MRP **Materials Reliability Program** ________________________________ MRP 2021-014

(via email)

September 28, 2021

U.S. Nuclear Regulatory Commission
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Subject: Transmittal of xLPR Welding Residual Stress Essential Parameters and Profile Selection

Reference:
1. NRC-EPRI Cooperative Nuclear Safety Research Memorandum of Understanding Addendum titled "*xLPR Version 2 Code Documentation and Leak-Before-Break Applications*," ML17040A146

Project 2.c, "Generalization Study," of the referenced Addendum describes cooperative NRC and EPRI efforts to investigate probabilistic leak-before-break methodologies for demonstrating compliance with the requirements of Criterion 4, "Environmental and Dynamic Effects Design Bases," of Appendix A, "General Design Criteria for Nuclear Power Plants," to Title 10 of the *Code of Federal Regulations*, Part 50, "Domestic Licensing of Production and Utilization Facilities." The attached document titled, "*xLPR Welding Residual Stress Essential Parameters and Profile Selection*," supports the data collection activities for this project. This transmittal is intended to facilitate reference of the document in publicly available NRC and EPRI reports that document the resulting generalization study analyses.

The document, "xLPR Models Subgroup Report—Welding Residual Stresses, Version 1.0," dated October 5, 2016, ML16341B049, describes methods for the development of dissimilar metal weld residual stress (WRS) profiles for use in analyses executed using the Extremely Low Probability of Rupture (xLPR) probabilistic fracture mechanics code. It provides a library of WRS profiles for select dissimilar metal weld configuration, but that library only addresses a limited set of such configurations.

The attached document was developed by members of the original xLPR WRS Subgroup and defines essential parameters influencing the WRS profiles to provide practical guidance for the selection and application of WRS profiles in the existing library to a broader range of dissimilar metal weld configurations. It was provided to the NRC and EPRI project teams as a working document in October 2019 for use in defining suitable inputs for the range of analysis cases within the scope of the Generalization Study project.

If you have any questions, please contact Craig Harrington, EPRI MRP Project Manager, at (charrington@epri.com).

Sincerely,

Craig Harrington
MRP Project Manager

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Attachment: *xLPR Welding Residual Stress Essential Parameters and Profile Selection*

xLPR Welding Residual Stress Essential Parameters and Profile Selection

The purpose of this document is to describe the fundamental parameters that influence the welding residual stress distributions calculated for use as inputs to the xLPR Version 2.0 program. It is anticipated that this document will be used to identify representative weld configurations from the xLPR library of residual stress profiles when evaluating plant- specific welds.

Background

The work performed to develop a library of welding residual stress inputs to support xLPR Version 2.0 development and testing is documented in a technical basis document report [1]. As discussed in this report, three different dissimilar metal weld geometries were selected for inclusion, based on two criteria: 1) they are nickel-base alloy welds subject to PWSCC conditions and 2) they are located on LBB systems. While not comprehensive, the intent of the WRS group was to select weld geometries that represent a significant portion of the welds that would require xLPR consideration. The WRS profile analyses for each weld geometry included repair cases with depths equal to 15% and 50% of the finished weld thickness. A summary of the three weld geometries are as follows; additional details on the selection process and analysis methodology are included in the technical basis document report. It is also noted that the residual stress values for xLPR-V2 (Figure 2, Figure 4, and Figure 6) represent averages from either three or four modelers.

Steam Generator Inlet Nozzle Weld

As shown in Figure 1 below, the steam generator inlet nozzle weld geometry is a single V groove weld, with both the DM weld and stainless steel (SS) safe end to pipe weld performed using narrow groove welds. The geometry information was obtained from a Westinghouse 4-loop example plant description of welds associated with installation of replacement steam generators. The residual stress distributions developed analytically for the steam generator nozzle weld are shown in Figure 2.

