IASMiRT

SMiRT 26
50 Anniversary Berlin/Potsdam

Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Division II

APPLICATION OF JASPER PROBABILISTIC ANALYSIS TO STRATEGIC PLANNING FOR MANAGING SCC OF J-GROOVE PENETRATIONS

Markus Burkardt[1], Glenn White[2], Kevin Fuhr[3]

[1] Senior Engineer, Dominion Engineering, Inc., Reston, VA USA (mburkardt@domeng.com)
[2] Principal Engineer, Dominion Engineering, Inc., Reston, VA, USA
[3] Senior Engineer, Dominion Engineering, Inc., Reston, VA USA

ABSTRACT

JASPER (J-groove Adapter SCC Probabilistic Evaluation for Reactors) is a probabilistic fracture mechanics code developed by DEI for predicting the occurrence of stress corrosion cracking (SCC) in populations of J-groove welded nozzles such as PWR reactor vessel bottom-mounted nozzles (BMNs), PWR cold-leg instrumentation nozzles, and BWR level instrumentation nozzles. JASPER simulates SCC initiation and growth in Alloy 600 nozzle base metal and the Alloy 82/182 J-groove weld metal. DEI has developed and implemented JASPER to assist utilities in the economic decision-making process to assess the benefit of peening mitigation and the optimal timing of peening on a plant-specific basis.

BACKGROUND

J-groove partial-penetration welded nozzles, which are installed at various locations in both pressurized water reactors (PWRs) and boiling water reactors (BWRs), are often fabricated with nickel-based Alloy 600 material and attached with Alloy 82 or 182 weld metal. These materials are susceptible to stress corrosion cracking (SCC) degradation due to the high tensile weld residual stresses that are present. In BWRs, some J-groove nozzles are fabricated using austenitic stainless steel and are also susceptible to SCC in the weld heat-affected zones. SCC has led to costly inspections, repairs, and component replacements.

To date, indications of primary water stress corrosion cracking (PWSCC) have been reported to have affected nearly 200 control rod drive mechanism (CRDM) penetrations installed on reactor vessel closure head penetrations in U.S. PWRs. Although the large majority of closure heads in U.S. PWRs that operate at temperatures above the reactor cold-leg temperature (T_{cold}) have been replaced with heads using PWSCC-resistant materials, most original heads operating at T_{cold} are still in service. As original heads with Alloy 600/82/182 material continue to operate, the potential for PWSCC to occur in those heads increases.

PWSCC indications have been reported in only three bottom-mounted nozzle (BMN) penetrations in U.S. PWRs, with at least five additional confirmed or possible cases in international PWRs. These indications in U.S. PWRs are believed to have been promoted by subsurface weld fabrication defects that became wetted. To date, about a third of U.S. BMNs have been examined using non-visual non-destructive examination (NDE) capable of detecting PWSCC. Although plant and laboratory experience demonstrate a large benefit of reduced PWSCC susceptibility at T_{cold}, some detections are expected as operating time increases. Some manufacturing defects promote PWSCC, but given sufficient operating time, manufacturing defects are not necessary for PWSCC to occur.

Within the past nine years, there have been three cases of leakage identified in BWR reactor vessel water level instrument penetration J-groove welds. These leaks have been due to cracking originating in the Alloy 82/182 J-groove weld metal, but cracking also has the potential to occur in the nozzle tube base metal. As intergranular stress corrosion cracking (IGSCC) initiation and growth in BWRs are also material aging degradation mechanisms, the risk of additional cases of leakage will increase over time as plants reach extended operating times.

STRATEGIC MANAGEMENT

Several options exist for strategic management of SCC in J-groove penetrations. These include the status quo periodic NDE for evidence of leakage with repairs as necessary, zinc injection, peening mitigation, and replacement or modification using PWSCC-resistant materials (e.g., Alloys 690, 52, 152, and 52/152 variants). In the status quo option, any SCC flaws that are detected during inspection would be repaired, and this process would continue for the duration of the plant life.

The addition of zinc to the primary coolant results in its incorporation into the surface oxide film of Alloy 600, which has been shown to substantially increase the time to PWSCC initiation (MRP-263) [EPRI (2009)]. The early application of zinc injection at Farley Unit 2 may have contributed to the lack of observed PWSCC in its CRDM penetrations, some of which were fabricated from the nozzle Alloy 600 material heat known to have the highest incidence of PWSCC observed in the U.S.

