ISSUE STATEMENT

Over the past 20 years finite element analysts have been using their own weld residual stress (WRS) analysis techniques to analyze stress conditions in nuclear plant materials and components. These techniques are based on limited validation and incorporate unspecified levels of conservatism. Further, based on recent operating experience and subsequent research results, these analytical techniques exhibit significant variability even when analyzing well-defined and controlled WRS conditions. This has resulted in reduced confidence in the assessment of component margins.

Depending on the material system and its operating environment, WRS can have a significant effect on crack growth rates, and ultimately on system structural integrity. Improved analytical methods are needed to optimize WRS conditions during fabrication, repair/mitigation, and to validate measurements and prediction capabilities for use in life prediction calculations.

DRIVERS

Operational

- Support of structural integrity assessments which directly supports the bases for mitigation, flaw assessments, and inspection interval optimization requires an increased level of confidence in obtaining surface stress and through-wall values.
- Limitations of existing technologies for accurate prediction and measurement of WRS including modeling inconsistencies, material property limitations (e.g., strain hardening laws), and measurement capability shortfalls needs to be addressed for field deployable and non-destructive techniques.

Repair/Replace and Manufacturing

- Support of new plant fabrication and optimization for new plant systems
- Optimization of repair and replacement approaches to reduce costs and ensure material and components remain functional and safe

Standards/Good Practices

- Support of bases for ASME Code activities and safety evaluations
- Support of bases for advanced mitigation techniques

RESULTS IMPLEMENTATION

The improved modeling capability and reliable measurement techniques developed under this roadmap will be incorporated into industry guidance for managing WRS in operating plants as well as new plants. Examples include providing more accurate WRS values for use in crack growth rate models and disposition curves that support utility decisions on inspection frequency, repair and replacements for existing fleet and weld details (joint design, weld process selection, post mitigation, etc.) for the new fleet. The Utility Requirements Document (URD) will be updated to include this information for new plants. The results will also be incorporated into the supporting bases for mitigation techniques such as peening.

PROJECT PLAN

This work is a highly coordinated effort between several issue programs at EPRI with the following general focus:

- MRP – Existing PWR fleet: Modeling validation, replacement 690 welds, J-groove welds, mitigation (peening)
- WRTC/LTO – Existing and new fleet: Managing existing alloy 600 welds, developing new repair options (excavate weld repair, inlay-onlay), developing new advance weld processes (hybrid welding)
- ANT – New fleet: RS guidelines, 690 weld metal crack initiation
- WRTC/Used Fuel – Spent fuel canisters weld process and RS guidelines
- BWRVIP/WRTC – Low stress welding process development

More specifically, this roadmap addresses the following research objectives:

- Advance modeling capabilities and validation to accepted standardized approaches
  - Reduce error margin of current practices
  - Benchmark modeling practices
  - Support repair applications
• Advance welding capabilities for fabrication of new plants and repair/replacement activities for existing plants by quantifying the role of WRS through a combination of controlled welding experiments, physical measurements and modeling
  – Weld repair effects
  – Joint design effects
  – Weld process effects (technique, parameter control, etc.)
• Validate stress mitigation techniques for repair, mitigation and fabrication processes
  – Peening processes
  – MSIP and other mechanical stress improvement methods
  – Welding process controls (heat sink welding, technique, joint geometry)

Measurement and Modeling

There is a consolidated effort by various groups at EPRI to advance understanding of WRS and stakeholder needs and regulatory considerations. This consists of activities related to WRS modeling consistency, addressing sources of uncertainty in models and measurements, validation of WRS finite element models, generation of best practices, and the development of repair applications for both the existing fleet and new plants.

Manufacturing and Repair Options

There is a significant effort underway to develop and optimize manufacturing and repair options where WRS is a key consideration. Repair approaches include inlay/onlay (weld sequencing), excavated weld repair (partial arc, 360-degree), optimized weld overlay (stress reversal) and full structural weld overlay. Key elements include weld sequencing, heat input, heat sink, process consistency, variability in weld geometry and other process parameters. Advanced thick section welding processes being studied for both new plant and repair/replacement include laser (diode), hot wire laser, hybrid laser (and combination of welding processes), narrow groove gas tungsten arc welding (GTAW), friction stir welding (including canisters and irradiated material), and low vacuum electron beam welding.

Support for code activities is an important part of the overall strategy, where WRS profiles (and the ability to model or validate the profile) are key considerations. Modeling is also an important part of the effort for manufacturing and repair options.

Mitigation

There is a concerted effort to further advance the understanding and application of mitigation techniques, including peening, mechanical stress improvement, and others. This effort includes the validation of stress conditions, both surface and through wall.

RISKS

The key risks in this area include:
• Confidence in modeling and/or measurements unable to be improved
• Lack of reliable weld residual stress assessments
• Mitigation tools not credited by regulators for inspection relief
• Potential to interfere with regulatory expectations around new plant builds

RECORD OF REVISION

This record of revision will provide a high level summary of the major changes in the document and identify the Roadmap Owner.

<table>
<thead>
<tr>
<th>Revision</th>
<th>Description of Change</th>
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<tr>
<td>0</td>
<td>Original Issue: August 2013</td>
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<tr>
<td>1</td>
<td>Revision Issued: January 2014</td>
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<tr>
<td></td>
<td>Changes: Added milestones and milestones legend.</td>
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<tr>
<td>2</td>
<td>Revision Issued: December 2014</td>
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<tr>
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<td>Changes: Milestones 3 and 4 completed.</td>
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<td>3</td>
<td>Revision Issued: August 2016</td>
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<td>Changes: Milestones 1 and 2 completed Added milestones 6 and 7.</td>
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Characterizing and Controlling Weld Residual Stress

**Advanced Nuclear Technology**

- ALWR RS Guidelines Rev 0
- LWSMR RS Guidelines Rev 0
- Guideline(s) Revision as needed

**Long-Term Operations**

- Relicensing issues

**Materials Reliability Program**

- xLPR, hardening laws, rs/Kj profiles, assessments, Code, databases
- Mockups, measurement, validate, mitigation
- Proven examples, practice, OE, hard data

**Replace and Mitigation - benchmarking, mockups, measurement, validate**

- Advanced welding repair - benchmarking, mockups, measurement, validate
- Long-term R&D - Fabrication processes and materials

**Welding Research Technology Center**

- University Gov't & International: Long-term R&D - Develop federal funding; leverage Int'l collaborations

**US NRC (MOU)**

- xLPR, NUREG, validation wrs models, rs measurements, Code, repairs

**Milestones**
1. ALWR RS Guidelines Revision 0
2. LWSMR RS Guidelines Revision 0
3. EWR Guidelines – Code Case Draft
4. Inlay-onlay - Residual Stress analysis
5. Critical components
6. Mock up Fabrication – SMR
7. Mock up Fabrication – large bore