Overview of the MERIT (Maximizing Enhancements in Risk-Informed Technology) Program

by

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ABSTRACT

As the technology associated with nuclear power generation has matured, risk management has become a cornerstone of the maintenance and operation of nuclear power generating plants. Risk management tools have evolved to the point that they are now frequently used in the decision making process. For example, probabilistic risk assessment (PRA) analyses are used both by the industry and regulatory staff. Risk-informed in-service inspection is being incorporated into criteria embodied in such documents as Section XI of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. In addition, probabilistic fracture mechanics codes and databases of operating experience are being used to assess potential risks associated with the operation of nuclear power plants, such as recent occurrences of PWSCC in PWR plants.

To enhance some of these risk management tools, a new international cooperative research program, known as MERIT (Maximizing Enhancements in Risk Informed Technology) is ongoing at Battelle Columbus. This paper describes some of the key features of this new program. One of the key risk management tools being developed as part of this program is a probabilistic fracture mechanics (PFM) code called PRO-LOCA. While the primary impetus behind the development of PRO-LOCA is to aide the assessment of the frequency of various size loss-of-coolant accident (LOCA) events, there are other potential uses for PRO-LOCA, such as in-service inspection (ISI) prioritization and enhancing leak-before-break (LBB) decisions.

MAJOR TECHNICAL ACTIVITIES OF THE MERIT PROGRAM

There are a number of technical activities being addressed as part of the MERIT program. As alluded to earlier, the major technical activity in the MERIT program is the continued developed of the PRO-LOCA probabilistic fracture mechanics code [1]. Other technical efforts include:

- the further development of a library of weld residual stress solutions for inclusion into PRO-LOCA to include addressing the effect of service loads and shake-down stresses on the weld residual stresses as well as addressing the effect of repair welds on the residual stresses,
- the further development of a methodology that accounts for the effects of weld residual stresses on the crack-opening-displacement analyses for leak-before-break evaluations [2],
- the further development of the SQUIRT leak-rate code [3], including the incorporation of a new transition flow model to model the flow regime as the fluid transitions between single and two-phase flow,
- the inclusion of new data into the CIRCUMCK, AXIAL_CK, and PIFRAC databases [4], to include the development of a new web-based database of material property data from which one would be able to extract statistical distributions of properties for use in a PFM analysis, and
- updating the pipe fracture encyclopedia CD-ROM set first developed as part of the Second IPIRG (International Piping Integrity Research Group) Program [5].

FURTHER DEVELOPMENT OF THE PRO-LOCA CODE

While the above activities are all important activities in MERIT, the primary effort associated with the MERIT program is the continued development of the PRO-LOCA code. PRO-LOCA was originally developed as part of a US NRC program conducted at Battelle and its subcontractor, Engineering Mechanics Corporation of Columbus. The technical basis of the code was a series of deterministic models, developed in other NRC sponsored programs, which were wove into a Monte

Carlo based probabilistic framework as part of this US NRC program. Some of the features included in this earlier version of PRO-LOCA were:

- the latest subcritical crack initiation and crack growth models for fatigue [6, 7], intergranular stress corrosion cracking (IGSCC) [8, 9, 10], and primary water stress corrosion cracking (PWSCC) [11, 12, 13, 14],
- previously developed models to estimate the distribution of pre-existing fabrication related flaws for different materials and welding processes [15],
- the ability to consider multiple crack initiation sites around the pipe circumference as well as models for crack coalescence,
- a library of weld residual stress solutions,
- the latest crack stability models for both surface and through-wall cracked pipe [16, 17], and
- a methodology for taking credit for in-service inspections through probability of detection (POD) curves.