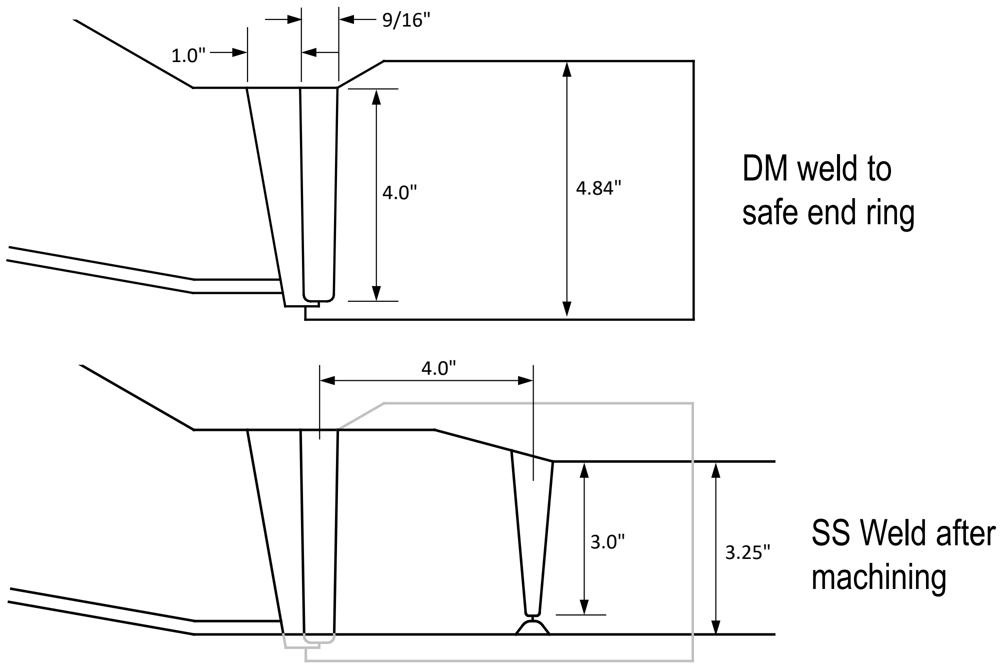

Figure 1. Steam Generator Nozzle Weld Geometry

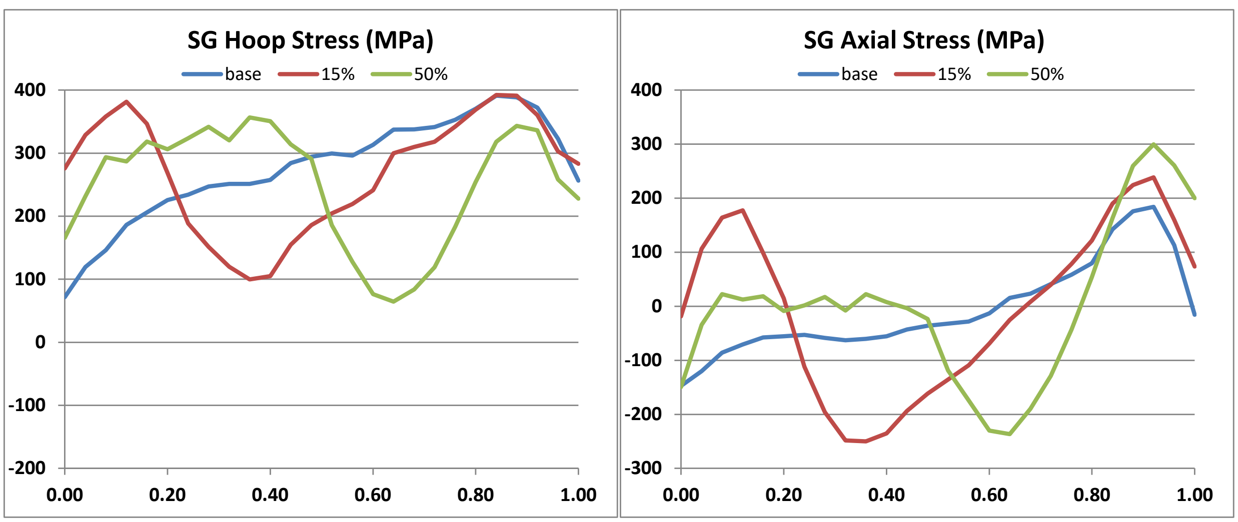

Figure 2. Weld Residual Stress Distributions for Steam Generator Inlet Nozzle Weld Geometry

Reactor Pressure Vessel Outlet Nozzle Weld

As shown in Figure 3 below, the reactor vessel outlet nozzle weld geometry is a single V groove weld; both the DM weld and the SS weld are larger weld grooves that included angle geometries more frequently seen in the original equipment and plant fabrication welds. The weld geometry is typical of many Westinghouse RPV nozzle welds. The weld residual stress distributions developed are shown in Figure 4.

