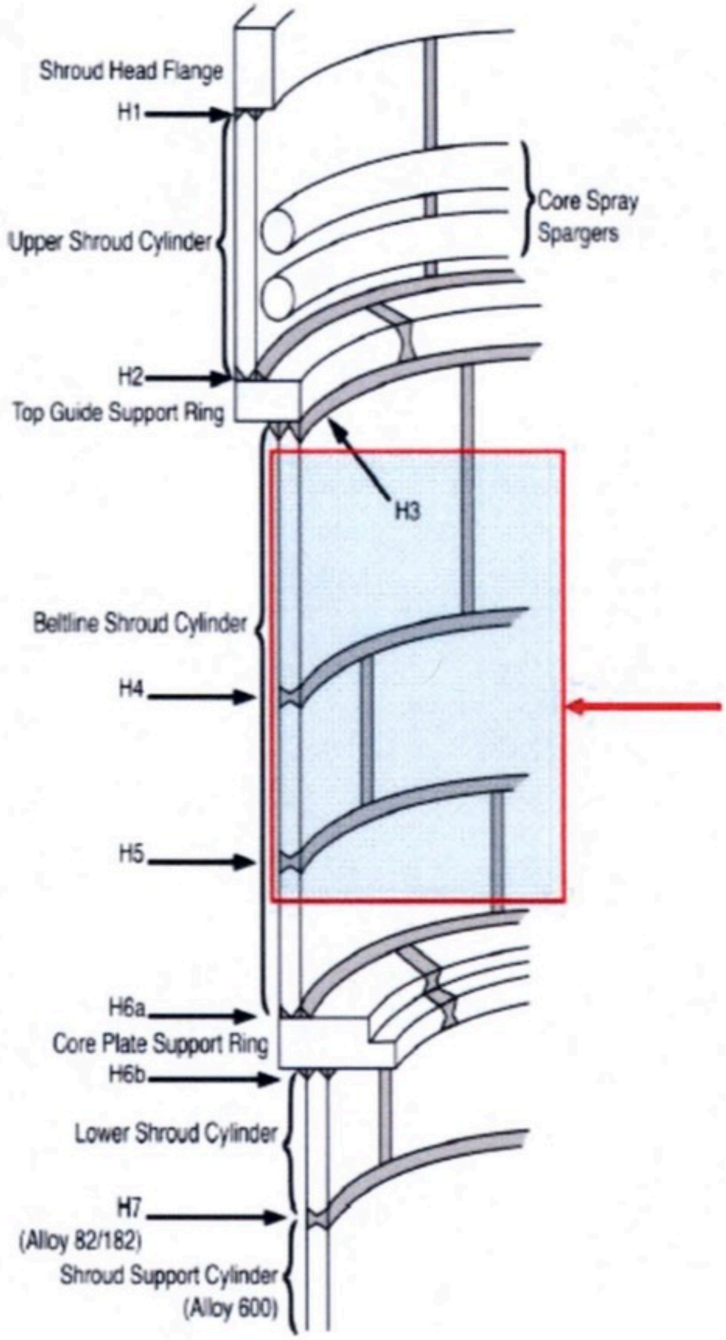

Figure 3 Location of BWR Shroud Welds and Off-axis Cracking. Nearly all off-axis cracking is between weld numbers H3 and H6a, as shown by the arrow. [8]

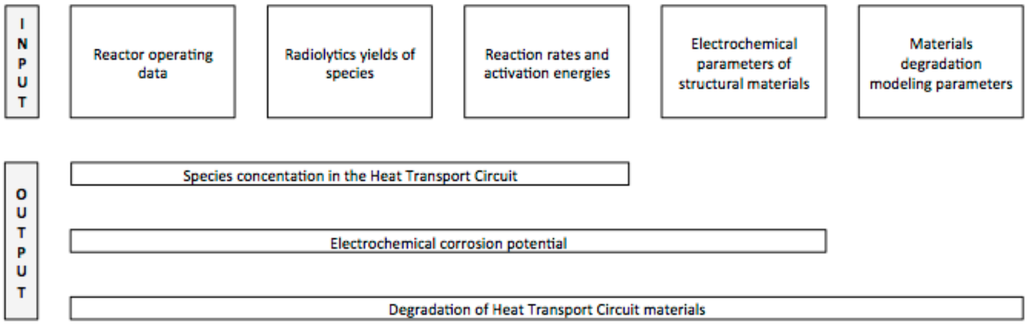

Figure 4 Modeling of IGSCC in BWRs

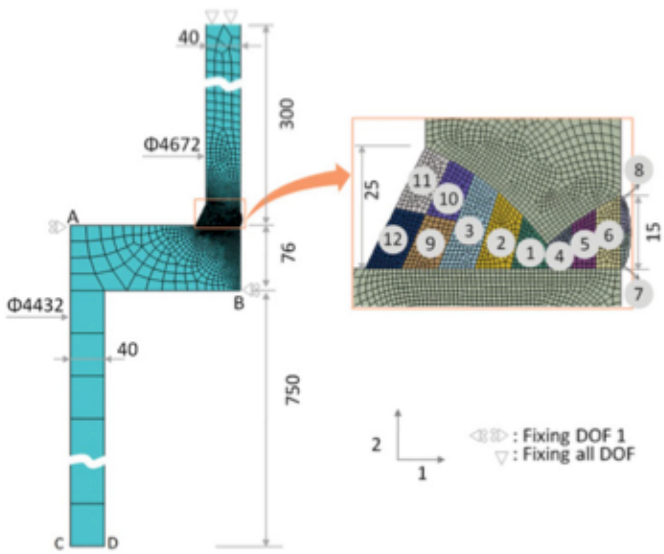

Figure 5 A Localized Model of the H6a Weld [43].

