PWSCC Chemical Mitigation

Hydrogen Optimization and Zinc Injection

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Chemical Mitigation of PWSCC

- Optimization of primary chemistry can mitigate PWSCC
  - Optimization of hydrogen concentration
  - Injection of zinc
- Chemical mitigation has several objectives
  - Reduction of risk
  - Asset preservation
  - Degradation management
    - Increased inspection interval
    - Reduced inspection scope
    - Optimized disposition
- Current task is to provide technical bases and implementation requirements
  - Identify appropriate "program"
  - Quantify benefits of a program

General Observations on Chemical Mitigation of PWSCC

Hydrogen Optimization

EPRI 1015017 (December 2007)

Provides a Snapshot of Then-Current Understanding of Primary Hydrogen Optimization

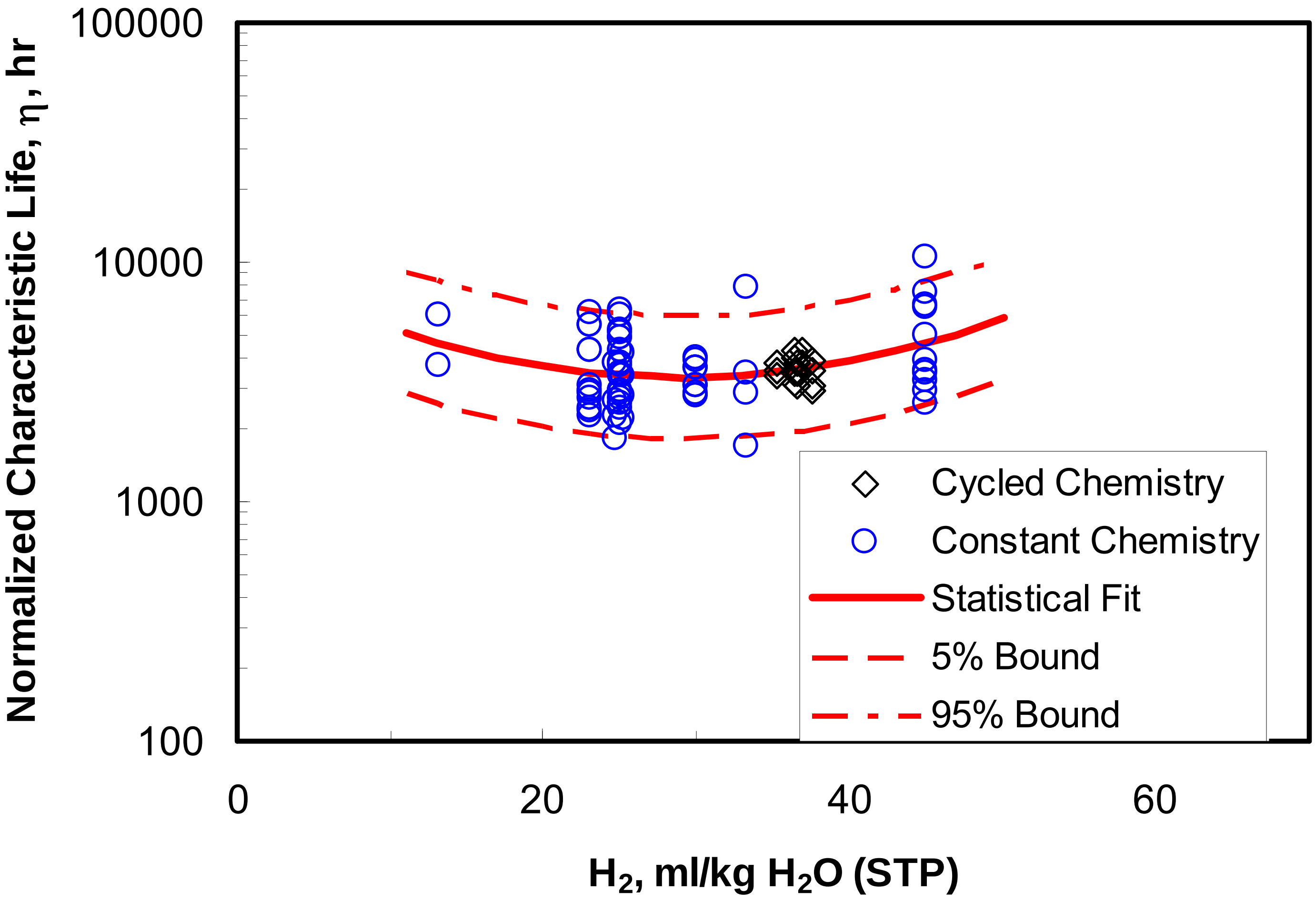
- Consider 5 – 80 cc/kg
- Consider only currently operating plants
- Consider only plants with PWSCC susceptible materials
- PWSCC
- Fuel Integrity
  - Hydriding
- Corrosion, corrosion product transport, corrosion product deposition
  - AOA/CIPS
  - Clad corrosion
  - Dose
- LTCP
- Radiolysis
  - Possible elevation of ECP
- Operations
- Safety
  - Pressure boundary integrity
  - Flammability
  - Safety-related systems operability
- Industry experience
- Ongoing research

