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PWSCC Mitigation by Peening

Peening Topical Report (*MRP-335 R1*) Safety Evaluation Update

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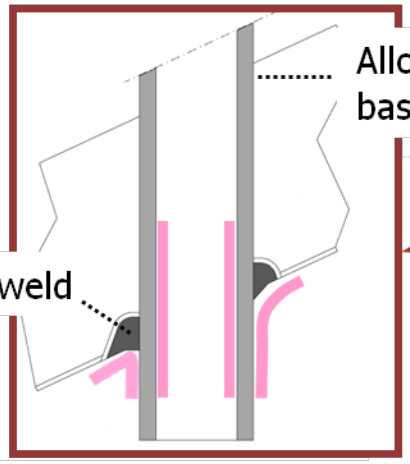
NRC-Industry Materials R&D Tech Update Meeting

Rockville, MD

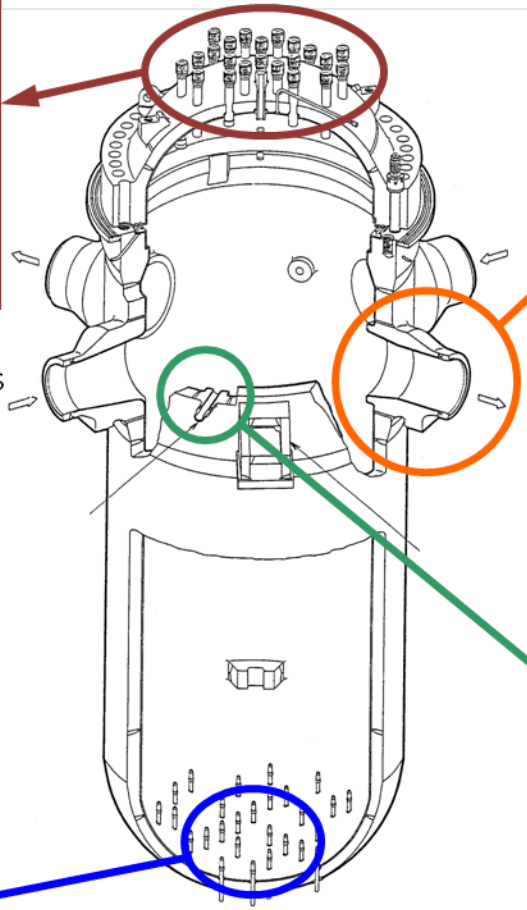
June 3-5, 2014

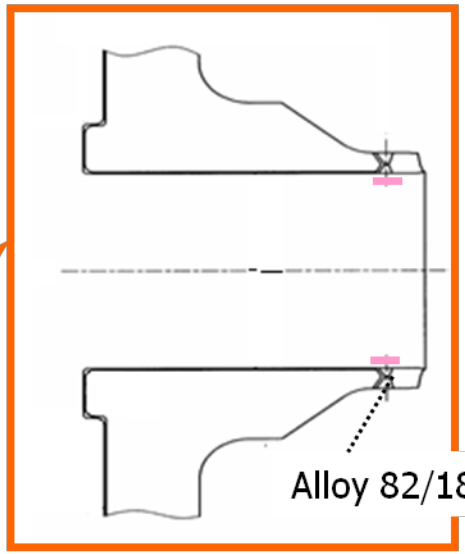
Peening for PWSCC Mitigation

- Components of Interest

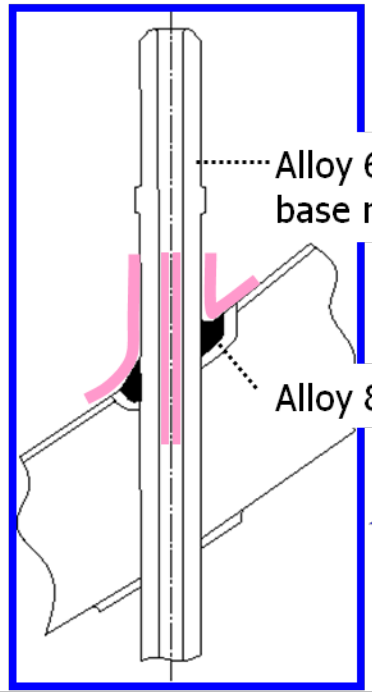


CRDM Nozzles
-Nozzles and J-Groove Welds



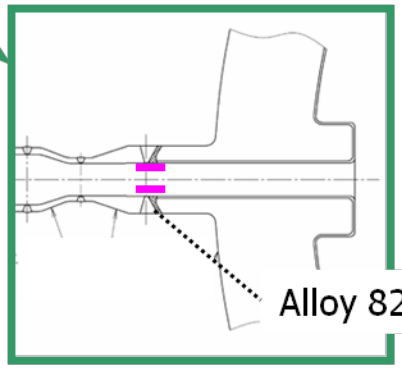


Outlet/Inlet Nozzle Safe End
-DM Butt Weld



BMN Penetrations
-Nozzles and J-Groove Welds

Reactor Vessel



Safety Injection Nozzle Safe End
-DM Butt Welds

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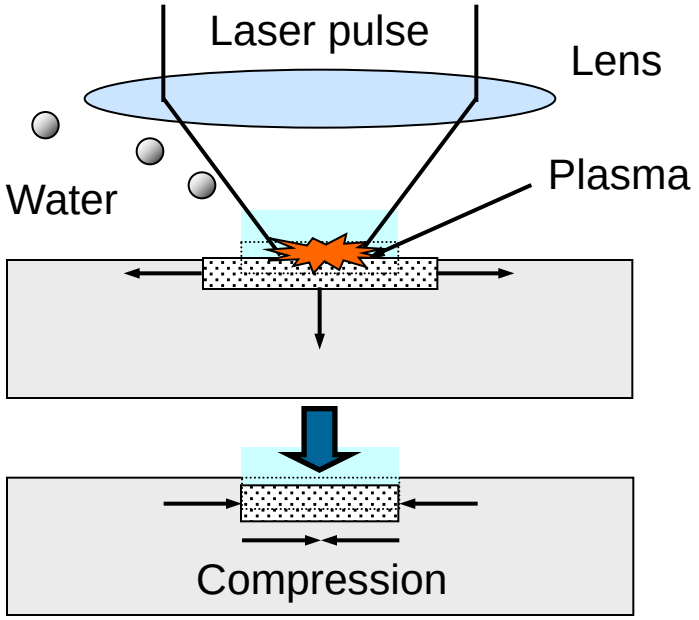
Peening Technologies