Peening of Alloy 600/82/182 components is the main technique that is available to mitigate SCC degradation and prevent future initiations. Peening induces a layer of compressive residual stresses at the treated surface, preventing future SCC initiation. Furthermore, if the stress layer developed by peening remains compressive when operating stresses are included, growth of shallow SCC flaws within the compressive stress layer is arrested (MRP-267 R2) [EPRI (2016a)], (MRP-335 R3-A) [EPRI (2016b)]. Figure 1 illustrates the influence of application of peening and normal operating stress on an example pre-peening weld residual stress profile. On the other hand, laboratory testing and analyses show that peening does not significantly affect growth of pre-existing SCC flaws that are deeper than the surface compressive stress layer, e.g., the cracks are not effectively sealed from the reactor coolant environment.

Peening surface stress improvement and zinc addition are effective because of their capability to prevent or delay SCC crack initiation. Thus, their effectiveness tends to be reduced if applied after initiation has already occurred. This creates an incentive to apply such methods before SCC flaws have the opportunity to initiate.

For reactor pressure vessel closure heads, a main additional strategic management option is replacement of the head with one using Alloy 690 nozzle tubes and Alloy 52/152 J-groove welds. These higher-chromium alloys are highly resistant to PWSCC. Pre-emptive nozzle replacement or weld modification using SCC-resistant materials is an option in the case of other types of J-groove penetrations, although not considered practical in the case of PWR reactor vessel bottom-mounted nozzles.

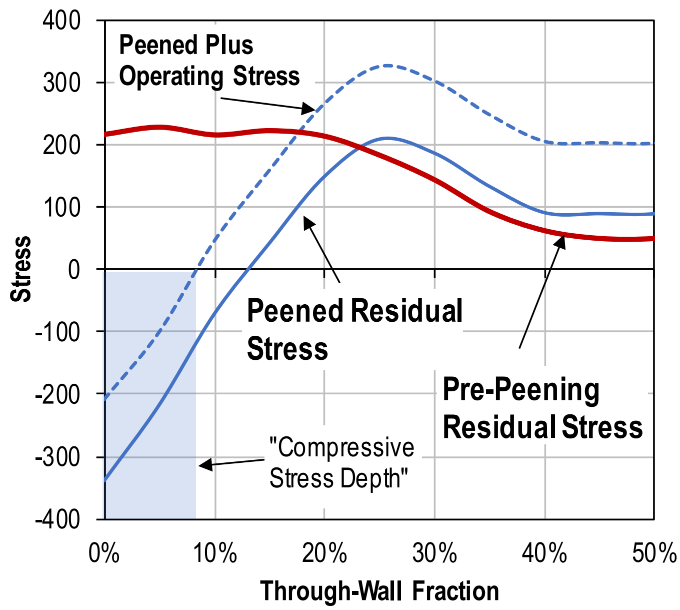

Figure 1. Illustrative comparison of stress profiles with the application of peening

JASPER APPROACH

DEI has developed and implemented a probabilistic Monte Carlo simulation code, JASPER (J-groove Adapter SCC Probabilistic Evaluation for Reactors), to assist utilities in the economic decision-making process to assess the benefit of mitigation options such as peening, zinc injection, or replacement versus a status quo approach, on a plant-specific basis. This code has been designed to provide best-estimate results with focus on supporting plant decision-making, rather than conservative results for regulatory purposes. JASPER can be applied generally to any set of J-groove partial-penetration welded nozzles in a plant, including reactor vessel BMNs, reactor vessel closure head nozzles (such as CRDM nozzles), and cold-leg instrumentation nozzles in PWRs,[1] as well as reactor vessel water level instrumentation nozzles in BWRs.

The JASPER code is used to determine the likelihood of SCC degradation developing in the penetration nozzles considered, the expected quantity of affected nozzles, and the likelihood of leakage occurring. JASPER simulates SCC initiation and growth in both the nozzle base metal and the J-groove weld metal, with the latest plant experience considered in modelling the frequency of occurrence of cracking.

