A Probabilistic-Mechanistic Approach to Modeling Stress Corrosion Cracking in Alloy 600 Components with Applications

Gary Wu
University of Maryland
College Park

Mohammad Modarres
University of Maryland
College Park

PSAM 2011/ESREL 2012
June 25 – 29, 2012
Helsinki, Finland

Overview

- Introduction
- Stress Corrosion Cracking (SCC) Background
- Model Development Process
- Crack Propagation Simulation Process
- Conclusion

Introduction

Motivation

- Nuclear power industry wishes to extend the lifecycle of currently operating nuclear power systems
- Probabilistic risk assessment is required to ensure that nuclear power system components do not fail due to the extension of operating lifecycle
- Stress corrosion cracking (SCC) is a primary degradation mechanism that affects Alloy 600 components in nuclear power systems

Rationale

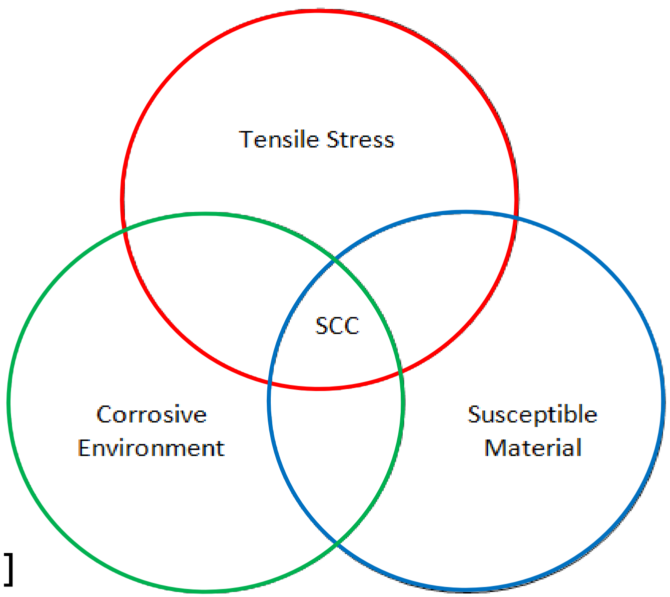
- Current research lacks simple probabilistic frameworks that are able to model stress corrosion cracking behavior with uncertainty measures
- Models proposed in research are deterministic and sometimes complex with many variables
- Goals for new proposed model:
  - Simple
  - Physics-driven
  - Probabilistic

Introduction: Project Approach

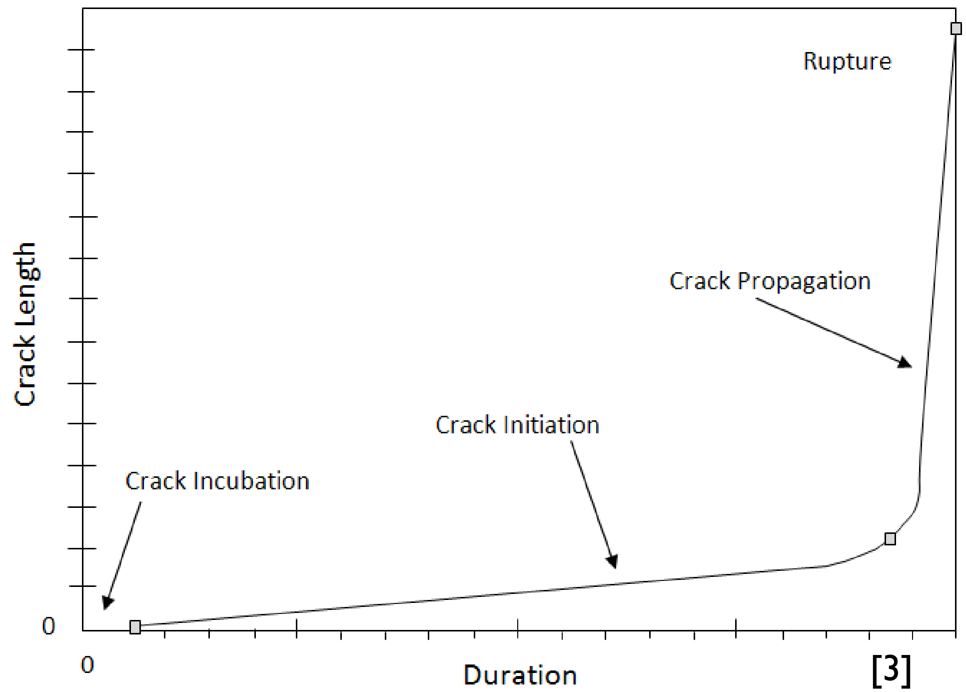
- Literature review to understand the proposed mechanisms and models that characterize stress corrosion cracking (SCC)
  - General SCC of Alloy 600
  - Specific SCC of Steam Generator Tubes
- Develop a **simple, physics-driven** model to estimate the crack growth rate of stress corrosion cracking of Alloy 600 with **uncertainty measures**
- Develop a simulation process to propagate stress corrosion cracking using developed probabilistic model

Stress Corrosion Cracking

- Stress corrosion cracking can be defined as a delayed cracking mechanism which only occurs with the combination of: Susceptible Material, Corrosive Environment, Constant Tensile Stress
- Can often cause catastrophic failure with little to no warning [2]



[1]



[3]

Adapting Existing Model

- MRP model developed by Hicking et al. from the Electric Power Research Institute [4] for PWSCC

$$\dot{a} = \alpha \cdot exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \cdot (K - K_{th})^{\beta}$$

where: $\dot{a}$ – crack growth rate

R – universal gas constant

T_{ref} – reference temperature

K_{th} – threshold SIF

β – model parameter

Q – activation energy for propagation

T – operating temperature

K – stress intensity factor (SIF)

α – crack growth amplitude parameter

- SCC factors considered:
  - Temperature (Arrhenius relationship)
  - Constant Tensile Stress (Power-Law relationship)

$$K = \sigma_{applied} Y \sqrt{\pi a}$$

$\sigma_{applied}$ – total effective stress
a – crack depth or length
Y – shape parameter

Incorporation of Other SCC Factors

pH

- pH is a property of the corrosive environment and has been shown to have an effect on SCC propagation rates [5] such that an increase of pH value increases the SCC propagation rate

$$CPR \propto [pH]^{\beta}$$

CPR – crack propagation rate
β – relationship parameter
pH – pH of bulk solution

- Power-Law relationship is proposed for crack propagation rate dependence on pH

Yield Stress

- Yield Strength is a property of the susceptible material and has also been shown to have an effect on SCC propagation rates [6], such that an increase in yield strength increases the crack propagation rate

$$CPR \propto [\sigma_{ys}]^{m}$$

CPR – crack propagation rate
m – relationship parameter
σ_{ys} – material yield strength