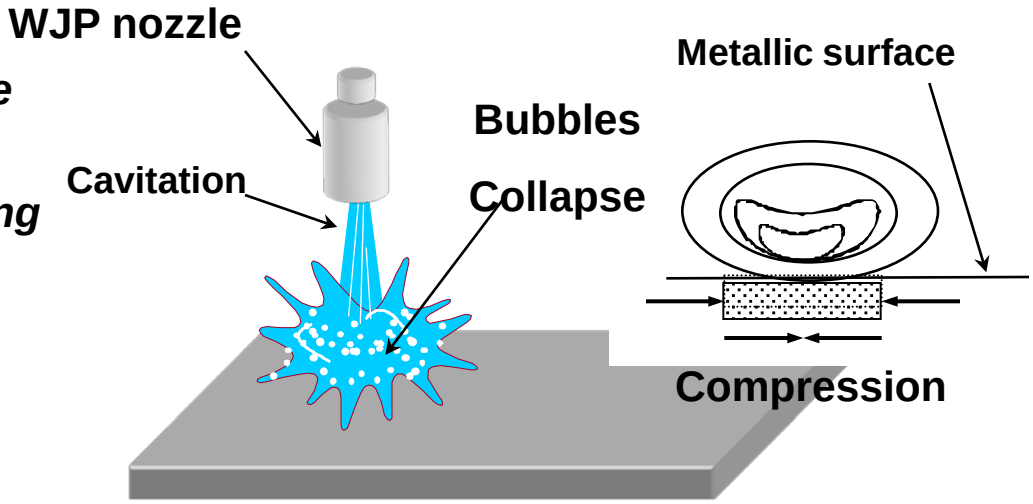


Laser

- *Laser pulse irradiates metal surface*
- *High-pressure plasma forms*
- *Shock wave creates permanent local strains*
- *Compressive residual stress results from constraint*

Cavitation (Water Jet)

- *Pressure drops below vapor pressure*
- *Vapor bubbles form in water*
- *Bubbles collapse at surface generating high pressures*
- *Compressive residual stress results from constraint*



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Peening for PWSCC Mitigation

- *Status and Readiness*

Light Water Reactors in Japan

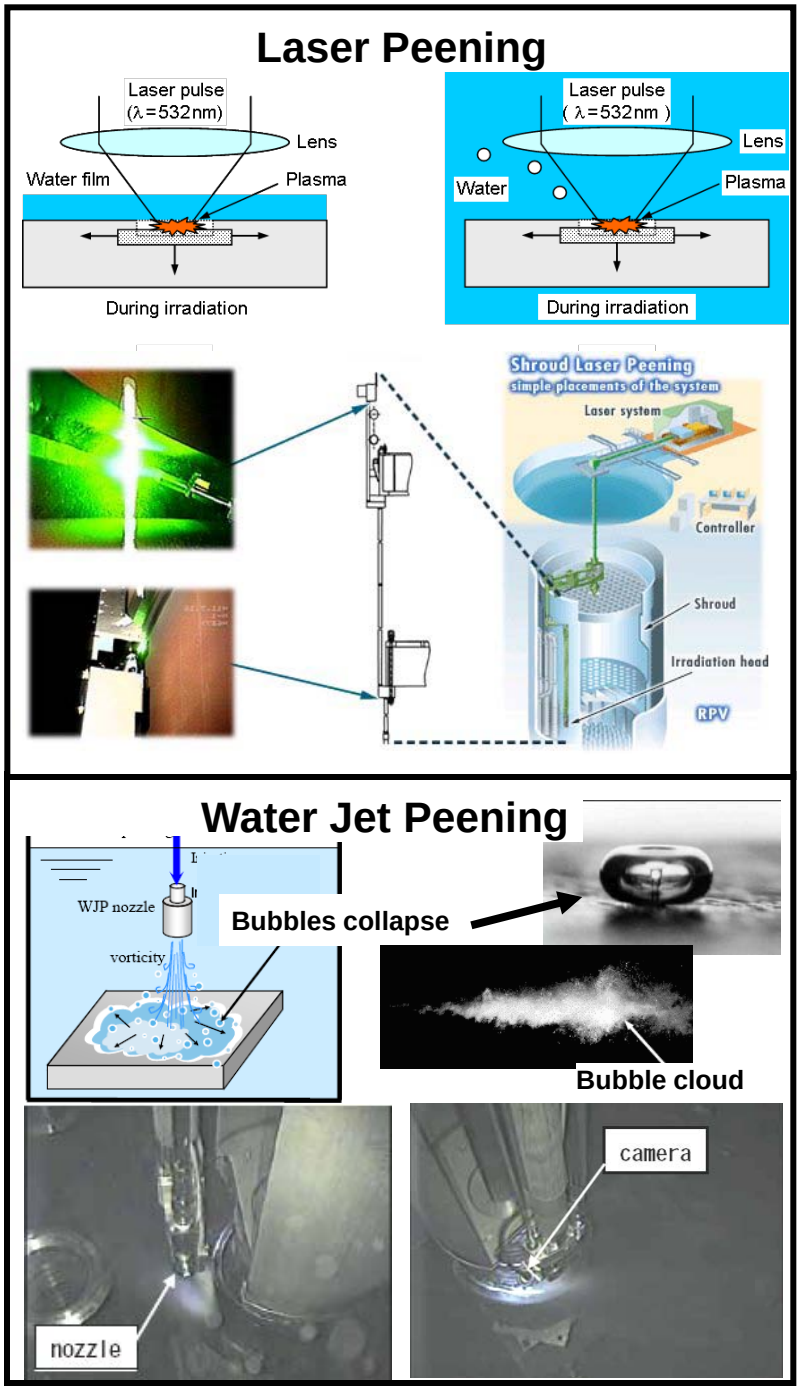
- 12+ years of peening OE in PWRs and BWRs
- 23+ PWRs mitigated, in-situ during RFOs
- Laser and Cavitation technologies
- Alloy 600 Nozzles, J-Welds and DM Butt-welds
  - Bottom-mounted Nozzles/J-welds
  - Reactor Inlet and Outlet Nozzles
  - Safety Injection Nozzles