Some of the enhancements to PRO-LOCA planned as part of MERIT program include the inclusion of:

- new weld residual stress distributions developed as part of this program and other ongoing NRC programs,
- a transition flow model developed as part of the updated SQUIRT leak rate code for this program,
- newly developed flaw distributions for fabricated-related flaws in dissimilar metal welds,
- a methodology for predicting the transition of a flaw as it grows from a surface crack to a through-wall crack,
- code efficiency improvements such as importance sampling as a means of decreasing the run time of the code so that the frequency of lower probability events can be estimated in a timely manner,
- a new graphical user interface (GUI), and
- extensive validation and benchmarking of the code.

Weld Residual Stress Analyses

As indicated above, the current version of PRO-LOCA includes weld residual stress solutions for a variety of geometries and materials. Some of the geometries and material systems for which there are solutions currently included in PRO-LOCA include: a hot leg/reactor pressure vessel (RPV) nozzle dissimilar metal weld, a surge line/pressurizer nozzle dissimilar metal weld, a spray line/pressurizer nozzle dissimilar metal weld, and a stainless steel recirculation line weld. For each case, solutions were developed for a range of material strength properties, i.e., for the means plus and minus 2 standard deviations, so that a distribution of weld residual stresses could be included into PRO-LOCA. Figures 1 and 2 are plots of the distributions of the axial and hoop stresses, respectively, through the wall thickness for the hot leg/RPV nozzle weld. Solutions are provided for the mean value of the weld metal strength properties as well as the plus 2 and minus 2 standard deviation strength data. In addition, for many of these geometries and material systems, solutions were developed for both the case of an unrepaired and repaired weld section. Figure 3 is a comparison plot of the maximum weld residual stresses through the thickness of the hot leg/RPV nozzle weld, with and without a repair weld. As can be seen in Figure 3, the stresses for the repaired case are significantly higher on the inside surface than they are for the case of an unrepaired weld.

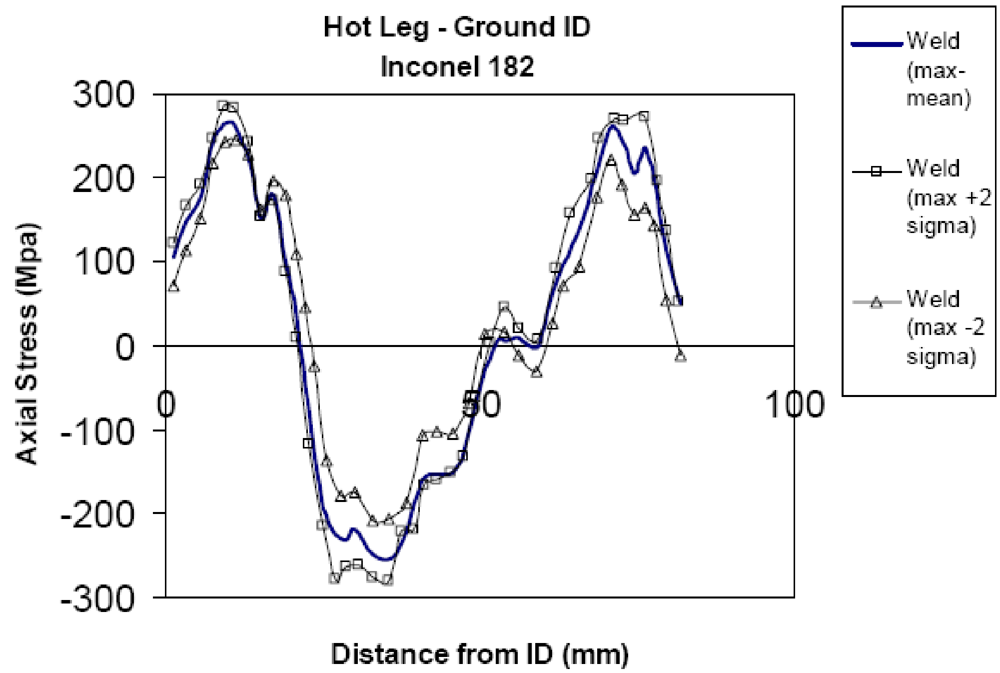

Figure 1. Axial weld residual stress solutions for the hot leg/RPV dissimilar metal weld with a repair weld along the path through the weld region where the weld residual stresses were the highest for the case where the Alloy 182 weld tensile properties (mean plus and minus 2 standard deviation) were used