- Power-Law relationship is also proposed for crack propagation rate dependence on yield strength

Final Proposed Model

- PWSCC Propagation Model for Alloy 600 Components

$$CPR_I = C_I \cdot exp\left[\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \cdot [\sigma_{ys}]^{m_I} \cdot [K - K_{th}]^{n_I}$$

$$CPR_{II} = C_{II} \cdot exp\left[\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \cdot [pH]^{\beta_{II}} \cdot [\sigma_{ys}]^{m_{II}} \cdot [K - K_{th}]^{n_{II}}$$

where:

CPR_I – crack propagation rate for Stage I crack propagation

CPR_{II} – crack propagation rate for Stage II crack propagation

and

Q – activation energy (130 kJ/mol) [6]

R – universal gas constant (8.314E-3 kJ/mol-K)

T – operating temperature

T_{ref} – reference temperature (588 K)

pH – pH of the bulk environment

K_{th} – threshold SIF (9MPa√m) [9]

C_I, C_{II} – model constants

β_{II} – parameter for pH

m_I, m_{II} – parameters for Y.S.

n_I, n_{II} – parameters for SIF

σ_{ys} – material yield strength

Final Proposed Model

$$CPR = \begin{cases} CPR_I & for\ K < K_{trs} \\ CPR_I(1-x) + CPR_{II}(x) & for\ K_{trs} \le K < K_{tre} \\ CPR_{II} & for\ K \ge K_{tre} \end{cases}$$

where:

K – stress intensity factor (SIF)

K_{trs} – approximate SIF at the beginning of the Stage I to Stage II transition

K_{tre} – approximate SIF at the end of the Stage I to Stage II transition

CPR – linearly combined crack propagation rate

CPR_I – crack propagation rate for Stage I crack propagation

CPR_{II} – crack propagation rate for Stage II crack propagation

x – transition ratio defined by $(K - K_{trs})/(K_{tre} - K_{trs})$

Bayesian Regression Analysis

- Estimate the model parameters using SCC propagation data
- The posterior distribution for the model parameters is:

$$\pi(\underline{\theta}|Data) = \frac{L(Data|\underline{\theta})\pi_o(\underline{\theta})}{\int L(Data|\underline{\theta})\pi_o(\underline{\theta})d\,\underline{\theta}}$$

where:

$$L(Data|\underline{\theta}) = \prod_{i=1}^{N} \frac{1}{s\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{CPR_{exp}[i] - CPR_{calc}[i,\underline{\theta}]}{s}\right)^2}$$

and:

$\mathbf{Data} - \{CPR_i, K_i, pH_i, T_i, \sigma_{ys_i}\}$

$\underline{\boldsymbol{\theta}} - \{C, n, m, b, s\}$

N – total number of data points

s – standard deviation of error

$\boldsymbol{L}(\mathbf{Data}|\underline{\boldsymbol{\theta}})$ – likelihood function

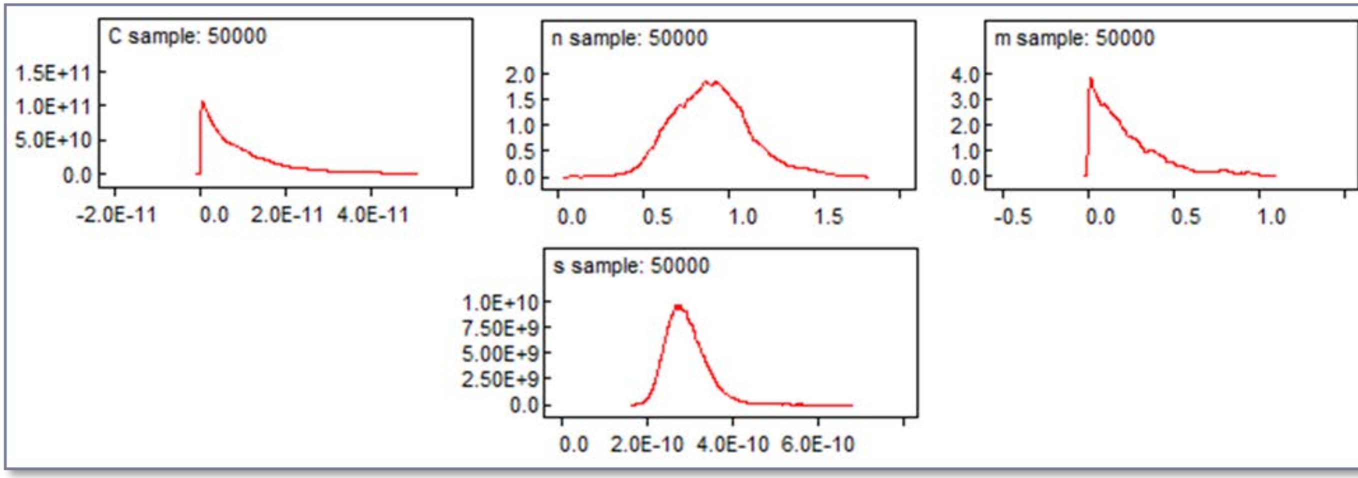
$\boldsymbol{\pi}_o(\underline{\boldsymbol{\theta}})$ – prior beliefs for model parameters