The flaw scenarios considered are illustrated for the case of a BMN geometry in Figure 2. For axial flaws initiating at the nozzle inner diameter (ID) in the base metal at an elevation below the weld, leakage occurs once the flaw reaches the nozzle outer diameter (OD) annulus after propagating through-wall in the nozzle radial direction. For axial flaws initiating at the nozzle OD in the base metal at an elevation above the weld, leakage occurs once the lower flaw tip reaches the weld root after propagating downward through the weld height. If this flaw is predicted to grow through the nozzle thickness before causing leakage, it is assumed to immediately transition to an idealized axial flaw extending through the nozzle wall. For axial-radial flaws initiating at the wetted surface of the weld metal, leakage occurs once the flaw extends through

[1] Small-diameter Alloy 600 instrumentation nozzles in U.S. PWRs operating at hot-leg or pressurizer temperatures and pressurizer heater sleeves operating at pressurizer temperatures have mostly already been replaced with nozzles using PWSCC-resistant materials.

the weld throat distance to the weld root and nozzle OD annulus. JASPER has the capability of modelling flaws initiating on either the uphill or downhill side of the head, incorporating the corresponding differences in stress profiles and weld geometries between the two sides. The regions on the uphill and downhill sides are generally the locations of the highest welding residual stress (and also the highest stresses during operation) owing to the effect of nozzle ovalization, and SCC indications that initiate in the nozzle base material tend to be detected near those azimuthal positions.

The JASPER code has three main components: modelling of flaw initiation using Weibull statistical distributions, fracture mechanics modelling of crack growth, and a Monte Carlo routine wrapper to handle variability and uncertainty of inputs. These components are discussed in the following subsections.

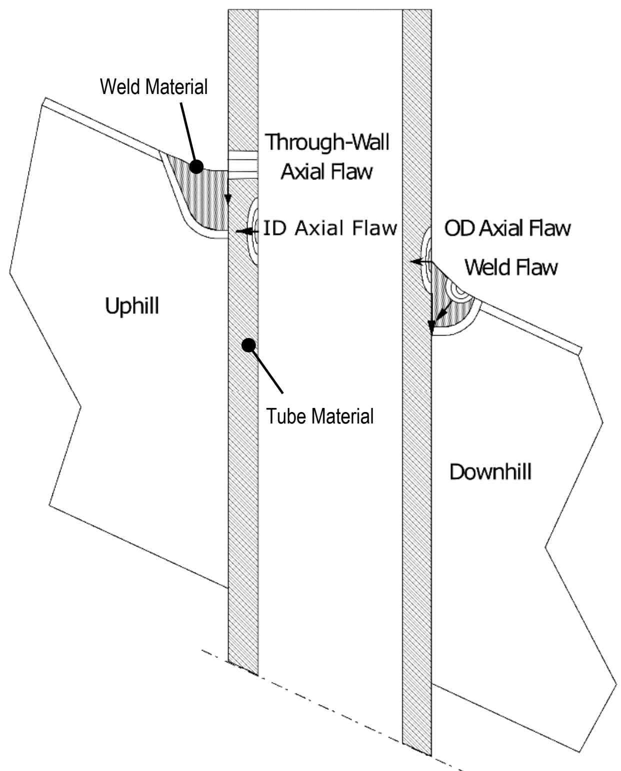

Figure 2. SCC initiation sites and crack shapes modelled in JASPER

SCC Initiation

To develop the initiation inputs to JASPER and model the probability of SCC initiating over time, Weibull distribution statistical fits are calculated for the operating experience with SCC in a given penetration type. The Weibull failure criterion is defined as the development of one or more SCC indications of an engineering size that would be detectable through volumetric or surface NDE. Thus, the Weibull assessment reflects variability in operating time until SCC is detectable via NDE. JASPER accounts for the latest plant experience to model the frequency of cracking occurring normalized for differences in operating time, operating temperature, and zinc injection history. The input distributions are tailored to emphasize the subset of experience most relevant to the component being modelled (e.g., based on material supplier or fabrication details).

Independent Weibull distributions are applied in JASPER for modelling initiation in the first affected penetration of that penetration type for a given plant, as well as modelling distributions for initiation in successive affected penetrations. The population of components at a given plant (e.g., on a single head) would be expected to be more homogeneous in exposure environment, fabrication techniques, and other factors than the overall fleet-wide population of penetrations, resulting in more similarity in the plant-specific penetration susceptibility to SCC and hence a higher Weibull slope. In JASPER, separate initiation models are applied to the nozzle tube base metal and J-groove weld metal to consider relevant differences.