MRP R&D Program Complete

- PWSCC Initiation Testing
- Residual Stress Relaxation
  - Testing and Modeling
- Vendor Technical Basis Information

Implementation Documentation Submitted to NRC for SE and for ASME Code Cases

- Technical Basis Document (MRP-267, Rev 1)
- Topical Report for Inspection (MRP-335, Rev 1)



Current Objective and Scope of Peening Program

- **Objective:**
  - Gain regulatory approval for inspection credit of peening mitigation of PWSCC for Reactor Pressure Vessel Head Penetration Nozzles (RPVHPN) and Dissimilar Metal Butt-Welds (DMW)
- **Scope**:
  - Revise MRP-335R1 to address comments and for SE
    - Produce comment and RAI resolution tables
  - Support ASME Code Committee
    - Ensure consistency between future ASME and SE process outcomes
    - Revise ASME Code Case N-770 and N-729
      - Code Case N-770-4 approved. N-729-4 being revised

Deliverables

- ***Approved Topical Report for PWSCC Mitigation by Surface Stress Improvement (MRP-335, Revision 2A)***
  - **Applicability/Use**:
    - Support of inspection credit subsequent to peening mitigation of PWSCC on Alloy 600 reactor pressure vessel head penetration nozzles (RPVHPNs) and Alloy 82/182 dissimilar metal welds (DMWs) in primary system piping
    - US Utility application through the regulatory process

Technical Justification Basis
- MRP-267R1 Tech Basis and MRP-335R1 Topical Report

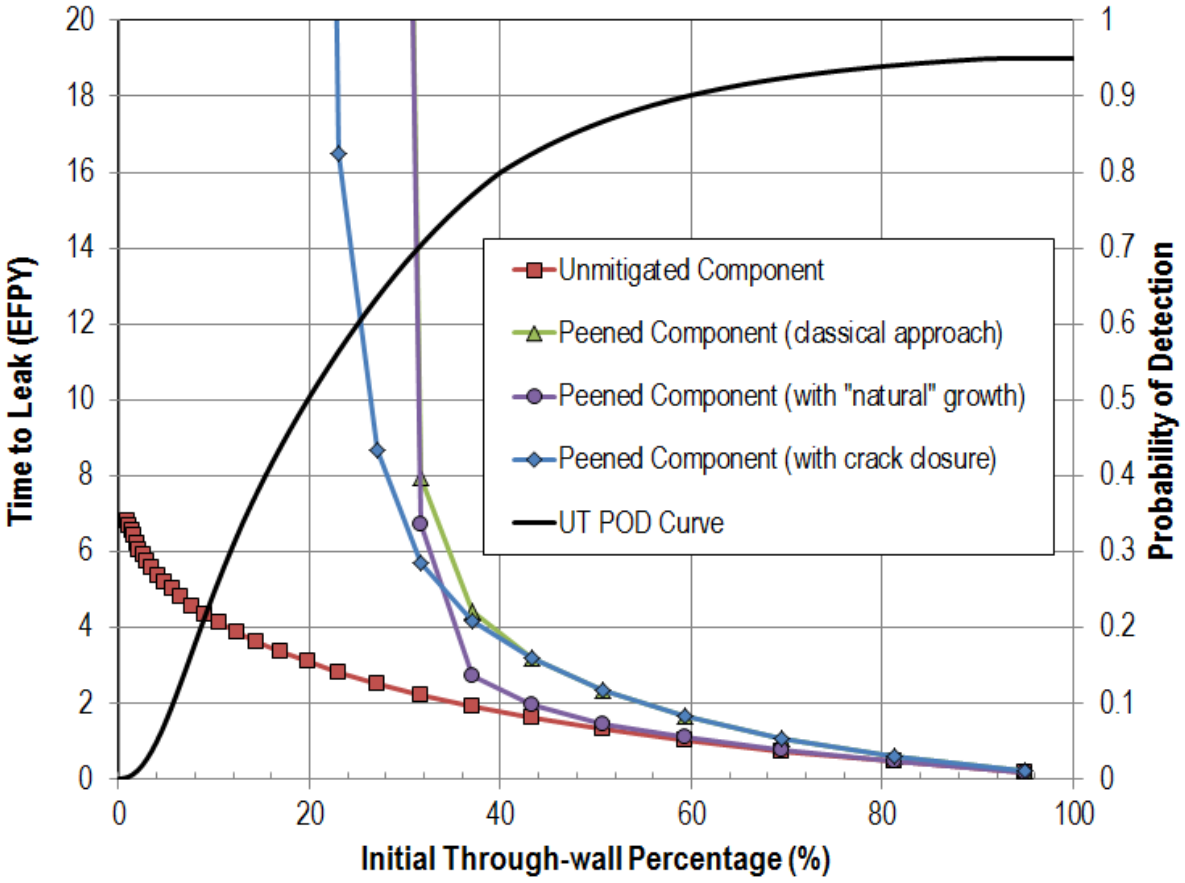
- Deterministic and probabilistic analyses were used to determine appropriate inspection requirements for key Alloy 600/82/182 components mitigated by peening
  - MRP-335R1 Inspection Table; With peening and the proposed inspection intervals:
    - For DMWs, the calculations showed a large reduction in risk
    - For RPVHNPs the calculations showed a nozzle ejection frequency that is acceptably low, and also that is close to that calculated for no mitigation and standard intervals (i.e., risk neutral)
    - See slide #13
  - Deterministic analyses assessed the effect of peening on crack growth as a function of time for various crack types at different locations
  - Probabilistic analyses assessed the effect of peening on the probability of pressure boundary leakage or rupture assuming reduced frequency of inspection, with explicit modeling of:
    - Component loading including effect of peening on residual stress field
    - PWSCC crack initiation
    - PWSCC crack growth
    - Various inspection options including UT, ET, and bare metal visual