$\boldsymbol{CPR}_{exp}[\boldsymbol{i}]$ – i-th experimental value for CPR

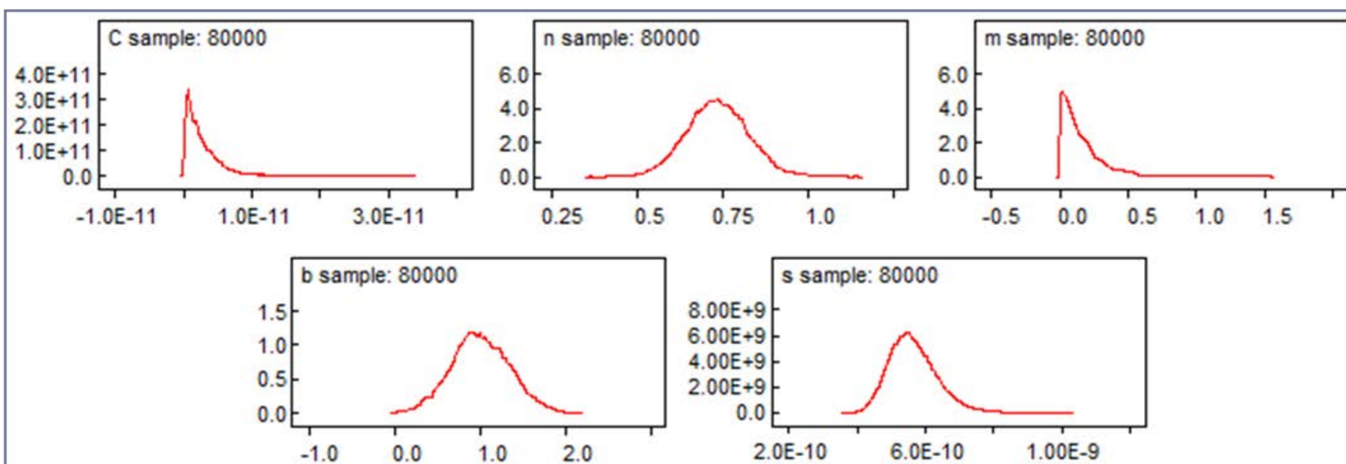
$\boldsymbol{CPR}_{calc}[\boldsymbol{i}, \underline{\boldsymbol{\theta}}]$ – i-th calculated value for CPR

Bayesian Regression Analysis

Stage I Model Parameter Marginal Distributions



Stage II Model Parameter Marginal Distributions



Simulation Assumptions

- Simulation Conditions
  - Alloy 600 Material
  - High Temperature Primary Water
  - MATLAB code to model Steam Generator (SG) Tubes
  - Does not simulate regular inspection and maintenance

- "Steam Generator Tube Rupture" versus "Failure"
  - "Steam Generator Tube Rupture" (SGTR) occurs when a crack substantially contributes to primary-to-secondary side leak rates exceeding certain amounts (100 gallons per minute) [7]
  - "Failure" in this simulation is defined as a 100% through-wall extent across the thickness of the steam generator tubes.

Process Summary

Set initial conditions

Sample model parameters

Sample initial crack size and location

Propagate crack to failure

Build TTF Distribution

Aggregate all TTF Distributions

- Initial Conditions
  - Crack Length/Depth Frequency
  - Crack Density
  - Total Constant Tensile Stresses
  - Steam Generator Operating Conditions
  - Model Parameter Marginal Distributions

Process Summary

Set initial conditions

Sample model parameters

Sample initial crack size and location

Propagate crack to failure

Build TTF Distribution

Aggregate all TTF Distributions

- Sample model parameters to formulate a deterministic model for crack propagation rate
- Stage I
  - $\{C, n, m\}$
- Stage II
  - $\{C, n, m, \beta\}$

Process Summary

Set initial conditions

Sample model parameters

Sample initial crack size and location

Propagate crack to failure

Build TTF Distribution

Aggregate all TTF Distributions

- Sample initial crack distribution for crack size and randomly choose a location for PWSCC
  - U-bend Region
  - Tube support plate interactions
  - Expansion Transition Region
- Different total stresses at three locations due to varying amounts of residual stress