Operating temperature is accounted for using a standard Arrhenius relationship, and zinc injection is modelled by slowing SCC initiation using a factor of improvement (FOI) approach. Stress is a known key parameter affecting initiation time, but J-groove penetrations generally all have high weld residual stresses in the vicinity of the J-groove weld on the order of the yield strength. Depending on the specific circumstances of the set of components being modelled, explicit modelling of stress differences may or may not be included in the simulations.

SCC Growth

Following the statistical modelling of initiation of SCC to an assumed macroscopic depth, JASPER simulates growth of the SCC flaw until it penetrates to the nozzle OD annulus and results in leakage. The growth of flaws is modelled using the latest industry PWSCC crack growth equations in MRP-420 R1 [EPRI (2018)]. Compared with the prior MRP-55 [EPRI (2002)] and MRP-115 [EPRI (2004)] equations, the MRP-420 R1 equations result in similar growth rates for Alloy 600 material but significantly slower growth rates for Alloy 82/182 weld material at PWR hot-leg and especially cold-leg temperatures. Axial flaws initiating at the nozzle ID and OD are grown using the revised Alloy 600 disposition equation, and flaws initiating in the weld metal are grown using the revised Alloy 82/182/132 disposition equation (generally using the Alloy 182 coefficient when the J-groove weld includes use of both Alloy 182 and Alloy 82). When modelling reactor vessel water level instrumentation nozzles in BWRs, IGSCC growth rate equations are instead applied as appropriate.

Stress intensity factors are calculated at key points through the component thickness, where detailed finite-element analysis modelling of operating and weld residual stresses and the influence coefficient method [EPRI (2007)] are applied. Variability in crack growth rates due to material variability and due to uncertainty regarding the magnitude of stresses is explicitly considered.

Crack propagation is simulated until leakage is modelled to occur. The time that a flaw takes to grow to cause leakage varies based on the residual and operating stresses in that area, the operating conditions (e.g., head temperature), the flaw size needed to cause leakage, and the susceptibility of the material (applied as a factor on the crack growth rate coefficient from MRP-420 R1).

Capabilities of the JASPER code include the ability to credit the absence of SCC or leakage detections in past examinations and the ability to represent the benefit of a peening application. The application of peening is modelled as halting initiation of all new flaws, but flaws that already exist at that time and are not simulated to be detected and corrected prior to peening continue to grow.

Monte Carlo Routine

An overview of the JASPER code structure is provided in Figure 3. The Monte Carlo routine wrapper, which executes each of the steps shown in Figure 3, is a collection of functions and subroutines which perform top-level functions including processing input and output, sampling of stochastic variables, setting up multi-processing, and calling the crack initiation and growth modules for flaws within each of the potential flaw initiation sites shown in Figure 2. The Monte Carlo routine wrapper is also capable of handling variable plant operating temperature histories (e.g., temperature as a function of effective full power years (EFPY)), modelling inspections (e.g., volumetric examinations of the nozzle tube material and visual examinations for leakage), and modelling strategic management options such as peening surface stress improvement or zinc injection.

Figure 3. Overview of JASPER code structure

EXAMPLE RESULTS

JASPER provides quantitative results to guide long-term strategic planning to manage SCC risk, including whether peening mitigation is warranted depending on utility-specific economic risk tolerance. Key outputs include the probability of SCC causing a first instance of through-wall cracking and leakage, the probability of detectable SCC occurring, as well as the likelihood of various quantities of penetrations having SCC that would be detectable by volumetric or surface examinations if performed. Some example results are provided below.

These key results can be calculated with and without credit for improved SCC initiation performance provided by zinc injection and specific to the time that zinc injection is first introduced. The modelling addresses the uncertainty in the magnitude of the delay in initiation time with use of zinc, as well as the possibility that initiation has already occurred at the time zinc injection is started. If the benefit of peening is simulated, the results reflect the risk of leakage occurring subsequent to peening mitigation due to the possible presence of pre-existing SCC flaws not detected in any pre-peening examination of the nozzle base metal and/or J-groove weld metal.