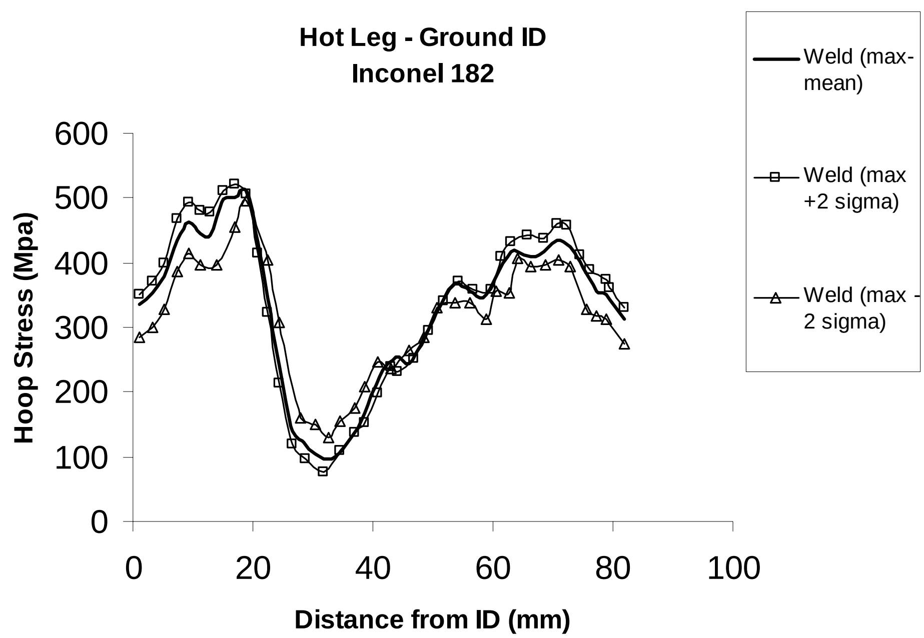

Figure 2. Maximum hoop weld residual stresses for the hot leg/RPV dissimilar metal weld region