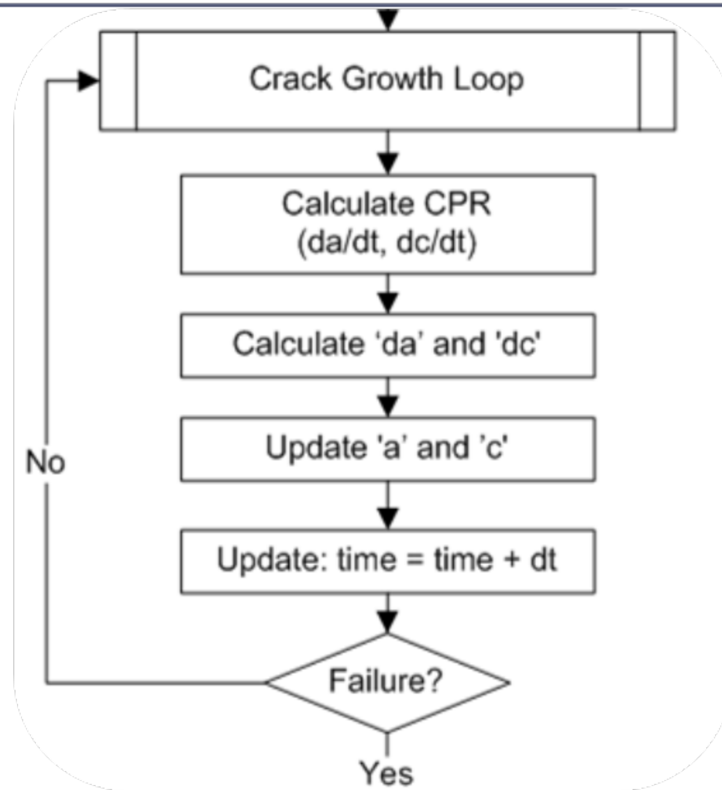
Process Summary

Set initial conditions

Sample model parameters

Sample initial crack size and location

Propagate crack to failure



Build TTF Distribution

Aggregate all TTF Distributions

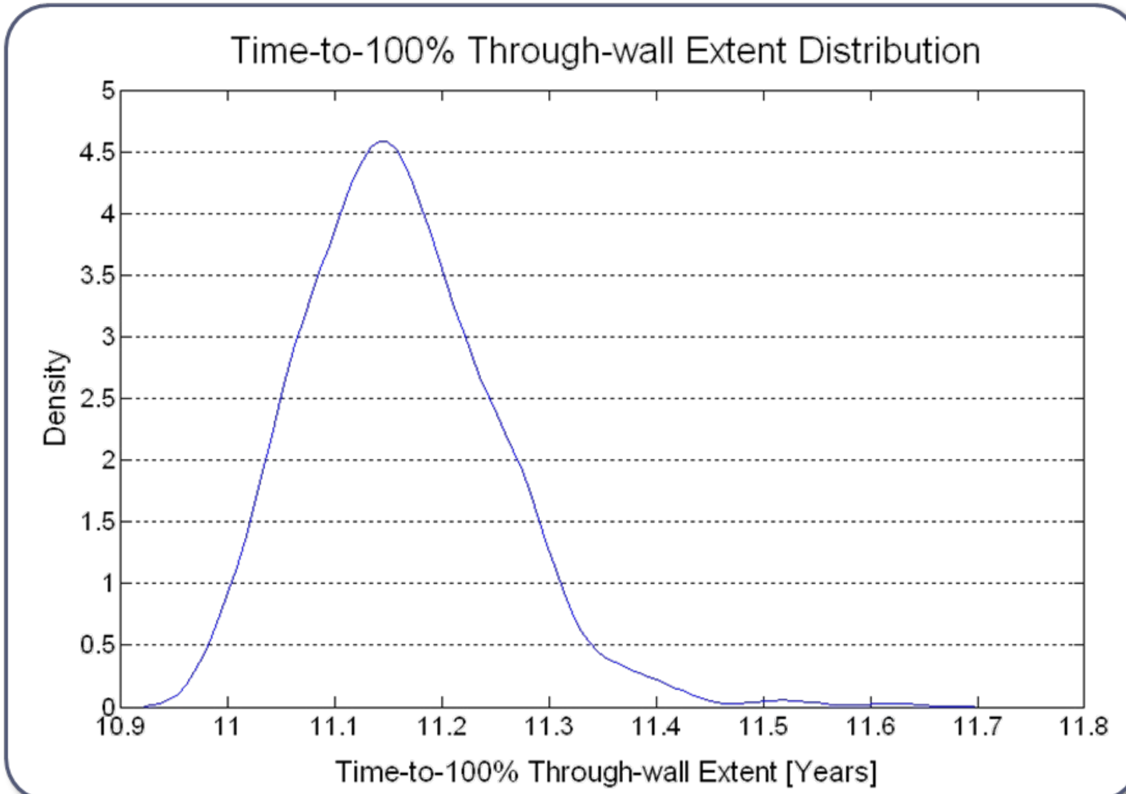
Process Summary

Set initial conditions

Sample model parameters

Sample initial crack size and location

Propagate crack to failure



Build TTF Distribution

Aggregate all TTF Distributions

Process Summary

Set initial conditions

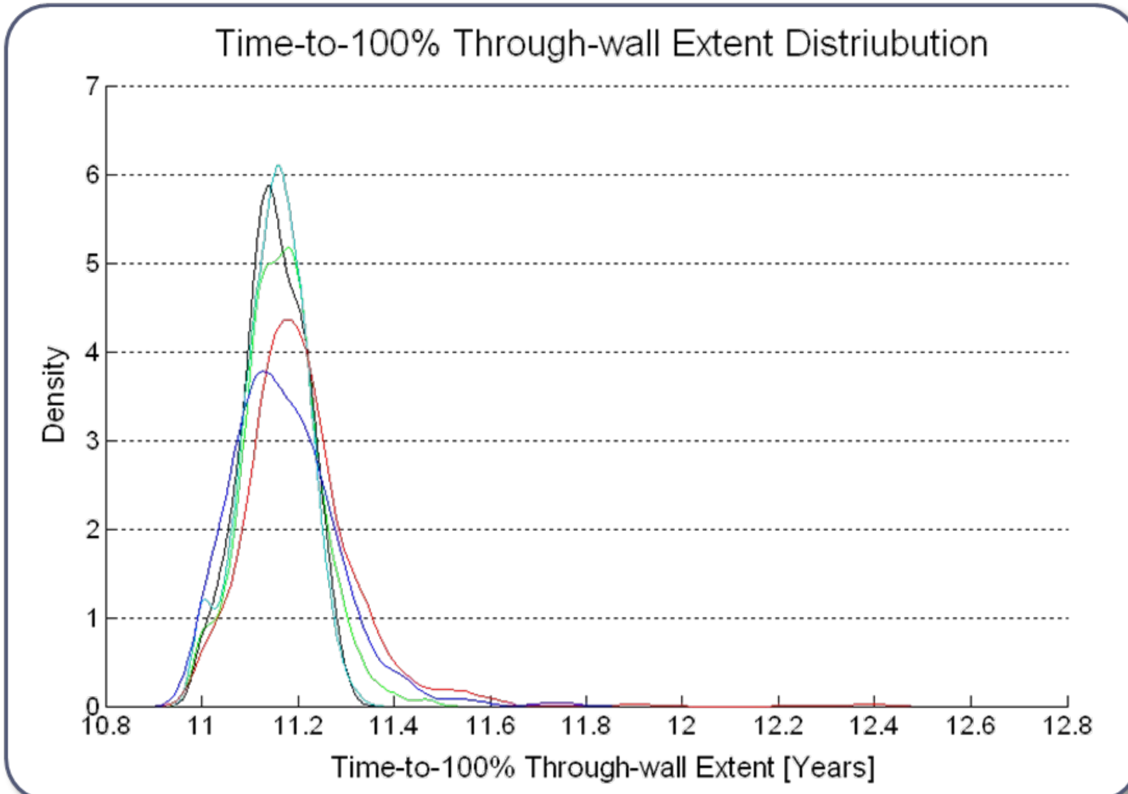
Sample model parameters

Sample initial crack size and location

Propagate crack to failure

Build TTF Distribution