In addition, JASPER includes the capability to model the benefit of past inspections that did not detect cracking or leaks to demonstrate a reduced probability of cracks and leaks during upcoming operation depending on the specific examination coverage obtained. Especially in the case of eddy current examinations, the depth of peening compressive stresses (when considering the influence of operating stress) may be greater than the minimum detectable flaw depth, which would be expected to result in arrest of any pre-existing flaws not detected. Typically, an examination interrogating the J-groove weld metal is not included because of the substantial risk of false calls and unnecessary repairs, or detection of incipient SCC that might not grow to cause significant degradation. For example, pre-peening examinations of CRDM penetrations have in practice not included a surface examination of the J-groove weld surface. Moreover, ultrasonic testing is generally not qualified to detect SCC occurrence in J-groove welds.

As the example results are illustrative and actual results vary depending on the plant-specific situation, no vertical axis scale is provided for each example results plot.

Probability of Leakage and Probability of Detectable SCC

Figure 4 shows example results for the probability over time of one or more nozzles developing leakage due to SCC. Even if peening is applied, the probability of leakage continues to increase with time. In this example, this behaviour reflects the assumed lack of a pre-peening examination interrogating the weld surface or volume for SCC and the potential for pre-existing SCC flaws in the weld material to be present that are too deep to be arrested by peening. Crediting zinc injection (resulting in reduced probability of PWSCC initiation) or performing peening mitigation have a greater effect on the probability of leakage near the end of an 80-year total licensing period.

Similar plots may be generated using JASPER for the probability over time of one or more penetrations developing SCC of a size of engineering significance that is detectable by surface and/or volumetric NDE. At such flaw sizes, growth is governed by fracture mechanics rather than microscale factors. Multiple scenarios may be evaluated with consideration of past and/or future examinations, with the assumed examinations including in each case the nozzle base metal and/or J-groove weld metal and butter.

Number of Affected Nozzles on Statistical Basis

Figure 5 shows example results for the number of nozzles predicted to be affected by SCC over time at different confidence levels (i.e., percentiles) and for different assumptions. These results are informative for the risk that any supplemental examinations detect multiple additional nozzles requiring repair during a single outage and over future operation. If a substantial number of repairs are required, the status quo option may cease to be economically feasible.