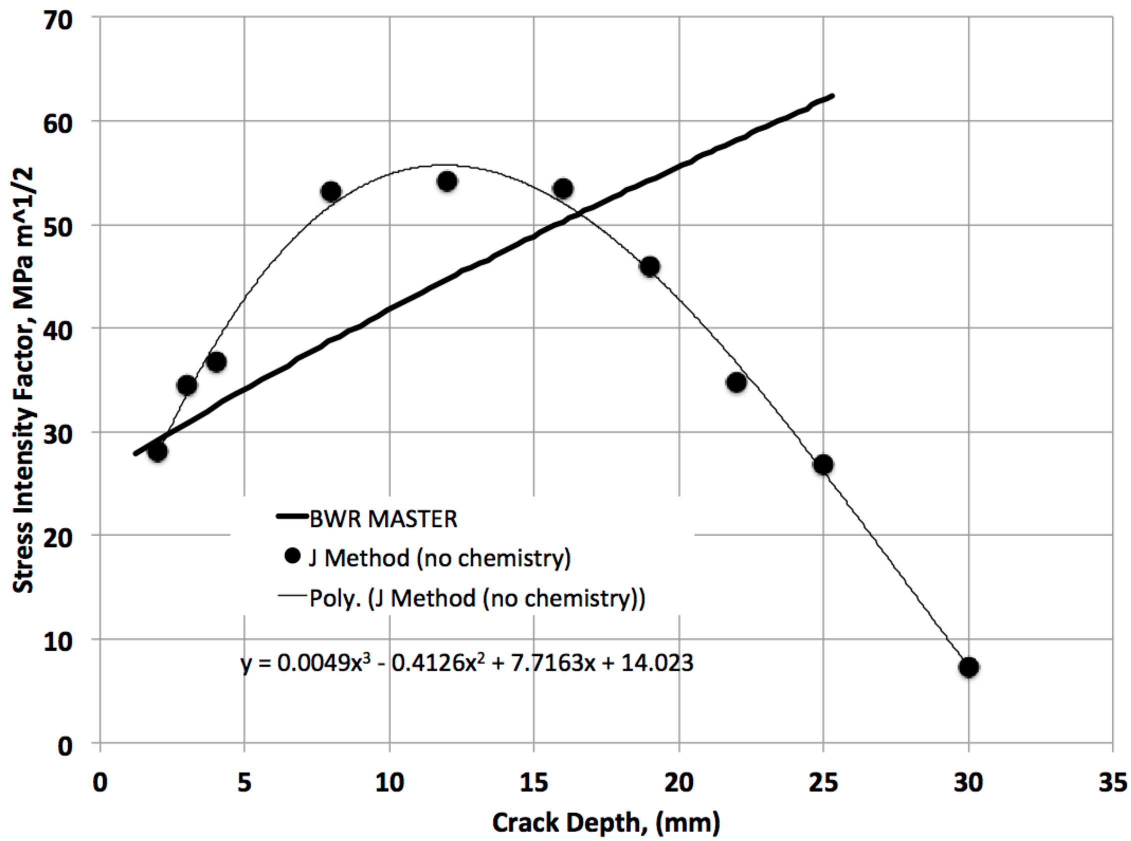

Figure 6 Stress intensity factor at the crack tip during crack propagation.