Aggregate all TTF Distributions



Process Summary

Set initial conditions

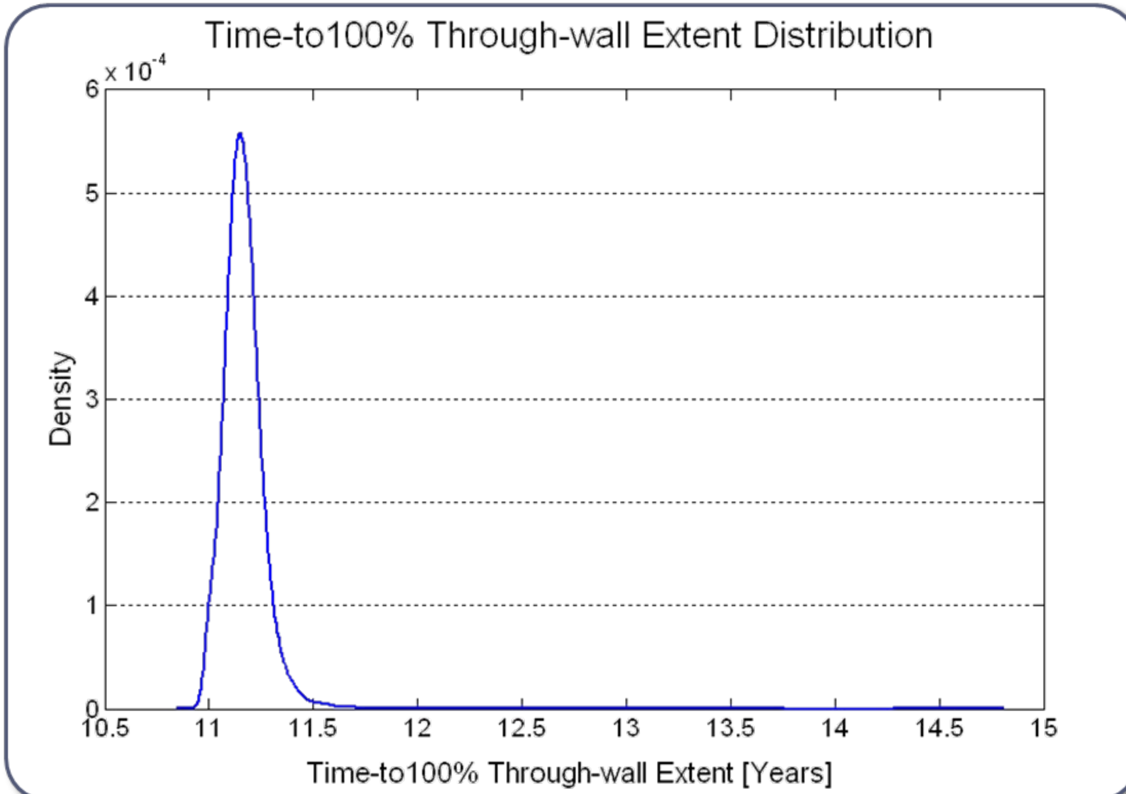
Sample model parameters

Sample initial crack size and location

Propagate crack to failure

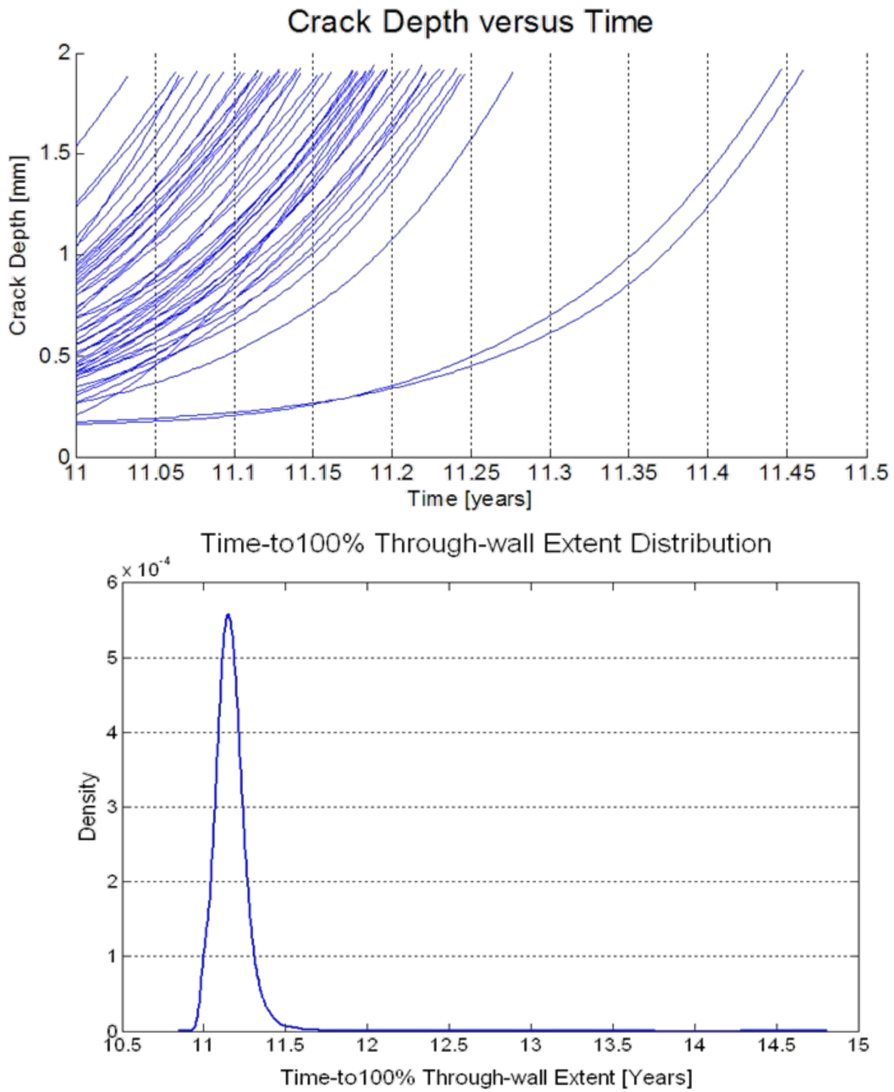
Build TTF Distribution

Aggregate all TTF Distributions



Discussion

- Results are dependent on simulation assumptions and initial distributions
  - Initial crack size distribution from inspection data at 11 years of operation
    - Not all cracks are in the crack propagation stage
  - Assume denting at tube support plates
  - Assume residual stresses are the same for all cracks in each location