EPRI 1015017 Assessment of PWSCC

- Based almost entirely on EPRI 1015288 (MRP-213)
  - Mitigation of PWSCC in Nickel-Base Alloys by Optimizing Hydrogen in the Primary Water
  - Andresen and Hickling, July 2007
- Considers initiation rates
- Considers crack growth rates
- Conclusions based largely on CGR factors of improvement

- Focuses mostly on KAPL and EPRI (GE) efforts
  - No comprehensive review of all available data
  - No assessment of statistical variability

PWSCC Initiation



EPRI 1012145 (Eason) as cited in Primary Guidelines R6

PWSCC Initiation Evaluation

- Y-axis is characteristic life
  - Based on Weibull fit to data
  - Time at which 63% of samples failed
  - A kind of inverse initiation rate
- Samples were reverse U-bends
- Fit is log-parabolic $\ln \eta = a[H_2]2 + b[H_2] + c$
  - Existence of a minimum could be due to choice of fitted equation
- Significant scatter

- Conclusion: no strong basis for effect of hydrogen from these data
- Other data sets considered; still no strong basis for conclusions
- In general consistent with more certain CGR trends

PWSCC Propagation Model

- Model from EPRI 1015288 (MRP-213)

$$V = 1 + (P-1)e^{-0.5\left(\frac{\Delta\phi}{\lambda(0.46)^{\frac{1}{P}}}\right)^2}$$

Material	P	λ
EN82H	8.09	20.2
Alloy 600	2.81	35.6
Alloy X-750 HTH	4.89	20.4
Alloy X-750 AH	7.19	40.0

$$\Delta\phi = 29.58\left(\frac{T_K}{T_{ref}}\right)\log\left(\frac{[H_2]}{[H_2]_{Ni/NiO}}\right)$$

$$[H_2]_{Ni/NiO} = 10^{(0.0111T_C - 2.59)}$$

- Model discards small offset used by KAPL
- Ni/NiO transition non-standard

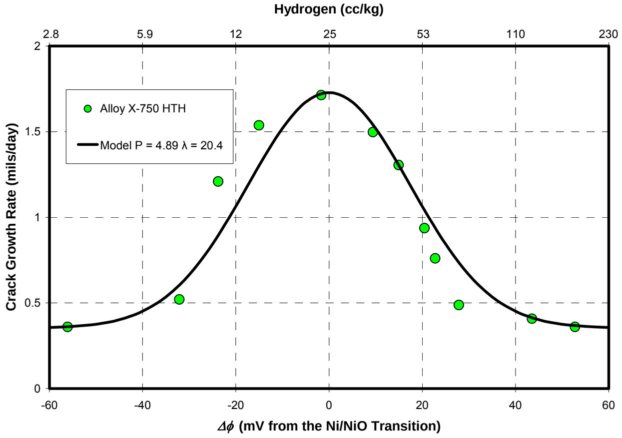
PWSCC Evaluation FOI

- PWSCC evaluated using factors of improvement (FOI)