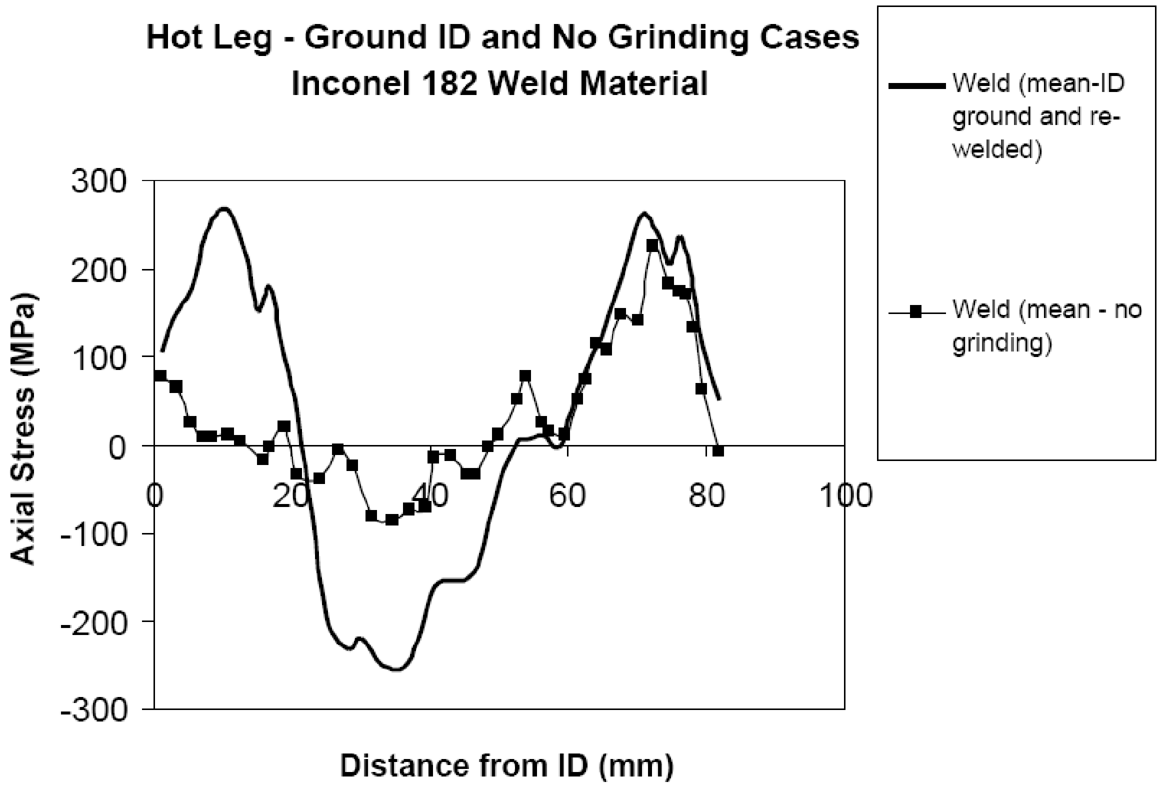

Figure 3. Comparison of maximum weld residual stresses through the thickness of the hot leg/RPV nozzle weld, with and without repair weld

Once these solutions were developed, they were curve fit to a fourth order polynomial (Equation 1) for inclusion into PRO-LOCA. Figure 4 is a plot of normalized stresses as a function of the normalized distance from the inside surface for the 6 geometries and material systems currently included in the PRO-LOCA library of weld residual stress solutions. Table 1 shows the coefficients from this curve fitting exercise.

$$\frac{\sigma_{WRS}}{\sigma_y} = \frac{\sigma_0}{\sigma_y} + \frac{\sigma_1}{\sigma_y}\left(\frac{x}{t}\right) + \frac{\sigma_2}{\sigma_y}\left(\frac{x}{t}\right)^2 + \frac{\sigma_3}{\sigma_y}\left(\frac{x}{t}\right)^3 + \frac{\sigma_4}{\sigma_y}\left(\frac{x}{t}\right)^4 \quad (1)$$