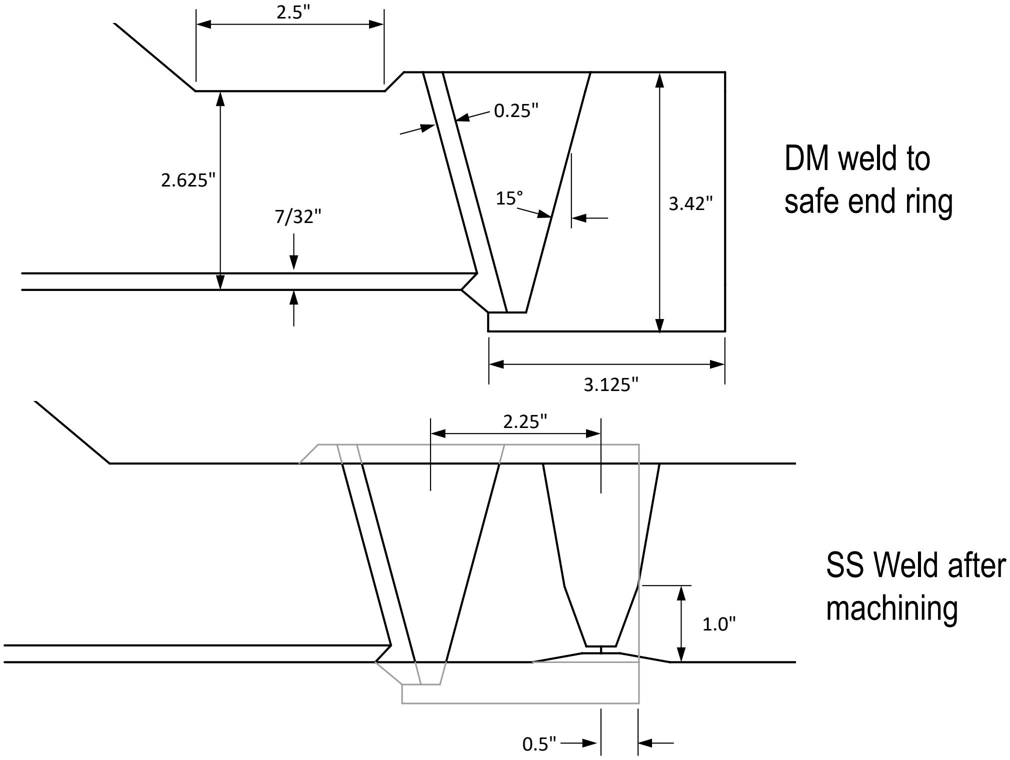

Figure 3. Reactor Pressure Vessel Outlet Nozzle Weld Geometry

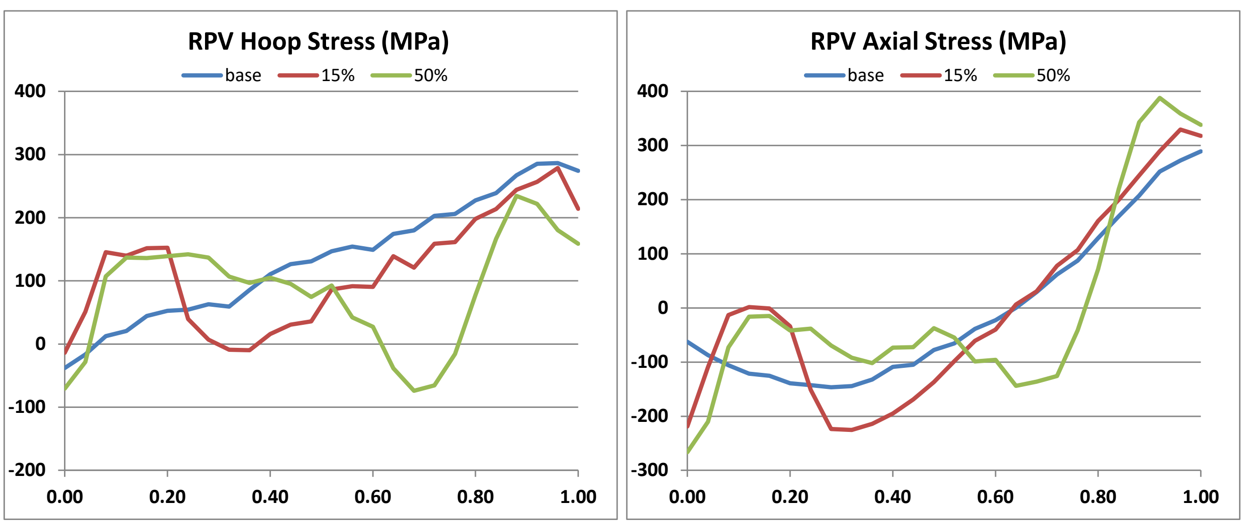

Figure 4. Weld Residual Stress Distributions for Reactor Pressure Vessel Outlet Nozzle Weld Geometry

Reactor Coolant Pump Inlet Suction Nozzle Weld

As shown in Figure 5 below, the reactor coolant pump inlet nozzle weld geometry is a single V groove weld; the DM weld and the SS weld grooves included angle sizes that are similar to the RPV nozzle weld.

The weld geometry is typical of B&W plant RCP inlet suction nozzles. The weld residual stress distributions developed are shown in Figure 6.