$$FOI = \frac{V_{old\ condition}}{V_{new\ condition}}$$

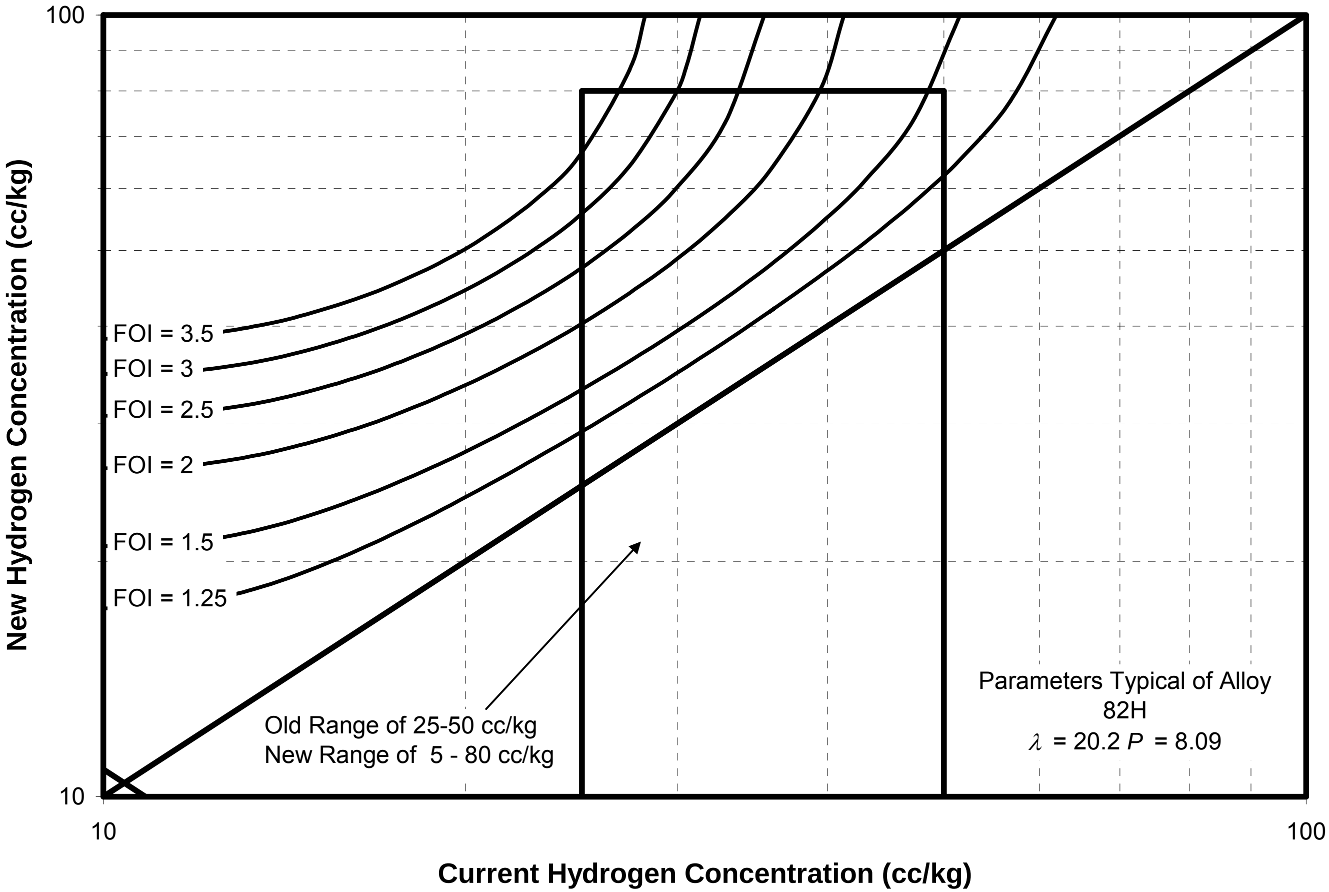
- FOI > 1 → slower CGR   FOI < 1 → faster CGR
- Special cases FOI = 1, no change
  - Obvious case: $H_{2,old} = H_{2,new}$
  - Also, “crossing the hump”