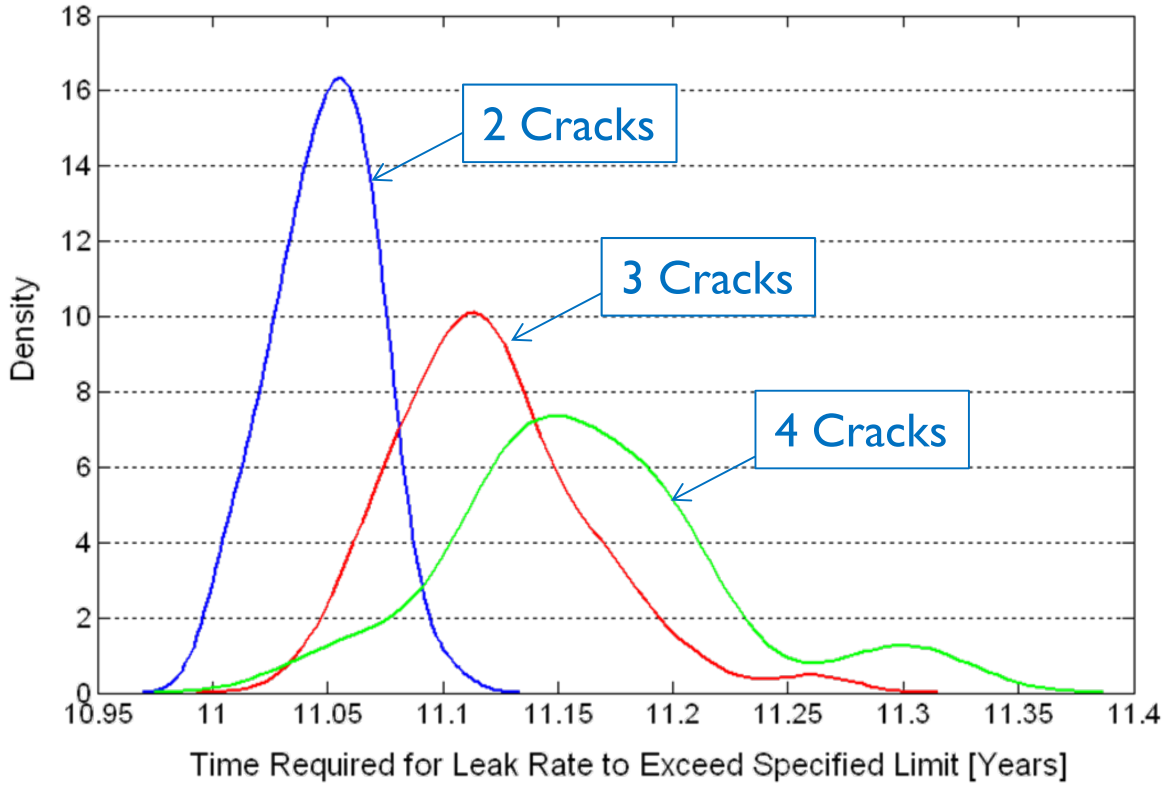
Discussion

- Before being able to estimate SGTR frequency using this model and simulation
  - Crack behavior after 100% through-wall extent
  - Implement a leak rate model for defined crack sizes
  - Consider regular inspection intervals and maintenance of SG tubes
    - Plugging
    - Sleeving

- Process for SGTR Frequency
  - Determine leak rates for final crack sizes
  - Check for sudden increase of leak rate exceeding 100 gallons per minute
  - SGTR Frequency = 1 / Time of leak rate exceeding specified limits

Discussion

- Suppose more than one crack with a constant leak rate within an hour time period is required to exceed the specified limit
  - Simulation provides ability to estimate the time required to reach specific limit (e.g. can be applied to estimate SGTR frequency)



Conclusion

- Explored the stress corrosion cracking mechanism in general and specifically for Alloy 600 steam generator (SG) tubes

- Proposed an simple, probabilistic model based on physics-driven relationships explicitly incorporating factors of SCC:
  - Stress
  - Temperature
  - pH
  - Yield Strength

- Developed a crack propagation simulation process for Alloy 600 SG Tubes in Primary Water conditions that predicts the time-to-100% through-wall extent with uncertainty measures

Questions?

References

[1] Denny A Jones, *Principles and Prevention of Corrosion*, 2nd ed. Upper Saddle River, United States of America: Prentice-Hall, Inc., 1996.

[2] Joseph R Davis, Ed., *Corrosion - Understanding The Basics*. Materials Park, United States of America: ASM International, 2000.

[3] Son Le Hong, Claude Amzallag, and Angel Gelpi, "Modelling of Stress Corrosion Crack Initiation on Alloy 600 in Primary Water of PWRs," in *International Symposium of Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, Newport Beach, 1999, pp. 115-122.

[4] Hicking, A McIlree, and R Pathania, "Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Material (MRP-55)," Electric Power Research Institute, Palo Alto, NRC ADAMS Accession No. ML023010510, 2002.

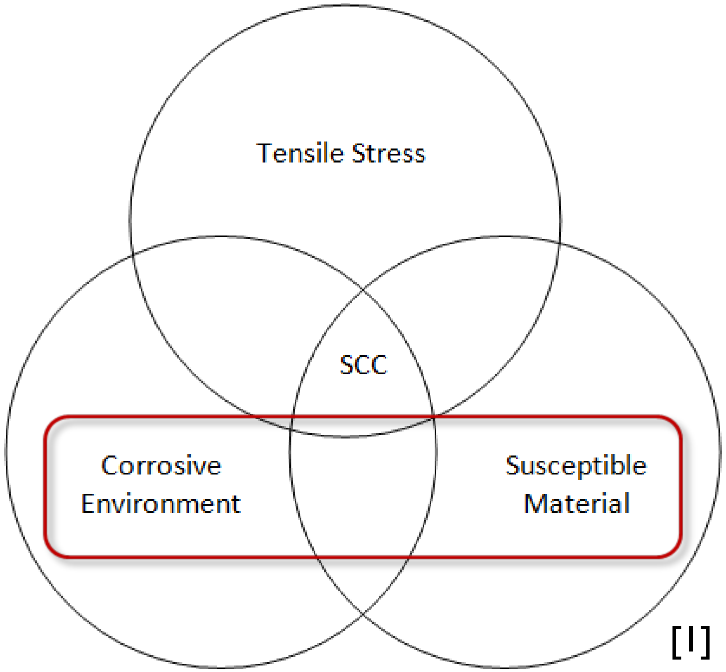
[5] R B Rebak, A R McIlree, and Z Szklarska-Smialowska, "Effects of pH and Stress Intensity on Crack Growth Rate in Alloy 600 in Lithated + Borated Water at High Temperatures," in *International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, Monterey, 1991, pp. 511-524.

[6] R B Rebak, Z Xia, and Z Szklarska-Smialowska, "Effect of Temperature and Cold Work on the Crack Growth Rate of Alloy 600 in Primary Water," *Corrosion*, vol. 51, no. 9, pp. 689-697, 1995.

[7] R Tregoning, L Abramson, and P Scott, "Estimating Loss-of-Coolant Accident (LOCA) Frequencies Through the Elicitation Process, U.S. Nuclear Regulatory Commission, Washington DC, NUREG/CR NUREG-1829, 2008

Backup Slides

Factors of Stress Corrosion Cracking

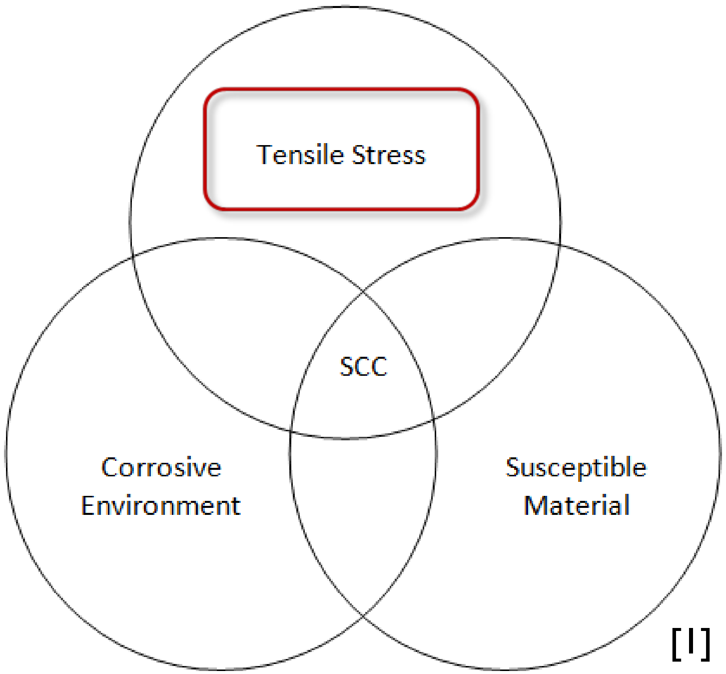


[1]