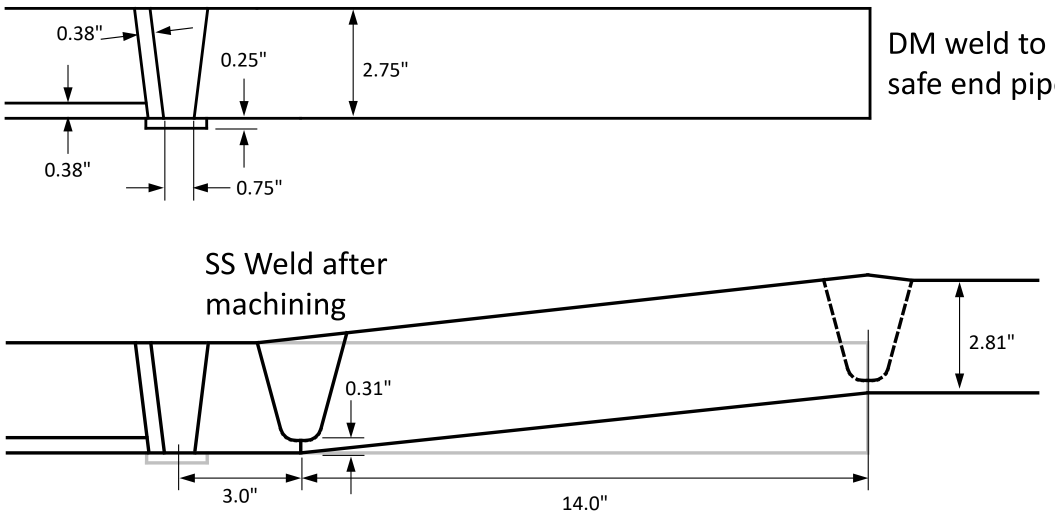

Figure 5. Reactor Coolant Pump Inlet Suction Nozzle Weld Geometry

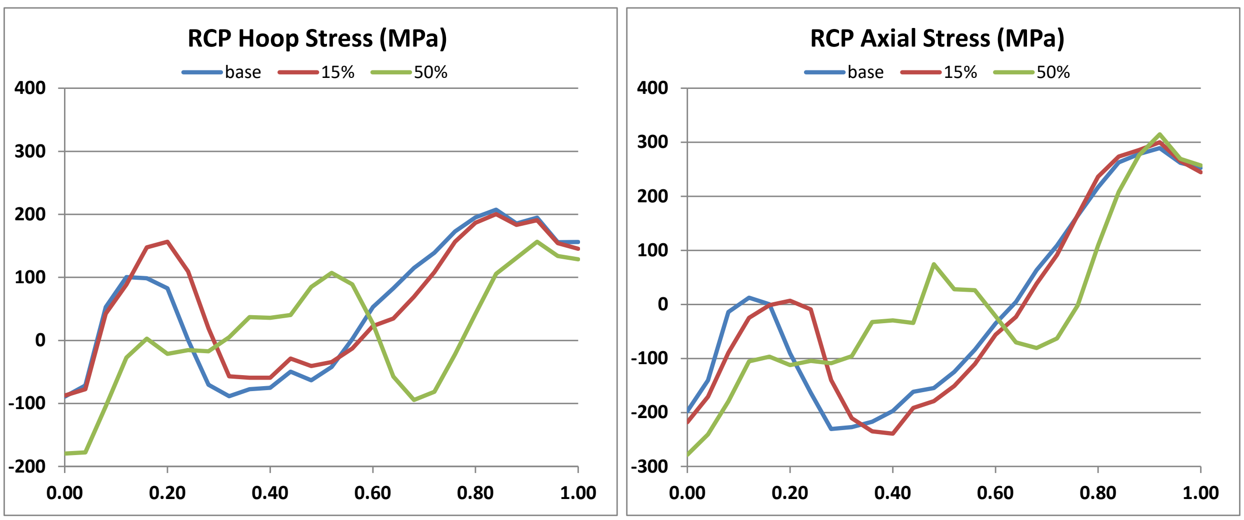

Figure 6. Weld Residual Stress Distributions for Reactor Coolant Pump Inlet Suction Nozzle Weld Geometry

Mitigation Processes

The welding residual stress technical basis document [1] also considered the effects of three mitigation processes on the three evaluated geometries: 1) full structural weld overlay (FSWOL), 2) mechanical stress improvement (MSIP), and 3) resistant material inlay weld deposition. Additional analyses were not performed to consider these processes; instead, existing analyses documented in technical literature were reviewed to assess and define the change in WRS distributions caused by the different techniques. When the ID region of the weld has tensile stresses (such as in the SG inlet hoop stresses), then the FSWOL and MSIP techniques generate a substantial compressive shift to the residual stress at the ID

region that generally decreases through the wall. When the ID region of the weld has compressive stresses (such as in the RCP nozzle cases), the FSWOL and MSIP techniques do not generate significant additional compressive stress. The resistant material inlay weld deposition cases result in tensile stresses at the ID surface, like a shallow ID repair.

While calculation methods have been established to define the effect of FSWOL and MSIP techniques, confirmatory analyses and physical measurements of the resulting residual stresses have not been performed for the three xLPR-V2 geometries. In order to support immediate piping system analyses, the NRC team plans to perform MSIP analysis for at least one case to verify prior solutions, and FSWOL analysis at a later date.

The mitigation processes considered were those that substantially effect the through wall residual stress distribution. Peening was not considered since it is a much shallower mitigation process.

Residual Stress Selection Process