$$\Delta\phi_{new} = -\Delta\phi_{old} \qquad [H_2]_{new} = \frac{[H_2]^2_{Ni/NiO}}{[H_2]_{old}}$$



Data from Morton, Attanasio, and Young (2001)
Model from EPRI 1015288 (Andresen and Hickling)

PWSCC Evaluation — 325°C, Alloy 82H Analysis for 8X Peak



Old Range of 25-50 cc/kg
New Range of 5 - 80 cc/kg

Parameters Typical of Alloy 82H
λ = 20.2 P = 8.09

PWSCC Evaluation — Conclusions

- EPRI 1015017 contains additional charts and tables
- "Optimum" hydrogen depends on component
  - Material
  - Temperature
- Component weighting is a unit-specific issue
- General conclusions
  - Moving to higher hydrogen is beneficial
  - Moving to lower hydrogen may not be beneficial in practical range
  - Incremental benefit of increasing hydrogen decreases at higher concentrations

- True optimization needs to consider costs as well as benefits

General Observations on Chemical Mitigation of PWSCC

Zinc Injection

Zinc Application Guidelines

- EPRI 1013420 December 2006
- Provides then-current summary of primary side zinc injection
- Developed by EPRI-organized committee
  - EPRI (MRP, Chemistry, FRP, LLWRM)
  - Utilities
  - Consultants
  - NSSS/Fuel Vendors (AREVA and Westinghouse)

Zinc Application Guidelines – Scope

- Fundamental zinc chemistry (e.g., solubility)
- PWSCC and general corrosion
- Fuel integrity considerations
- Corrosion product transport and activation
- Monitoring requirements
- Radiation field control
- Injection strategies
- Materials compatibility
- Post-accident considerations
- 50.59 Issues
- Summary of then-current experience
- Economic considerations