Alloys	Environments
Stainless Steels	- Chlorides - Caustic - Water + O_2
Nickel Alloys	- Hot caustic - High temperature water - Steam
Cooper Alloys	- Ammonia - Water vapor + SO_2
Aluminum Alloys	- Water vapor - N_2O_4 - Alcohols
Titanium Alloys	- Methanol - Dilute HCl or H_2SO_4

[2]

Factors of Stress Corrosion Cracking



- Tensile stress required for SCC is of constant magnitude, usually less than macroscopic yield strength
- Total constant stress is the arithmetic sum of:
  - Externally applied stress as a result of operating conditions
  - Residual stresses as a result of material manufacturing processes

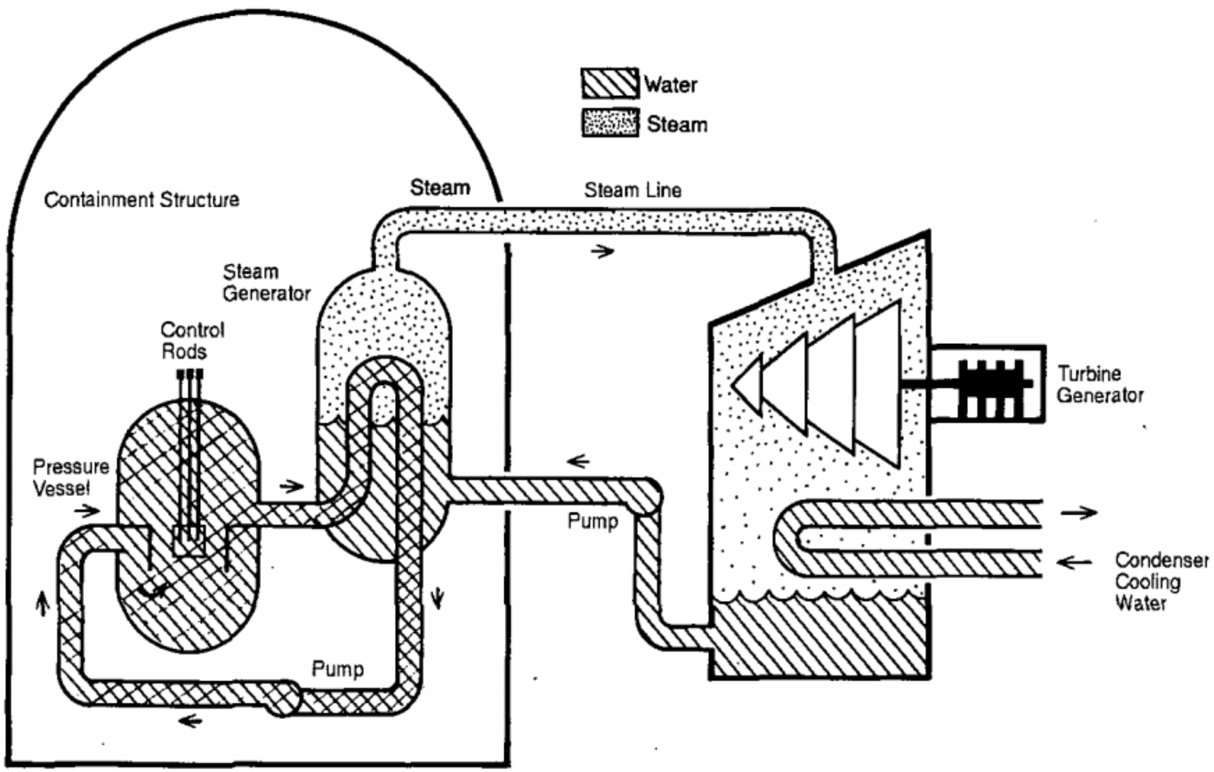
Steam Generator Tube Background

- 104 nuclear reactors in the United States
  - 35 are Boiling Water Reactors
  - 69 are Primary Water Reactors

- Primary Water Reactors
  - Two closed-loop systems
  - Primary loop uses primary coolant (high temperature water) to circulate heat energy from the radioactive material
  - Secondary loop uses treated feedwater to turn into steam for power generation
  - Steam generator acts as the connection between primary and secondary loops

Steam Generator Tube Background

Primary Water Reactor

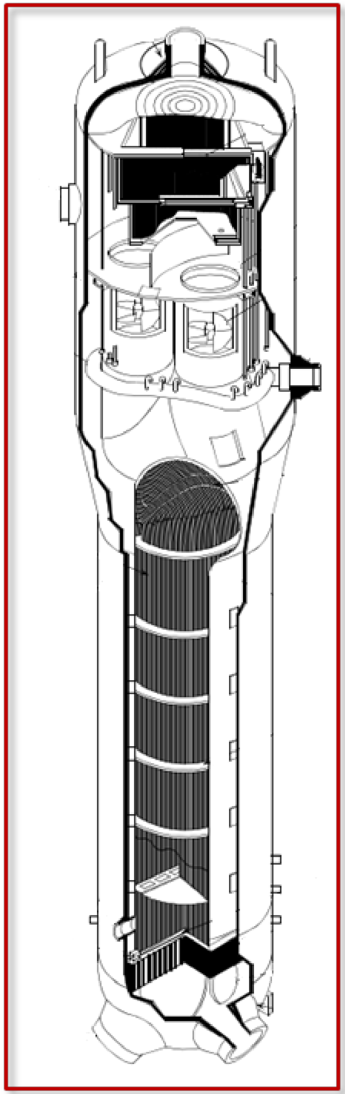


[3]

[4]

Steam Generator Tube Background

[3]



[4]

Recirculating Steam Generator

SG Mechanical/Environmental Properties

Steam Generator Mechanical/Environmental Properties	
Property	*Value*
Number of SGs	2
Number of tubes	10025
Tube outside diameter [mm]	17.5
Tube inside diameter [mm]	15.5
Tube thickness [mm]	2
Tube length [m]	22
SG Tube material	Alloy 600
SG Tube treatment	LTMA
Number of tubesheet support plates	7
Primary side pressure [MPa]	17.24
Secondary side pressure [MPa]	5.67
Primary side temperature [Kelvin]	588
Primary water pH	7.3