As summarized in the previous section, xLPR Version 2.0 includes an initial library with a total of 36 potential welding residual stress distributions from which to choose. There are three geometries, each with three different repair options, and there are four potential mitigation scenarios (unmitigated and mitigated with one of three processes). The following selection logic should be used when evaluating other plant-specific welds using xLPR-V2.

Identify and Characterize Weld Geometry Details

The first step in selecting a residual stress distribution is to define the geometry of the weld being considered. The information required to perform this step includes: 1) drawings that provide enough information to define the weld configuration evolution during fabrication and in the final as-built condition and 2) information, as available, on repairs performed following completion of the weld. The final configuration alone of the weld may be insufficient to define completely the appropriate weld for evaluation. The following specific characteristics of the weld should be identified:

- Weld groove configuration; examples include:
  - single V groove
  - double V groove
  - weld opening (standard vs narrow-groove) is not a significant factor in the DM weld stress
- Weld fabrication details; examples include:
  - oversized weld with machined ID/OD (see Figure 3)
  - butt weld with ID back-gouge and re-weld
  - other weld characteristics such as weld buildup, weld cladding, last pass location, etc.
- Weld geometry information including:
  - final DM weld thickness
- Safe end configuration information including:
  - presence of safe end (yes/no)
  - safe end weld thickness (if applicable)
  - distance from DM weld centerline to safe end weld centerline (if applicable). The distance of the safe end weld from the DM weld can have an important effect on the WRS distribution. If the distance is sufficiently large or the safe end weld is narrow

groove, then the proximity rules discussed below do not apply. The nozzle diameter and safe-end thickness also plays a role in closure (last-pass) weld effect.