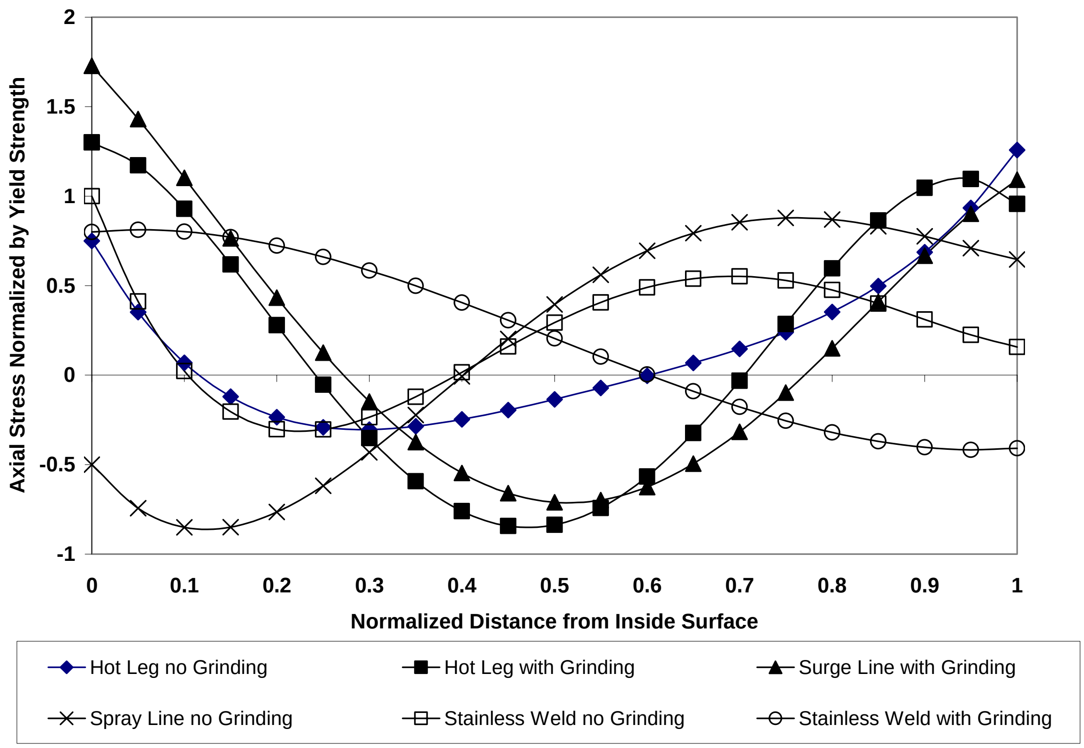

Figure 4. Plot of the normalized stresses as a function of the normalized distance from the inside surface for the six geometries and material systems currently included in the PRO-LOCA library of weld residual stress solutions

Table 1. Coefficients from the curve fitting exercise used in the existing version of PRO-LOCA

Weld Case Description	σ_0/σ_y	σ_1/σ_y	σ_2/σ_y	σ_3/σ_y	σ_4/σ_y	σ_y, MPa
Hot leg - Alloy 182 weld at 324 C (615F), using maximum stress in buttered region	0.75	-9.271	27.71	-32.91	14.98	213.3
Hot leg - Alloy 182 weld at 324 C (615F), using maximum stress in butter region, 15% grind out at ID	1.3	-1.084	-33.19	73.31	-39.38	213.3
Surge line - Alloy 182 weld at 324 C (615F), 15% grind out at ID	1.728	-5.494	-10.65	32.05	-16.53	213.3
Spray line - Alloy 182 weld at 324 C (615F), no grind out at ID	-0.5	-6.427	33.16	-41.32	15.73	213.3
Stainless steel weld at 288 C (550F), using maximum stress in HAZ, no grind out at ID	1.00	-14.04	48.04	-56.32	21.47	160.3
Stainless steel weld at 288 C (550F), using maximum stress in HAZ, last pass deposit	0.800	0.485	-5.007	3.314	0.00	160.3

As part of the MERIT program (and other ongoing NRC programs) additional weld residual stress solutions will be developed. Some of the cases to be analyzed as part of these programs address the effects of the geometry, material properties, hardening law, heat input, and weld repairs. Once these solutions are developed, the coefficients for the curve fit of the 4^{th} order polynomial (Equation 1) will be incorporated into generic distributions of stresses for PRO-LOCA.

Improvement in PWSCC Initiation Model

One of the major limitations of the current version of PRO-LOCA is the initiation model for PWSCC. The existing PWSCC initiation model in PRO-LOCA is based on the analysis of available service history CRDM Alloy 600 PWSCC cracking data at 315 C (600 F) [11], with a typical temperature correction. Laboratory testing and field experience with PWSCC suggests that the temperature dependence is Arrhenius with an activation energy (Q) of about 50 kcal/mole. Since there is very limited data for PWSCC initiation as a function of temperature, there is no precise way to verify this PWSCC model. As can be seen in Figure 5, which is a plot from one of the sensitivity analyses conducted in the earlier NRC program, this model appears to be too severe. Figure 5 is a plot of the probability of occurrence as a function of LOCA category (which is an indication of LOCA size) for a sensitivity analyses conducted based on the hot leg/RPV nozzle weld geometry. In Figure 5, LOCA Category 0 is for the occurrence of a through-wall crack while LOCA Category 6 is of the occurrence of a large break LOCA with a resultant leak rate greater than 500,000 gpm. The fact that resultant probability of occurrence for such a large break is on the order of 10^{-1}, illustrates the fact that something is drastically wrong with these models. In reviewing the detailed output from the analyses, it was found that multiple cracks are initiating at multiple sites around the circumference very early in the life of the component, e.g., in first few months of operations. The fact that so many cracks are initiating so early in the life, and they then link up to form long surface cracks is the root cause of the high probability of occurrences for these larger break openings. As this problem is addressed in this and other related programs, and new models for PWSCC initiation are hopefully developed, then these new models will be incorporated into PRO-LOCA.