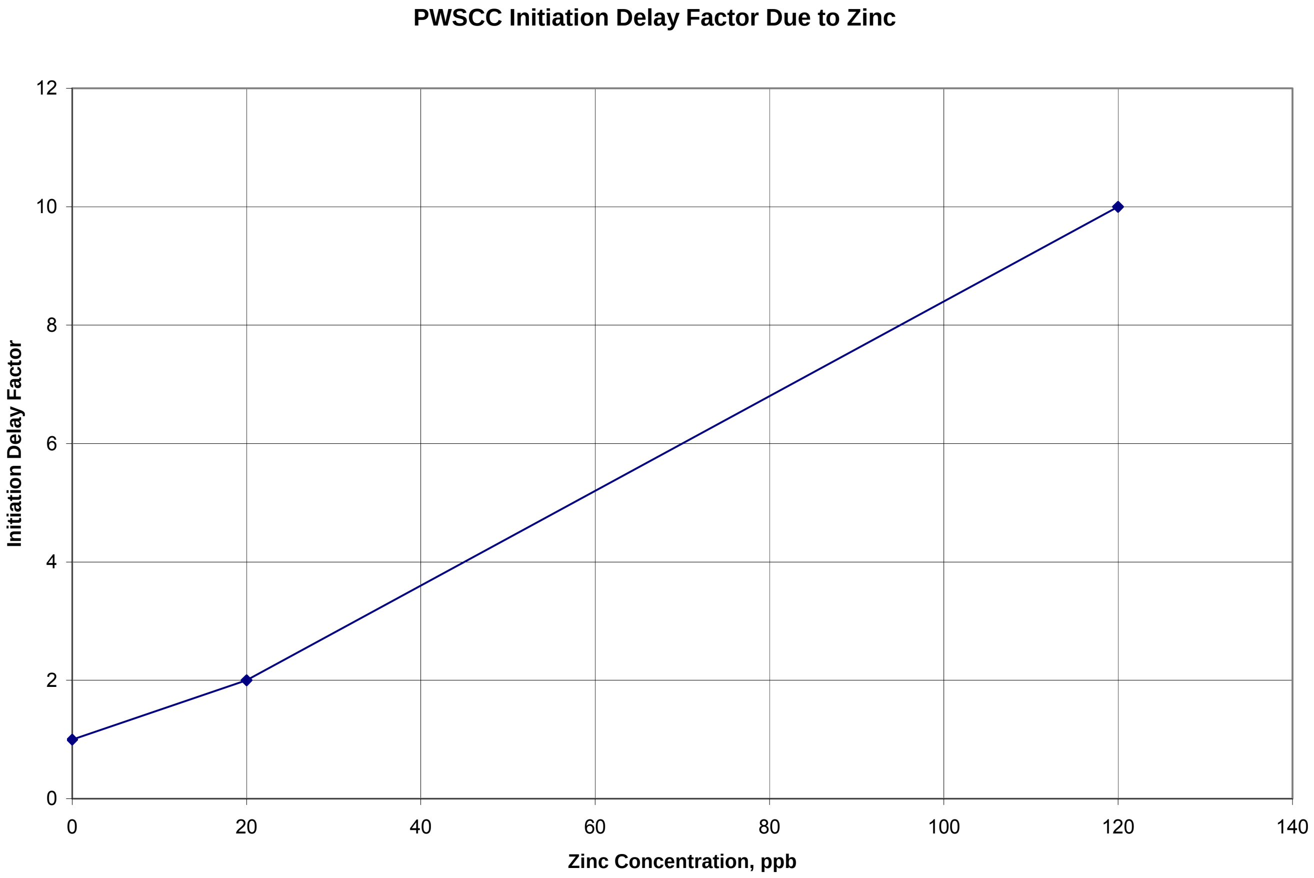
Zinc Application Guidelines – PWSCC

Initiation Laboratory Testing

- Notes that nearly all tests indicate a significant delay in initiation of Alloy 600 cracking
- Focus is on “engineering” initiation versus “true” initiation
- Recommends linear interpolation of three data points (0, 20, and 120 ppb Zinc) for improvement factor for initiation

Zinc Application Guidelines – PWSCC

Initiation Laboratory Testing – Recommended Derivation of Improvement Factor



Zinc Application Guidelines – PWSCC

Crack Propagation Laboratory Testing

- Laboratory results are mixed
  - Slow growing cracks may be mitigated
  - Fast growing cracks may not
- Does not address most recent testing
  - Andresen (GE) for EPRI
  - About a factor of 2 reduction in CGRs with 150 ppb zinc
    - Alloy 600, CRDM nozzle material
    - 325°C, 600 ppm B, 2.2 ppm Li, pH_T=7.58 ($pH_{300°C}$ = 7.21)
    - Possible delay in reduction
  - For lower concentrations (50 ppb) – No Reduction
- No specific guidance on quantifying benefits

Zinc Application Guidelines – PWSCC

Field Data – CRDM Nozzles

Plant Name	# of Nozzles Heat No. M3935	% In Industry Heat No. M3935	# Inspected by UT	# Required Repair	% of M3935 in RV Head with Defect	Estimated EDY Observation of PWSCC
Oconee 3	68	49	68	14	20	22.5
Davis-Besse	5	4	5	4	80	19.2
ANO 1	1	< 1	1	1	100	21.2
Beaver Valley 1	4	3	4	4	100	14
Farley 2	61	44	61	0	0	17.1*
Total	139		139	23		
%			100%	17%		