- Mitigation process (if applicable)

Weld Match Identification

This section provides guidance on identifying the closest match between the weld to be evaluated and the library of residual stress distributions provided in xLPR. In some cases, there may not be a representative configuration among the library of residual stress distributions.

Category 1: Westinghouse RPV Nozzles

The xLPR RPV nozzle weld case (see Figure 3 and Figure 4) is generally considered appropriate for all subject RPV nozzle DM welds at Westinghouse design plants, subject to the following conditions: 1) single V groove weld (symmetric or asymmetric), and 2) with a safe end close to the weld. This is because most Westinghouse designs have similar geometry for RPV welds. The following additional cases and details also apply:

- RPV welds without a safe end or with a narrow groove safe end weld should use the steam generator nozzle weld case, noting that:
  - The safe end weld in the steam generator weld case generates little to no change in the DM weld stresses
  - The steam generator nozzle case is a narrow groove DM weld, which may result in a through-wall distribution of higher tensile stresses
- RPV welds with cladding over the weld surface do not have a representative configuration in the library of residual stress distributions
- RPV welds that were subject to post-weld heat treatment do not have a representative configuration in the library of residual stress distributions

Category 2: B&W RCP Nozzles

The xLPR RCP inlet nozzle weld case (see Figure 5 and Figure 6) is generally considered appropriate for all subject RCP nozzle DM welds at B&W design plants, since B&W plants typically have similar component and weld geometries. However, the weld geometry at a given plant should be reviewed, and, if the geometry is different from the xLPR case, a case-specific analysis should be applied.

Category 3: Other Single-V Groove Welds

These welds cover a broad range of geometries and sizes. The following conditions should be considered in order to select an appropriate residual stress distribution:

- Welds with a finished thickness less than 1.5 inches should apply a case-specific analysis result
- The following geometry check should be performed for the weld and safe end configuration
  - Is there a safe end weld (Y/N)
  - Is the safe end weld at least 75% of the finished DM weld thickness (Y/N)
  - Does the safe end weld have a total included angle of at least 20° (Y/N)
  - Is the safe end weld centerline less than a distance of $1.1\sqrt{R_m t}$ from the DM weld centerline, where R_m is the mean radius at the weld centerline and t is the finished weld thickness (Y/N)
- If the answer to ALL four questions above is Yes, then the RPV nozzle weld case (see Figure 3 and Figure 4) should be used

  - In general, V-groove welds greater than 1.5 inches thick result in similar through-wall stress distributions. The RPV nozzle weld case is a suitable representation of a DM weld that is impacted by a safe end weld.
- If the answer to ANY of the three questions is No, then the steam generator nozzle weld case (see Figure 1 and Figure 2) should be used
  - In general, V-groove welds greater than 1.5 inches thick result in similar through-wall stress distributions. The steam generator nozzle weld case is a suitable representation of a DM weld that is not impacted by a safe end weld.
- Welds with an as-designed back gouge and reweld should use the 15% repair case
- Welds with an ID side weld buildup should use the 50% repair case

<u>Category 4: Westinghouse Double-V Steam Generator Nozzle Welds</u>
A representative configuration for these welds is the steam generator nozzle case with a 50% weld repair.

Repair Case Selection Considerations

Once a suitable weld match is identified, it may be necessary to select an appropriate repair case. Guidance is provided for the following conditions:

- If a known depth of repair has been performed, the repair case that is closest to the known depth of repair should be used for the evaluation.
- If it is known that a repair was performed but the depth is unknown, the 15% and 50% repair cases should be used for the evaluation, and the results from both cases should be considered.
- If the repair condition is unknown, the no repair case along with the 15% and 50% repair cases should be used for the evaluation, and the results from all three cases should be considered.