Technical Justification

- *Example Deterministic Analysis*

- Time to Nozzle Leakage for Axial Crack on Downhill Side of CRDM Nozzle Tube OD (assuming 3-mm nominal depth (19% of wall) of compressive residual stress)
- Result is compared to a conservative UT probability of detection (POD) curve

Deterministic results demonstrate the reduction in crack growth rate for flaws deeper than the compressive residual stress zone



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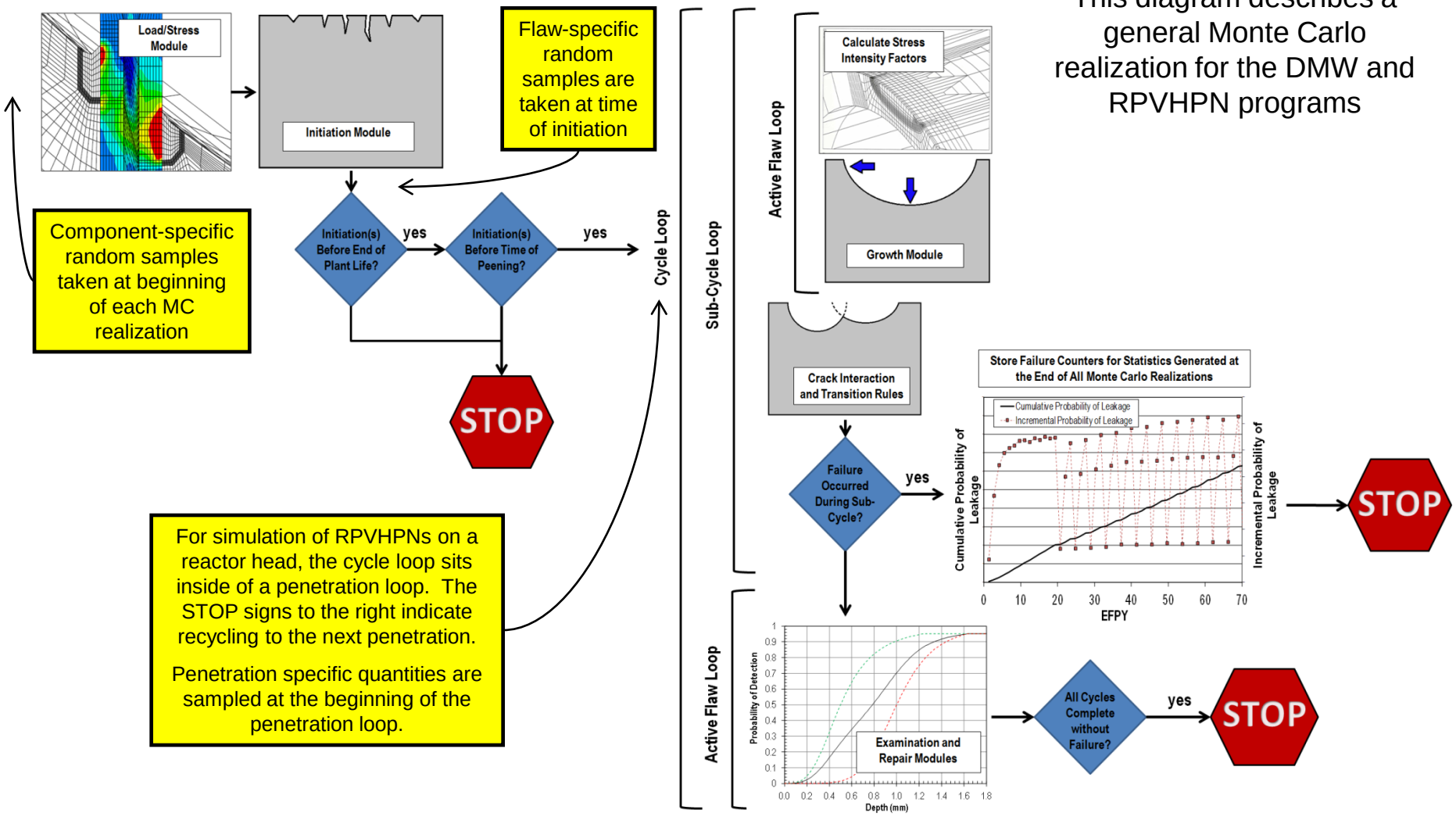
MRP-335R1 Probabilistic Analysis