* EDY at 2R16, last inspection before head replacement, no PWSCC indications

Observations at O3, DB, and ANO1 by leak, BV1 and F2 by NDE

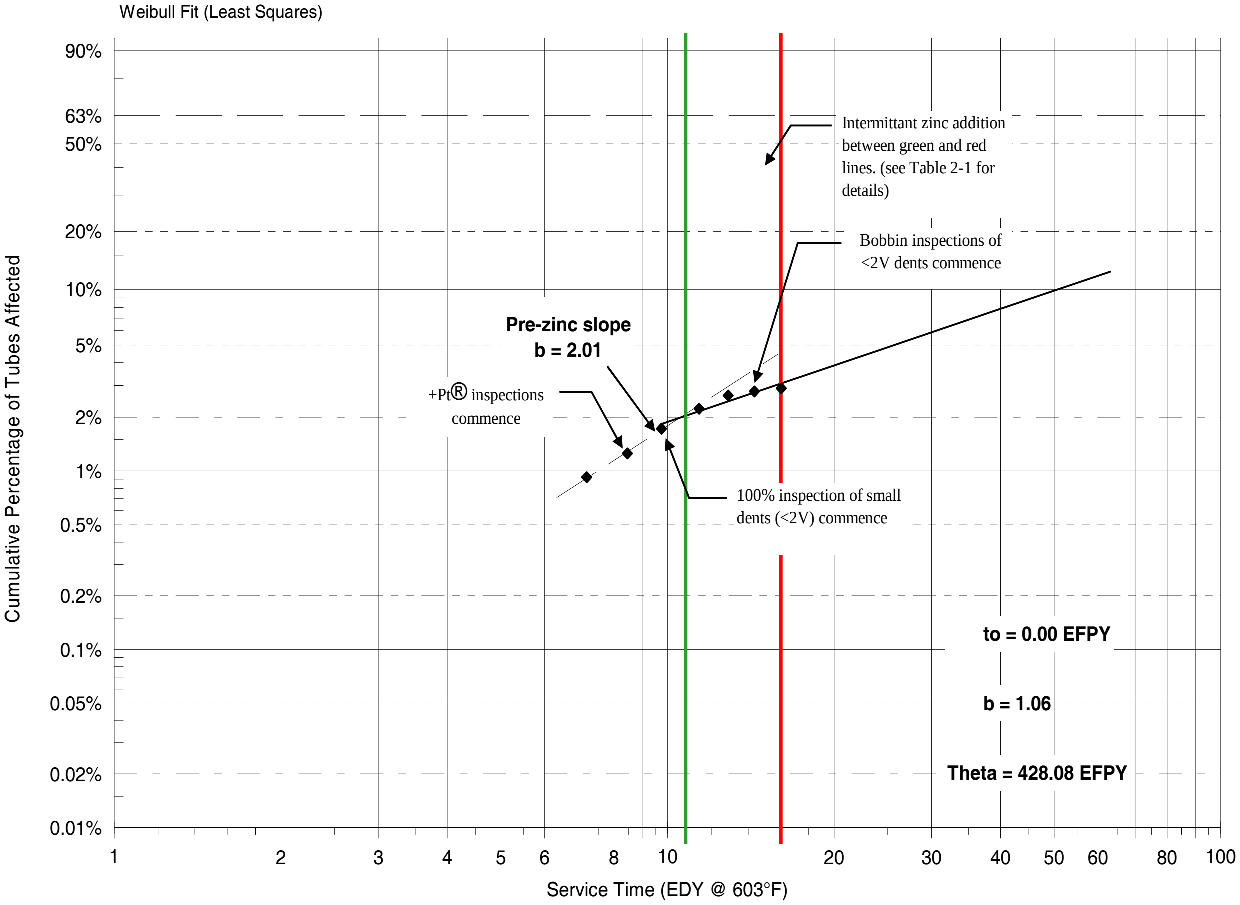
Zinc Application Guidelines – PWSCC

Field Data – CRDM Nozzles

- Effective Degradation Years
  - EFPY adjusted for temperature
  - E_{act} = 50 kcal/mol
  - Temperature of EDY is 600°F
- Different observation techniques
  - O3, DB, and ANO1 by leak
  - BV1 and F2 by NDE
- Zinc added to Farley 2 at beginning of Cycle 10
  - About 10.3 EFPY (~10 EDY)
- Implications for consideration of initiation not assessed
  - Very long initiation time; is it realistic?
  - PWR OG results need to be assessed in light of long initiation time