Uncertainties

The WRS profile description is for mean values and deterministic in nature. However, another essential parameter is the uncertainty on the mean values. Since the uncertainty is characterized by a normal distribution at each point there is only one parameter that needs to be assessed – the standard deviation. The WRS profiles developed for xLPR-V2 use the following standard deviations at ALL points through the thickness is shown in Table 1.

Table 1 WRS Profile Standard Deviations for Axial and Hoop WRS		
PROFILE	Axial Std Dev, MPa	Hoop Std Dev, MPa
RCP unrepaired	28.3	50.4
RCP 15%	28.3	50.4
RCP 50%	37.1	50.6
RPV unrepaired	16.7	33.7
RPV 15%	32.6	39.4
RPV 50%	28.7	48.0
SG unrepaired	18.3	19.7
SG 15%	44.8	47.5
SG 50%	41.5	55.5

The rationale for using a constant standard deviation through the thickness is described in the WRS Group Report [1]. It fundamentally derives from the requirements to be able to importance sample, the equilibrium constraint (for axial WRS), the point to point correlation to maintain the general profile shape, and, most importantly, only having 4 analyses, 3 analyses in some instances, to estimate a distribution at 26 points through the thickness. Therefore, the standard deviation at each point was calculated and the average of these 26 results was used throughout the thickness. The ratio of the standard deviation to the mean value at the ID is shown in Table 2.

Table 2 WRS Profile Ratio of Standard Deviation to the Mean Value at the ID for Axial and Hoop WRS		
PROFILE	Axial WRS Ratio	Hoop WRS Ratio
RCP unrepaired	-14.3%	-56.6%
RCP 15%	-14.3%	-56.6%
RCP 50%	-13.4%	-28.2%
RPV unrepaired	-26.7%	-88.9%
RPV 15%	-14.9%	-280.7%
RPV 50%	-10.8%	-67.9%
SG unrepaired	-12.5%	27.6%
SG 15%	-237.8%	17.2%
SG 50%	-27.7%	33.5%

This is of less value because if the WRS at the ID is near zero then the ratio can be misleading. The probability that the WRS at the ID is greater than zero can also be examined as shown in Table 3.

Table 3 WRS Profile Probability That the ID Stress is Greater Than Zero for Axial and Hoop WRS		
PROFILE	Probability for axial WRS	Probability for hoop WRS
SG 50%	0.016%	99.856%
RCP unrepaired	0.000%	3.852%
RCP 15%	0.000%	3.852%
RCP 50%	0.000%	0.019%
RPV unrepaired	0.009%	13.020%
RPV 15%	0.000%	36.081%
RPV 50%	0.000%	7.046%
SG unrepaired	0.000%	99.986%
SG 15%	33.708%	100.000%
SG 50%	0.016%	99.856%

As Table 3 shows, the probability of the axial WRS stress at the ID being greater than zero is very small for all cases other than the steam generator 15% repair case. If the minimum axial stress needed to have initiation is examined, then the values are relatively high as shown in Table 4.

Table 4 WRS Profile Minimum Axial and Bending Stresses at the ID to Initiate Circumferential Cracks		
PROFILE	Axial stress mean value, MPa	Bending stress mean value, MPa
RCP unrepaired	197.4	162.7
RCP 15%	197.4	162.7
RCP 50%	278.0	243.4
RPV unrepaired	62.7	24.0
RPV 15%	218.7	180.0
RPV 50%	266.4	227.6
SG unrepaired	147.2	119.9
SG 15%	18.8	-8.5
SG 50%	149.5	122.2

The third column in Table 4 shows the minimum mean value of bending stress to have initiation when the pressure stress is accounted for in the calculation. From this table, it is seen that the RPV unrepaired and SG 15% repaired cases are the only two that have axial or bending stresses with a reasonable chance of initiating circumferential cracks.

References

1. Technical Basis Document Welding Residual Stress Model Development for xLPR Version 2.0, Report xLPR-MSGR-WRS V1, October 2016.