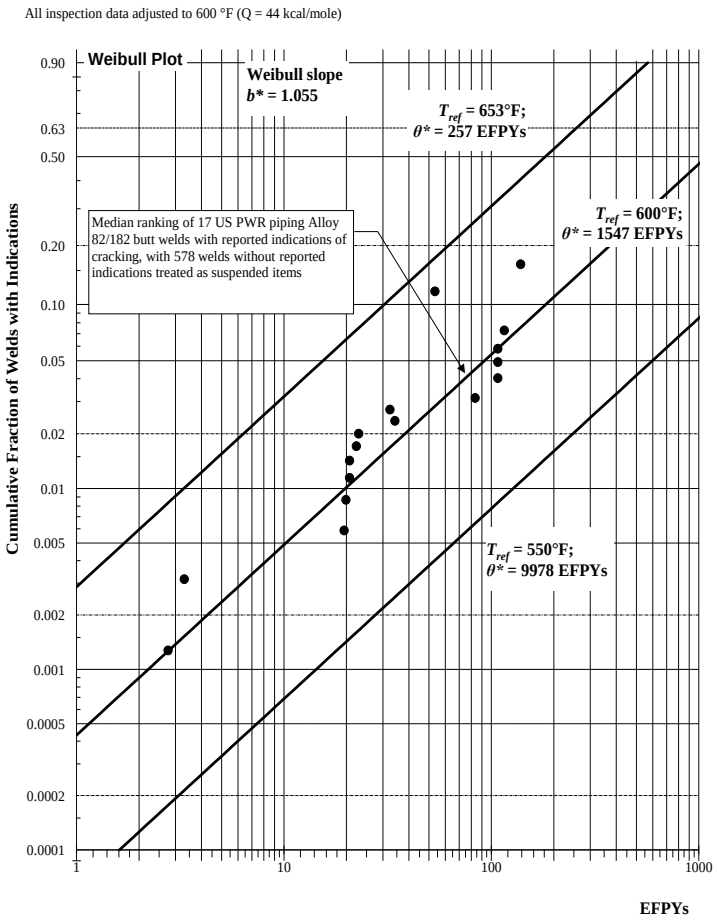
Overview of Single Monte Carlo Realization for General PWSCC Model



This diagram describes a general Monte Carlo realization for the DMW and RPVHPN programs

MRP-335R1 Technical Justification

Approach to Crack Initiation in Probabilistic Analyses



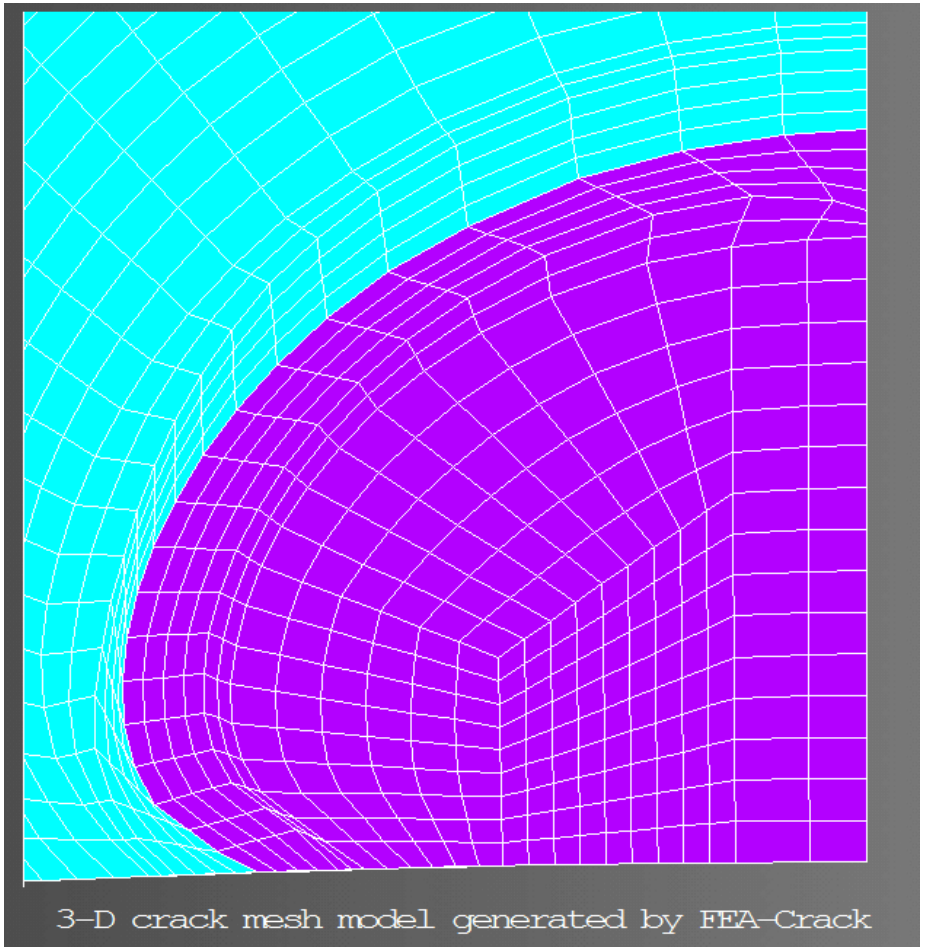
Two-parameter Weibull model fit to existing U.S. plant data for time of first detected PWSCC in Alloy 82/182 DMWs