[5]

PWSCC Region Assumptions

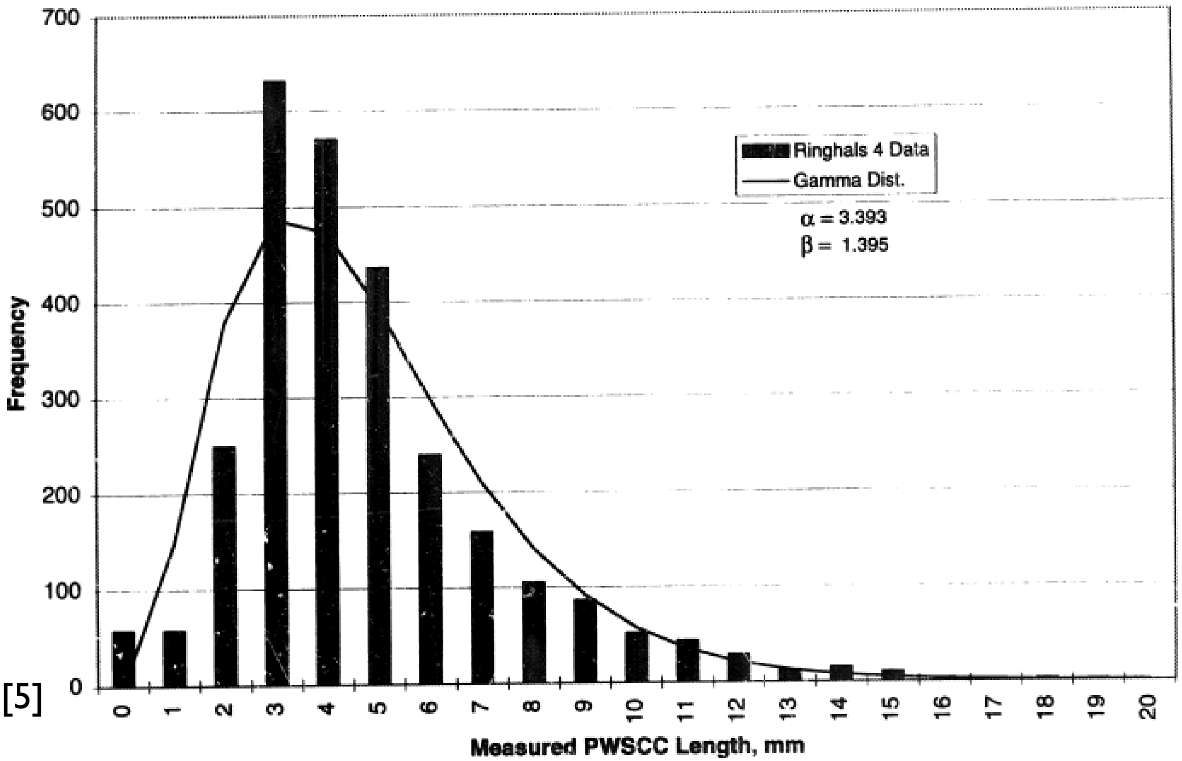
PWSCC Region Assumptions	
Expansion Transition Region	
Property	*Value*
Number of flaws per affected tube[2] [3]	16
Number of affected tubes per SG	10025
Total effective stress [MPa]	430
Yield Strength[1] [MPa]	390
Ultimate Strength[4] [MPa]	737
Tubesheet Support Plate (TSP) Region	
Property	*Value*
Number of flaws per affected tube[2]	34
Number of tubes affected per SG[2]	501
Total effective stress [MPa]	415
Yield Strength[1] [MPa]	478
Ultimate Strength[4] [MPa]	737
U-Bend Region	
Property	*Value*
Number of flaws per affected tube[3]	20
Number of tubes affected per SG	230
Total effective stress [MPa]	510
Yield Strength[1] [MPa]	513
Ultimate Strength[4] [MPa][6]	737

[1] Yield strength is calculated assuming the 2% CW at expansion transition, 7% CW at TSP with a dent, 9% at U-bend

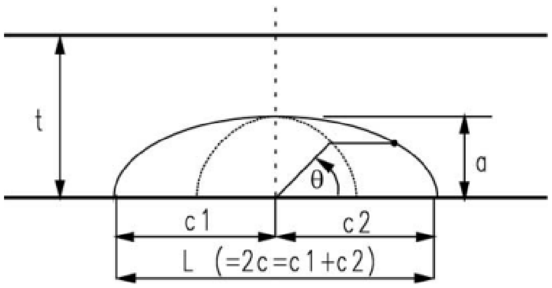
[3] U-bend flaw density is estimated given flaw densities for expansion transition and TSP

Initial Crack Size Distribution

- SG Commissioned in 1983 – data from 1994 inspection
- Crack depth converted with aspect ratio assuming semi-elliptical [0.24-0.35]



[5]



[7]

References

[1] Denny A Jones, *Principles and Prevention of Corrosion*, 2nd ed. Upper Saddle River, United States of America: Prentice-Hall, Inc., 1996.

[2] R B Rebak and Z Szklarska-Smialowska, "The Mechanism of Stress Corrosion Cracking of Alloy 600 in High Temperature Water," *Corrosion Science*, vol. 38, no. 6, pp. 971-988, 1996.

[3] Peter N Paine, "Steam Generator Reference Book, Revision 1," Electric Power Research Institute (ERPI), Palo Alto, Reference Book RP2858; RP4004, 1994.

[4] U.S. Nuclear Regulatory Commission, "Reactor Concepts Manual: Pressurized Water Reactor (PWR) Systems," U.S. Nuclear Regulatory Commission Technical Training Center, Washington DC, Educational Teaching Material 0603, 2007.

[5] J A Gorman, A P.L. Turner, M A Kreider, and J E Harris, "Estimating Probable Flaw Distributions in PWR Steam Generator Tubes," Nuclear Regulatory Commission/Argonne National Laboratory, Washington DC, NUREG/CR NUREG/CR-6521, 1998.

[6] Precision Castparts Corp. (2008) SpecialMetals.com - The Alloy Experts. [Online]. http://www.specialmetals.com/

[7] Kyu In Shin, Jai Hak Park, Hong-Deok Kim, and Han-Sub Chung, "Simulation of stress corrosion crack growth in steam generator tubes," *Nuclear Engineering and Design*, vol. 214, pp. 91-101, 2002.