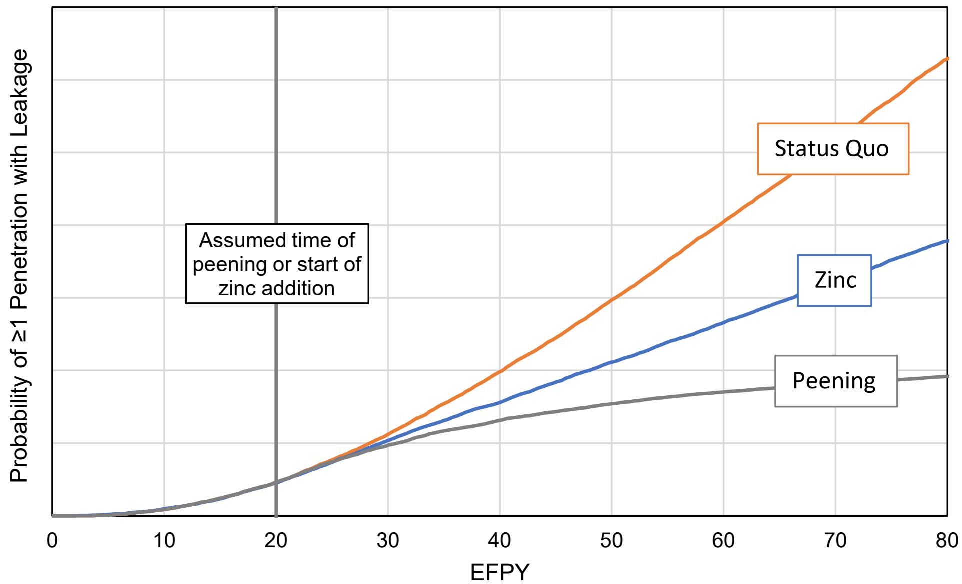

Figure 4. Example results – probability of leakage

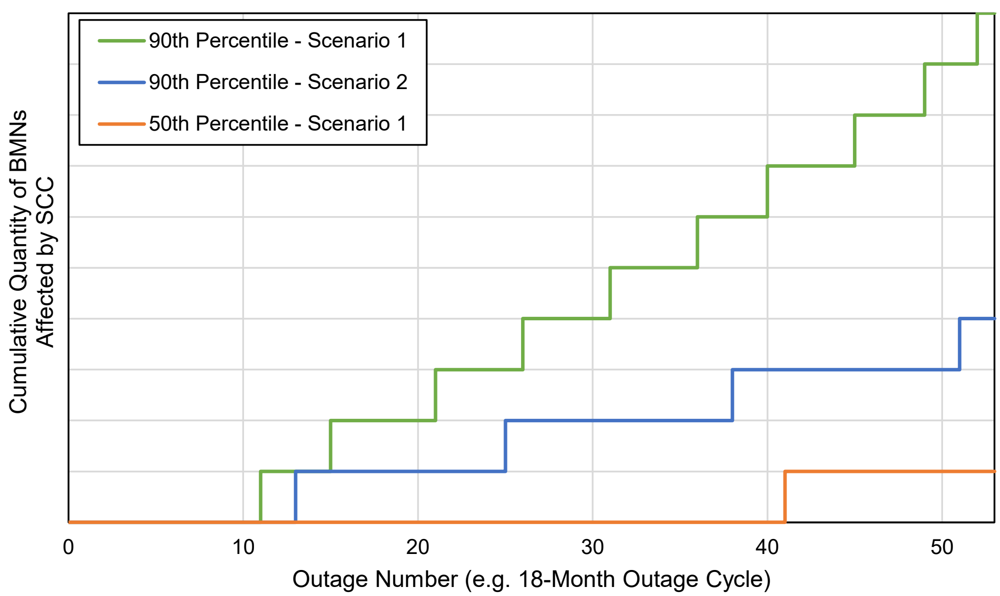

Figure 5. Example results – number of BMNs with detectable SCC

CONCLUSIONS

JASPER is a flexible PFM tool that can be applied to simulate SCC affecting a population of PWR BMNs, PWR cold-leg instrumentation nozzles, and BWR level instrumentation nozzles. SCC is inherently a stochastic process, so the PFM approach is key to strategic planning and economic decision-making. Outputs produced by JASPER are appropriate for input to probabilistic or expected value economic assessments.

In JASPER, susceptibility of the weld material is modelled separately from the base material. This allows for consideration of different pre-peening inspection programs on the probability of leakage after peening is performed. This also provides flexibility for treatment of differences in initiation likelihood and past volumetric and/or surface examinations, for example treatment of differences in known SCC susceptibility for particular heats of Alloy 600 nozzle material.

This paper demonstrates example JASPER outputs that can be leveraged as inputs to expected value or probabilistic economic evaluations and utility strategic planning. Example results are presented illustrating how key factors such as peening mitigation, zinc addition, and total operation for 60 or 80 years influence the long-term SCC risk.

REFERENCES

EPRI. (2002). *Materials Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials (MRP-55) Revision 1*. EPRI, Palo Alto, CA: 2002. 1006695.

EPRI. (2004). *Materials Reliability Program Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds (MRP-115)*. EPRI, Palo Alto, CA: 2004. 1006696.

EPRI. (2012). *Materials Reliability Program: Technical Bases for the Chemical Mitigation of Primary Water Stress Corrosion Cracking in Pressurized Water Reactors (MRP-263NP)*. EPRI, Palo Alto, CA: 2009. 1025669.

EPRI. (2016a). *Materials Reliability Program: Technical Basis for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-267, Revision 2)*. EPRI, Palo Alto, CA: 2016. 3002008083.

EPRI. (2016b). *Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335, Revision 3-A).* EPRI, Palo Alto, CA: 2016. 3002009241.

EPRI. (2018). *Materials Reliability Program: Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials and Alloy 82, 182, and 132 Welds (MRP-420, Revision 1)*. EPRI, Palo Alto, CA: 2018. 3002014244.

Marie, S., Chapuliot, S., Kayser, Y., Lacire, M., Drubay, B., Barthelet, B., Le Delliou, P., Rougier, V., Naudin, C., Gilles, P., and Triay, M. (2007). "French RSE-M and RCC-MR code appendices for flaw analysis: Presentation of the fracture parameters calculation – Part III: Cracked Pipes," *International Journal of Pressure Vessels and Piping*, 84, pp. 614-658.