- Weibull model methodology employed to predict crack initiation times based on plant inspection data
- Alloy 82/182 DMW initiation model:
  - Allows for initiation of multiple flaws on DMW with circumferential or axial orientation
    - Multiple flaw modeling important for modeling peening benefit
  - Incorporates functional dependence of initiation on temperature
  - Incorporates functional dependence of initiation on stress allowing higher likelihood of cracks near maximum tensile bending stress
- Crack initiation in RPVHPNs modeled in a similar manner

MRP-335R1 Technical Justification

FEA Simulation of Flaw Growth Under Influence of Peening Stress

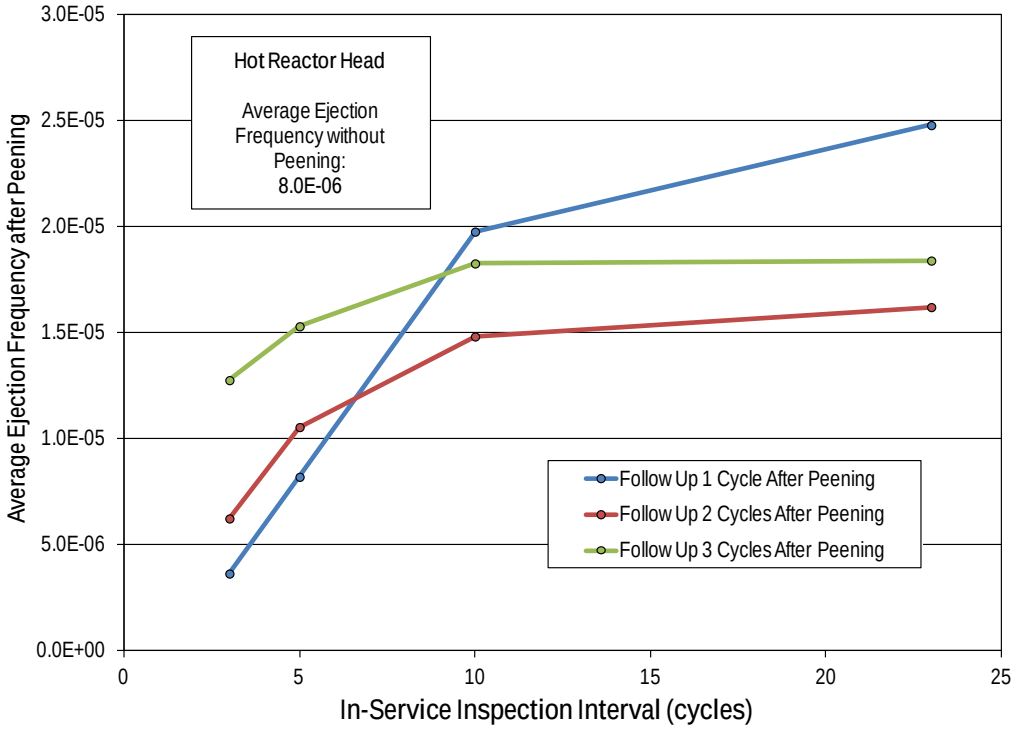
- FEA simulation of change in flaw shape with growth illustrates the balloon shape that develops because of pinning of crack front on the free surface, where the stress is compressive
- The results of the FEA simulation support the simplifications necessary to model crack growth on a probabilistic basis in the Monte Carlo simulations



Technical Justification

- *Example Probabilistic Analysis*

- Post-Peening Time-Averaged Nozzle Ejection Frequency for Hot RV Top Head
- Result supports extension of ISI interval to every 10 years (i.e., 5 x 2-year cycles)
  - Acceptably small nozzle ejection frequency
  - Nozzle ejection frequency close to that for unmitigated case with exams per N-729-1
- Optimal follow-up exam timing balances time for crack growth to size that is more detectable with time for crack to grow through wall



Technical Justification
- MRP-335R1 Conclusions

- Deterministic analyses show that peening:
  - Eliminates PWSCC growth for cracks located in the peening surface compressive stress zone
  - Slows growth for shallow cracks that extend beyond the peening compressive stress zone
- Probabilistic analyses for:
  - Alloy 82/182 piping butt welds show that peening mitigation with the recommended inspection interval results in a large reduction in the probability of leakage compared to no mitigation and standard intervals
  - RPVHPNs show that peening mitigation with the recommended inspection interval results in an acceptably low nozzle ejection frequency, and also a nozzle ejection frequency that is close to that calculated for no mitigation and standard intervals (i.e., risk neutral)