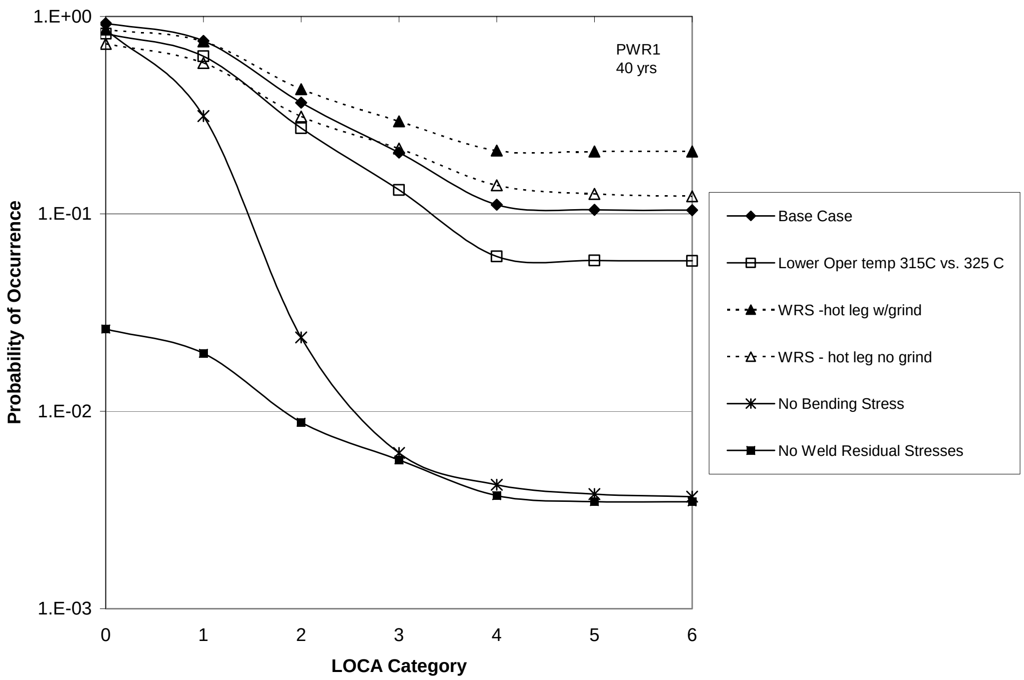

Figure 5. Probability of occurrences per weld versus LOCA category for the previously conducted sensitivity analyses for the hot leg/RPV weld geometry subjected to PWSCC at 25 years of plant operations

CONCLUSIONS

A new probabilistic fracture mechanics code, PRO-LOCA, has been developed as part of a recently completed US NRC effort. This code is being extensively updated as part of the MERIT program. Two of the major enhancements to be made to PRO-LOCA as part of MERIT include the addition of new distributions for weld residual stresses for more geometries and material systems typically found in nuclear power plant piping systems and the inclusion of an improved initiation model for primary water stress corrosion cracking.

ACKNOWLEDGMENTS

The authors would like to thank the participating members in the MERIT program. The current membership includes the US NRC, Rolls Royce in the United Kingdom, SKI in Sweden, a consortium of interests in South Korea, and a consortium of interests in Canada.

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