Zinc Application Guidelines – PWSCC

Field Data – SG Tubes, Diablo Canyon Unit 1 Weibull Slopes TSP PWSCC



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Zinc Application Guidelines – PWSCC

Field Data – SG Tubes, Summary for TSP PWSCC

Plant	Pre-/No Zinc Slope	Post-zinc Slope	Reduction
Diablo Canyon 1	2.01	1.06	47%
Diablo Canyon 2	1.76	1.22	31%
North Anna 1 (orig. SGs)	2.08		
North Anna 2 (orig. SGs)	6.68		
Sequoyah 1 (orig. SGs)	2.27		

Median =	2.08	1.14
Average =	2.96	1.14

Zinc Application Guidelines – PWSCC

Field Data – SG Tubes, Summary for TS EZ PWSCC

Plant	Pre-/No Zinc		Post-zinc Slope		Reduction
	Data Description	Slopes	Data Description	Slopes	
Beaver Valley 1	No peening	4.35	No peening	0.90	79%
Farley 1 (orig. SGs)	No peening	4.23			
North Anna 1 (orig. SGs)	No peening	4.33			
North Anna 2 (orig. SGs)	No peening	3.71			

No Peening Median =		4.28		0.90	
No Peening Average =		4.16		0.90	

Diablo Canyon 1	Post shot-peening	1.92	Post shot-peening	1.29	33%
Diablo Canyon 2	Post shot-peening	1.40	Post shot-peening	0.52	63%
Salem 2	Post shot-peening	0.80			
Sequoyah 1 (orig. SGs)	Post shot-peening	1.10			
Sequoyah 2	Post shot-peening	1.64	Post shot-peening	1.13	31%

Post-peening Median =		1.40		1.13	
Post-peening Average =		1.37		0.98	

Status of Industry Research

Hydrogen Optimization

- Most recent comprehensive reviews:
  - EPRI 1015288 (MRP-213)
  - EPRI 1015017
- Ongoing Research
  - GE CGR testing
  - NRC sponsored testing (ANL/PNNL)
  - International efforts
- Other industry efforts
  - MRP Chemical Mitigation Technical Bases
  - FRP fuel qualification
  - Others as available

Zinc Injection

- Most recent comprehensive reviews:
  - EPRI 1013420
- Ongoing Research
  - GE CGR testing (includes zinc/hydrogen synergy tests)
  - PWR OG Farley nozzle testing
- Other industry efforts
  - MRP Chemical Mitigation Technical Bases
  - FRP fuel qualification
  - ZUG evaluations
  - SGMP Evaluation of SG tubing data

Technical Bases Program

Tasks

- Task 1: Collection and analysis of PWSCC initiation and crack growth rate data
- Task 2: Meetings with investigators generating data included in the analysis
- Task 3: Application of assessment to susceptible components
- Task 4: Interim review meetings
- Task 5: EPRI Technical Report

Task 1: Data Collection and Analysis (1)

- Published and as yet unpublished (to the extent available)
- Build on previous EPRI works, for example:
  - Zinc guidelines
  - SG tube degradation analyses
  - MRP-213 (Andresen and Hickling hydrogen summary)
  - MRP-147 (Eason statistical analysis)
  - EPRI 1015017 (Marks hydrogen summary)
  - Other statistical analyses (e.g., Eason and Pathania, 2007)
- Consider effects of other experimental parameters
  - Stress intensity factors
  - Material properties
  - Temperature (re-evaluate current activation energies)
  - Chemistry
- Limit scope to full power conditions (no LTCP)