Comparison of MRP-335R1, N-770, N-729 and "N-BMN" Requirements

(differences are highlighted by RED text)

	Ref.	Inspection Item	Nominal Peen Depth	Pre-Peening	Post-Peening (Pre-service)	Follow-up Exams	ISI Volumetric and Surface Exams	ISI Visual Exam for Leakage
A82/182 Piping Butt Welds	MRP-335R1	Peened Alloy 82/182 Piping Butt Weld HL Operating Temperature ≤ 625°F	ID surface of 82/182 at least 0.04 in.	Volumetric and ID Surface	None	Volumetric at 1st or 2nd RFO; VE at 1st and 3rd RFOs	Volumetric Each Interval	VE Each Interval
	MRP-335R1	Peened Alloy 82/182 Piping Butt Weld CL Operating Temp. ≥ 525°F and < 580°F	ID surface of 82/182 at least 0.04 in.	Volumetric and ID Surface	None	Volumetric and VE at 2nd or 3rd RFO	Volumetric Every 2nd Interval	VE Each Interval
	N-770-4 Draft 11	Uncracked butt weld mitigated by peening (Item L)	Satisfy Appendix I Performance Criteria	Volumetric and ID Surface (ET)	None (Pre-Peening is the Pre-Service Exam)	Vol. + Surface (ET): (a) 2nd RFO (hot leg welds only) (b) within 10 years	Volumetric and ID Surface (ET) for 25% Sample Each Interval	None
A600 RPV Head Nozzles	MRP-335R1	Upper heads with peened Alloy 600 nozzles (EDY ≥ 8)	ID at least 0.02 in. (0.5 mm) OD/weld at least 0.12 in. (3 mm)	Volumetric and Surface from nozzle ID only	None	Volumetric and VE at 1st RFO	Volumetric Each Interval	VE Each RFO
	MRP-335R1	Upper heads with peened Alloy 600 nozzles (EDY < 8)	ID at least 0.02 in. (0.5 mm) OD/weld at least 0.12 in. (3 mm)	Volumetric and Surface from nozzle ID only	None	Volumetric and VE at 2nd or 3rd RFO (but within 5 Yr)	Volumetric Every 2nd Interval	VE Every 3rd RFO or 5 Yr, whichever is less (with general visual other RFOs)
	N-729-5 Draft 5	Upper heads with peened Alloy 600 nozzles	Satisfy Appendix M Performance Criteria	Volumetric and Surface excluding Weld Wetted Surface	None (Pre-Peening is the Pre-Service Exam)	Volumetric at 2nd RFO; VE at 1st and 2nd RFO	Volumetric Each Interval	VE Every 3rd RFO (with general visual other RFOs)
A600 Bottom Mounted Nozzles	N-722-1	RPV bottom-mounted instrument pens. (B15.80)	N/A (MRP-335R1 does not address BMNs)	N/A (MRP-335R1 does not address BMNs)	N/A (MRP-335R1 does not address BMNs)	N/A (MRP-335R1 does not address BMNs)	None	VE Every Other RFO
	Draft BMI Code Case (N-BMI)	Peened BMNs (Inspection Item C)	Satisfy Appendix I Performance Criteria	Surface Exam excluding Weld Wetted Surface, plus VT of exterior	None (Pre-Peening is the Pre-Service Exam)	None in addition to the ISI exams	None	VE every other Code period (~7 yrs), plus Suppl. Visual in period with no VE
	Draft BMI Code Case (N-BMI)	Peened BMNs (Inspection Item D alternative to Item C requirements)	Satisfy Appendix I Performance Criteria	Surface Exam Excluding Weld Wetted Surface, plus VT of exterior	None (Pre-Peening is the Pre-Service Exam)	None in addition to the ISI exams	When a volumetric and surface exam is performed in lieu of the VE of Inspection Item C and indications are not detected, future VE's are only required every fourth period. A Supplemental Visual Exam is required every other period.	

Current SE Review and Approval Schedule

- MRP-335, Revision 1 – NRC Safety Evaluation

Task	Description	Start Date	Status/ Target Date	Deliverable
1	Meet with NRC to discuss TR submission	07/20/12	COMPLETE	Presentation
2	Publish MRP-267 Rev 1, and MRP-335	8/10/12	COMPLETE	Reports
3	Submit MRP-335, Rev 1 for SE with MRP-267 Rev 1 as Companion Reference, and Fee Exemption Request	02/07/13	COMPLETE	Transmittal Letter, Reports, and Fee Exemption Request
4	Issued contract to SE Lead Contractor	02/11/13	COMPLETE	Engineering to support SE
5	NRC performs Fee Exemption Reviews	02/07/13	COMPLETE	Fee Exemption Granted
6	NRC performs Acceptance Reviews and Work Plan	08/05/13	COMPLETE	Acceptance Letter and Work Plan
7	NRC performs Technical Review and Issues RAIs	12/06/13	06/2014	RAIs
8	Final Responses to RAIs	06/30	11/2014	RAI Responses
9	NRC Issues DRAFT and FINAL Safety Evaluation	11/2014	04/2015	Final SE Issued
10	Publish MRP-335 Revision 2A (MRP-335-2A)	06/2014	07/2015	Publish MRP-335 Rev 2A