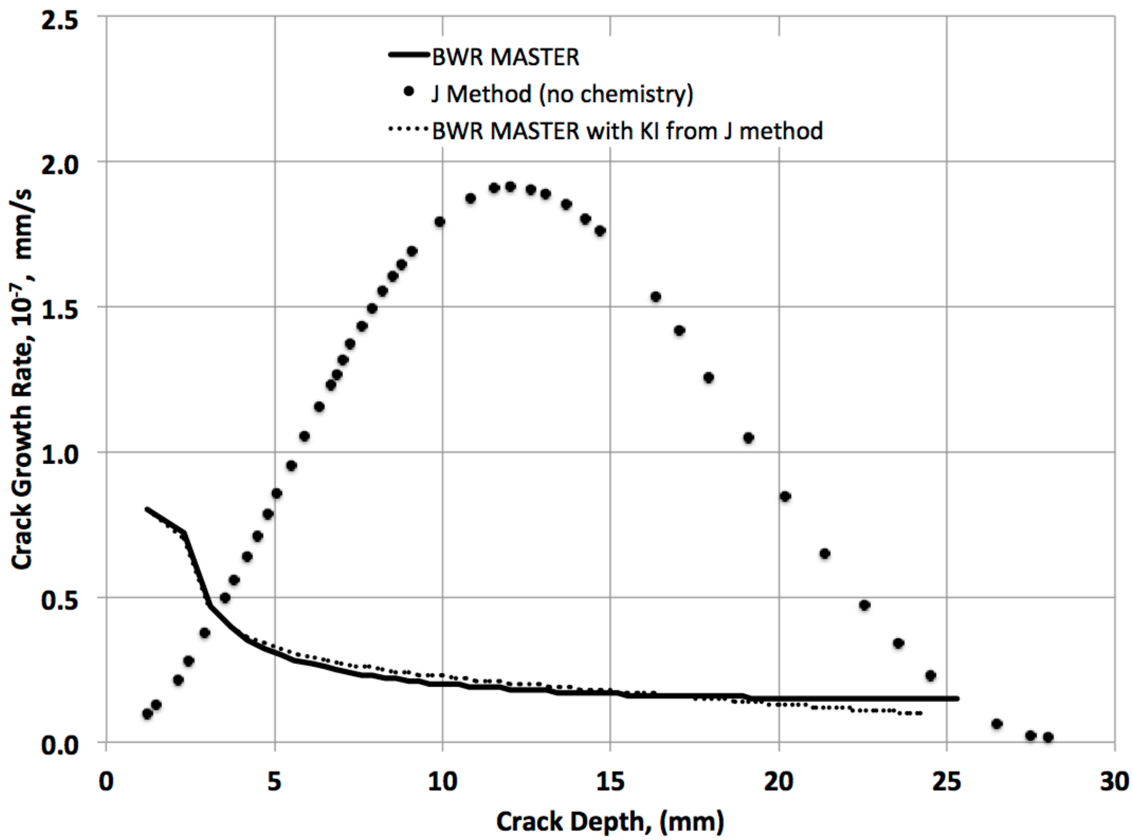

Figure 7 Crack growth rate during crack propagation through the H6a weld.

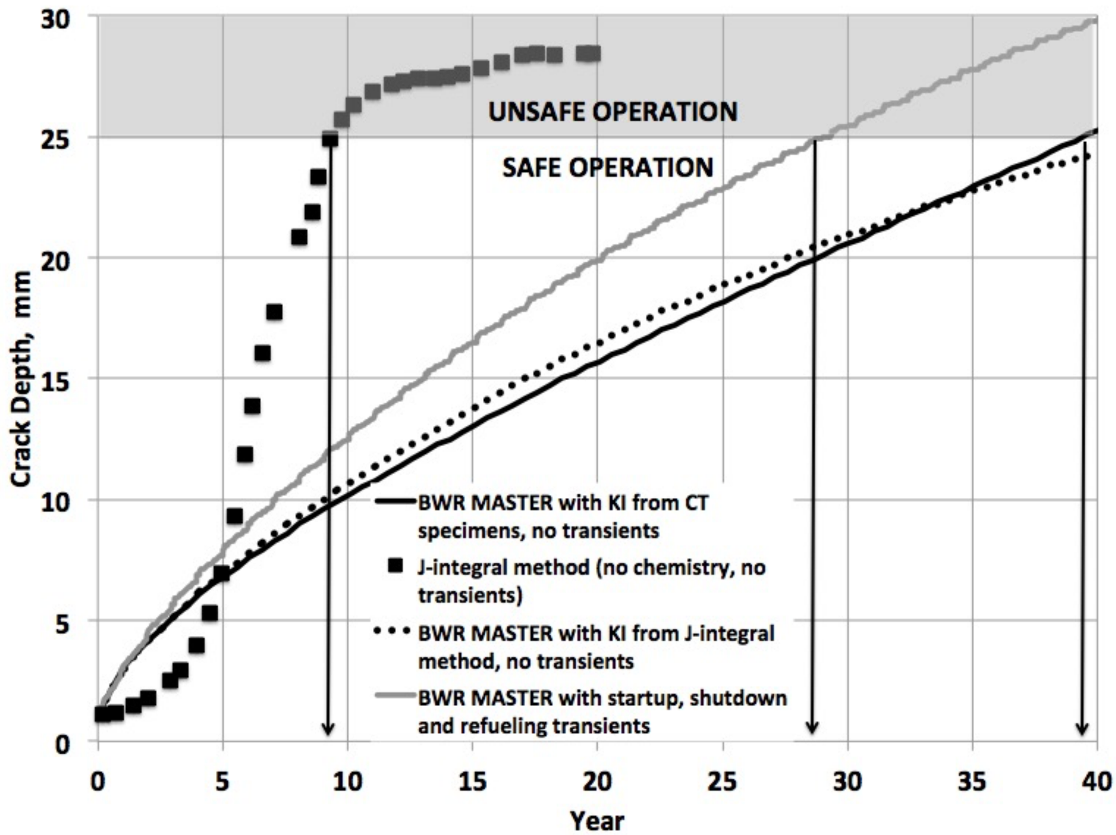

Figure 8 Predicted core shroud remaining lifetime based on crack propagation in H6a weld.