Task 1: Data Collection and Analysis (2)

- Consider all nickel alloys and weld metals in RCS pressure boundary plus SG divider plates, but not SG tubes
- Evaluate available plant data as well as laboratory data

- Results will include a quantitative assessment of the magnitudes of mitigative effects with statistical significance and expected variation

Task 2: Meetings with Investigators

- As necessary, meeting with original investigators
- Always additional details that don’t get published
- Possibly additional data
- Potential for additional insight into sources of variability

Task 3: Component Assessment

- Consider specific components
  - RCS pressure boundary
  - Nickel alloys and weld metals
  - Not SG tubes
  - Include SG divider plates
- Assess mitigation, accounting for other factors
  - Stress intensity factor
  - Temperature
  - Material condition (e.g., cold work)
  - Chemistry

- Result is statistical distribution of improvement factors for different mitigation strategies, for example:
  - 90% confidence that increasing hydrogen from 40 cc/kg to 55 cc/kg will provide a factor of improvement of 1.3 or higher for CRDM nozzle J-groove weld

Task 3: Component Assessment

Different Strategies

- Two different strategies pursued
  - Development of a factor of improvement
    - Measure of relative improvement
    - Does not directly address, e.g., inspection intervals
  - Development of separate crack growth rate curves
    - Alternatives to, e.g., MRP-115 curve
- Alloy 600 versus 690
  - Initially will address 690 as well as 600
  - Data is expected to be less definitive
    - 690 more difficult to crack
    - Demonstration of improvement therefore more difficult
- Initiation versus propagation
  - Initially will address initiation as well as propagation

Task 3: Component Assessment

Consideration of Initiation (1)

- Current evaluations generally do not address initiation
  - Cracks assumed to be initiated already
  - Inspection intervals based on crack growth
- Chemical mitigation expected to reduce initiation
  - Good evidence for zinc
  - Less quantified benefit from hydrogen
- Assumption of initiated cracks does not credit significant time required for initiation, especially for replacement components
  - Some replacement components have only seen chemically mitigating environments (i.e., zinc)
  - Generally replacements are 690TT and weld metals
    - Already difficult to quantify realistic crack initiation
    - Quantifying mitigation may not be realistic
- If a probabilistic approach is taken, initiation becomes a key factor
  - Chemical mitigation likely to affect projection of future crack initiation

Task 3: Component Assessment

Consideration of Initiation (2)

- Steam generator analogy
  - SG 90-day report Monte Carlo analyses
- Assumes some cracks still in service
  - Based on POD
  - Assume a distribution of sizes
- Assumes some new cracks will initiate
  - Based on past history
  - Uses a distribution of initiation probability
- Assumes a distribution of crack growth rates
  - Based on “look backs”
- Evaluate failure within planned operating time
  - Based on well established criteria associated with tube rupture
  - Demonstrate a low probability of rupture

Task 3: Component Assessment

Consideration of Initiation (3)

- Initiation implicit in CRDM nozzle consideration
- Units classified by susceptibility
- Classification based on effective degradation years (EDY)
- EDY concept essentially an “engineering” initiation consideration, i.e., expected time till detectable crack

- Chemical mitigation example:

$$\Delta \text{EDY (Zn)} = 0.3\ \Delta \text{EDY (no Zn)}$$

  - Analogous to temperature reduction

Task 4: Interim Review Meetings

- Developing a review team
  - Utility, Vendor, Government Labs
- Specific membership and duties still to be defined
- Anticipate participation mostly via e-mail and conference calls
- Possible add-on to November 12-14 2008 Expert Panel Meeting, Los Angeles, CA

Task 5: Technical Report

- EPRI style technical report
- Report will summarize technical bases and provide requirements regarding their use

- Anticipated schedule

– Commence project	March 2008
– Initial draft report	January 2009
– Final draft report	March 2009