ASME Code Case and SE Parallel Paths

- MRP-335, Rev 1, and MRP-267, Rev 1, provide the technical bases for Code changes
- Code Case N-770-4 for peening dissimilar metal butt-welds is approved
- Code Case N-729-5 for RPVHPNs will be voted on by TG in August 2014
- New BMN Code Case is draft and will be voted on by TG in August 2014
- These Code Case revisions are in the priority category
- Parallel SE and Code case paths will ensure needed NRC requirements are known and accounted for in Utility materials aging management plans
  - Utility Executive Oversight Committee supports parallel paths

Peening Mitigation Options for RPVHPNs

- In 2013, when MRP-335 Rev 1 was published, there was only 1 vendor offering in-service peening mitigation for RPVHPNs
- Now, in 2014, application technology has improved, and there are multiple vendors offering peening mitigation for RPVHPNs
  - Water jet- and laser-based peening technologies
  - Consistent approach and technical basis
    - Supplemental Technical Memo Ready for Submission
  - Revised application parameters from MRP-335 Rev 1
    - Revised parameters do not have a material impact on the risk results of previous technical basis
    - Nominal peening compressive stress depth of 1 mm for nozzle OD and weld, and 0.25 mm for nozzle ID
    - Pre-peening surface exams are not necessary when appropriate follow-up exam requirements are implemented
    - Providing technical basis to ASME Code Case N-729
    - Request including in current SE
    - Include in MRP-335 Rev 2A

Discussion and Next Steps

- **Review Schedule, Implementable Solution and Requirements**
  - Industry is planning peening mitigation
    - Reactor Vessel Inlet/Outlet Nozzles *(2 plants under contract for 2016 applications)*
    - BMNs *(2 plants under contract for 2016 applications)*
    - RPVHPN Heads *(multiple utilities evaluating feasibility)*
  - Expedited review and approval needed to support early plants
- **Next Steps**
  - Dialogue on plans for RAIs
  - Requirements and schedule that support 2016 implementation
  - Other items

Conclusions

- Peening is effective and has been deployed for over a decade for mitigating PWSCC in LWR materials
- The US nuclear industry would like to incorporate peening into materials aging management plans to maintain safety margins and reduce the risks of PWSCC corrosion and leakage
  - Plans for peening mitigation of RV outlet and inlet nozzles, and bottom-mounted nozzles have been announced for two U.S. PWRs for 2016
  - In-service peening of RPVHPNs is under consideration by multiple U.S. utilities for several heads
- MRP has prepared and submitted the technical basis for peening to:
  - the ASME Code for consensus process revisions and approvals for mitigating DMWs and RPVHPNs,
  - the NRC for Safety Evaluation
- Completion of the ASME Code revisions and the US NRC's SE review will facilitate Industry's plans to implement peening in 2016

Questions

Back-up Slides

Basis for Not Requiring a Pre-Peening Surface Exam for RPVHPNs

- The post-peening inspection requirements of MRP-335R1 were developed on the basis of not requiring a pre-peening surface exam of the nozzle OD and weld wetted surfaces:
  - Requirements for visual exams for leakage are same as prior to peening
  - Follow-up volumetric exams of nozzle tube address potential for subsequent growth of base metal flaws just deeper than the compressive residual stress zone that are not detected in the pre-peening volumetric exam

Basis for Not Requiring a Pre-Peening Surface Exam for RPVHPNs (cont'd)

- Basis for not requiring a pre-peening surface examination of the Alloy 82/182 J-groove weld material:
  - Experience has shown that PWSCC flaws located in the weld metal often extend into the base metal, and are thus detectable via UT from the nozzle ID. There have been no cases of weld flaws growing to the annulus and causing leakage after a UT examination has been performed of 100% of the CRDM/CEDM nozzles in a head
  - There is minimal safety significance of flaws exclusively located in the weld metal:
    - The leak rate produced by a flaw exclusively located in the weld metal is likely to be much smaller than that which could result in significant boric acid corrosion of the low-alloy steel material
    - For a weld flaw to lead to the possibility of a safety-significant circumferential flaw in the nozzle tube would very likely require that detectable leakage be produced

Basis for Not Requiring a Pre-Peening Surface Exam for RPVHPNs (cont'd)

- The possibility of pre-existing flaws located in the weld metal is effectively addressed through periodic visual exams for leakage
- The follow-up volumetric exams are opportunities to detect any flaws that grow from the weld metal and into the nozzle base metal subsequent to the time of peening
- The detailed probabilistic calculations of MRP-335R1 explicitly model the possibility of a pre-existing weld flaw ultimately leading to nozzle ejection
  - The modeling work demonstrates an acceptably small effect on nuclear safety
  - The probabilistic modeling maintains the key conservatism of the original MRP-105 probabilistic technical basis that a weld flaw reaching the nozzle annulus is assumed to immediately produce a 30° through-wall circumferential flaw in the nozzle tube

Basis for Not Requiring a Pre-Peening Surface Exam for RPVHPNs (cont'd)

- Basis for not requiring a pre-peening surface exam of the nozzle ID surfaces:
  - Follow-up volumetric exams and periodic visual exams for leakage address the possibility that any PWSCC flaws are located on the nozzle ID surface that are too shallow to be detected via the pre-peening volumetric exam
  - Any flaws located on the nozzle ID surface are very likely to be axial in orientation and lead to detectable leakage prior to the possibility of safety-significant circumferential cracking
  - The main probabilistic cases of MRP-335R1 do not credit any pre-peening surface exams on any of the RPVHPN surfaces
- In summary, pre-peening surface exams are not necessary when appropriate follow-up exam requirements are implemented

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