PNNL-SA-77706

Risk-Informed Safety Margins and the Proactive Management of Materials Degradation

Stephen Unwin
Pacific Northwest National Laboratory

NRC/DOE/NEI 2011 Second Workshop on
US Nuclear Power Plant Life Extension and Development

Washington, DC

February 22-24, 2011

Pacific Northwest
NATIONAL LABORATORY

RISMC Framework and the Management of Materials Degradation

R-7

Interactive Multi-Physics Environment

Stressors and Environment

Physical Stressors

- Operating histories
-Thermal hydraulics
-Neutronics

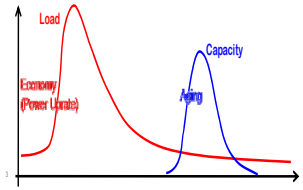
Passive Component Reliabilities

- Materials degradation
- Materials management

Component/System Performance

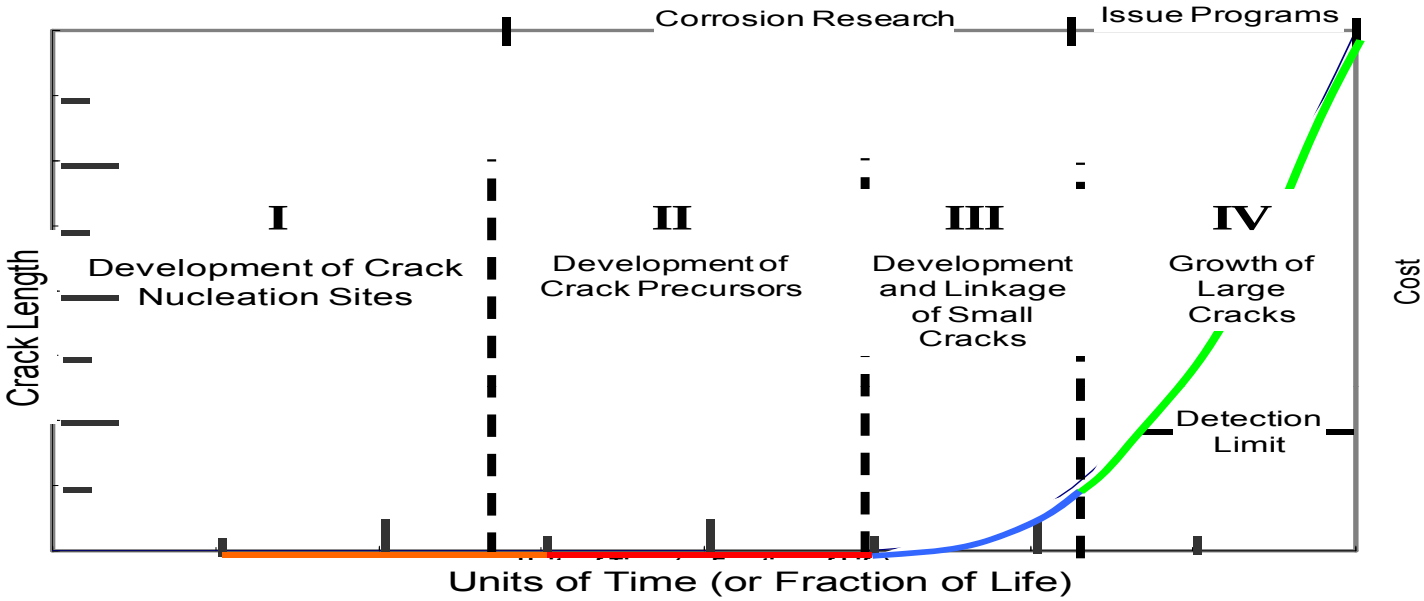
Decision-Making on Materials Management

Impact on Safety Margins

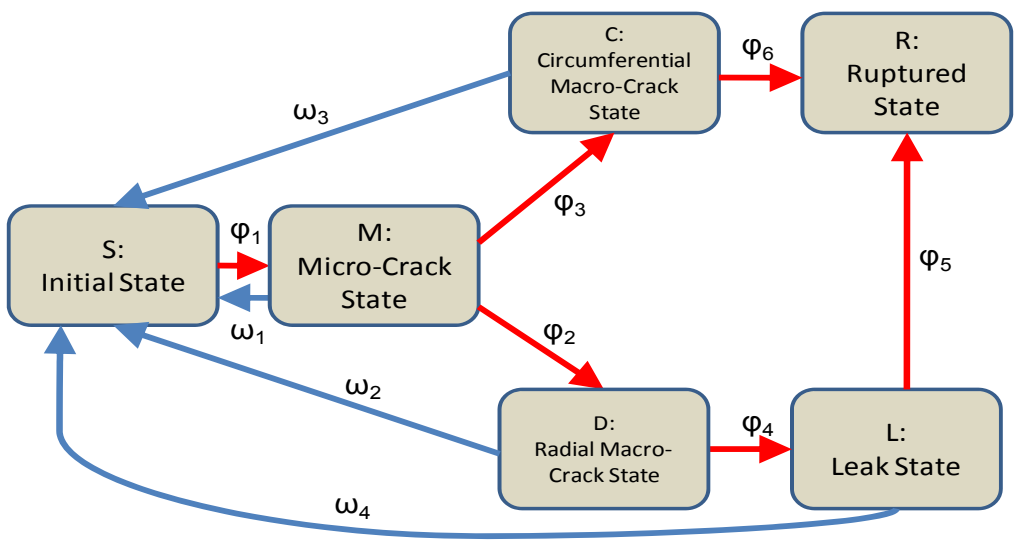


Complementarity of RISMC and NRC Proactive Management of Materials Degradation (PMMD) Program

PMMD (NRC):
Methods and technologies for materials flaw precursor detection and proactive intervention



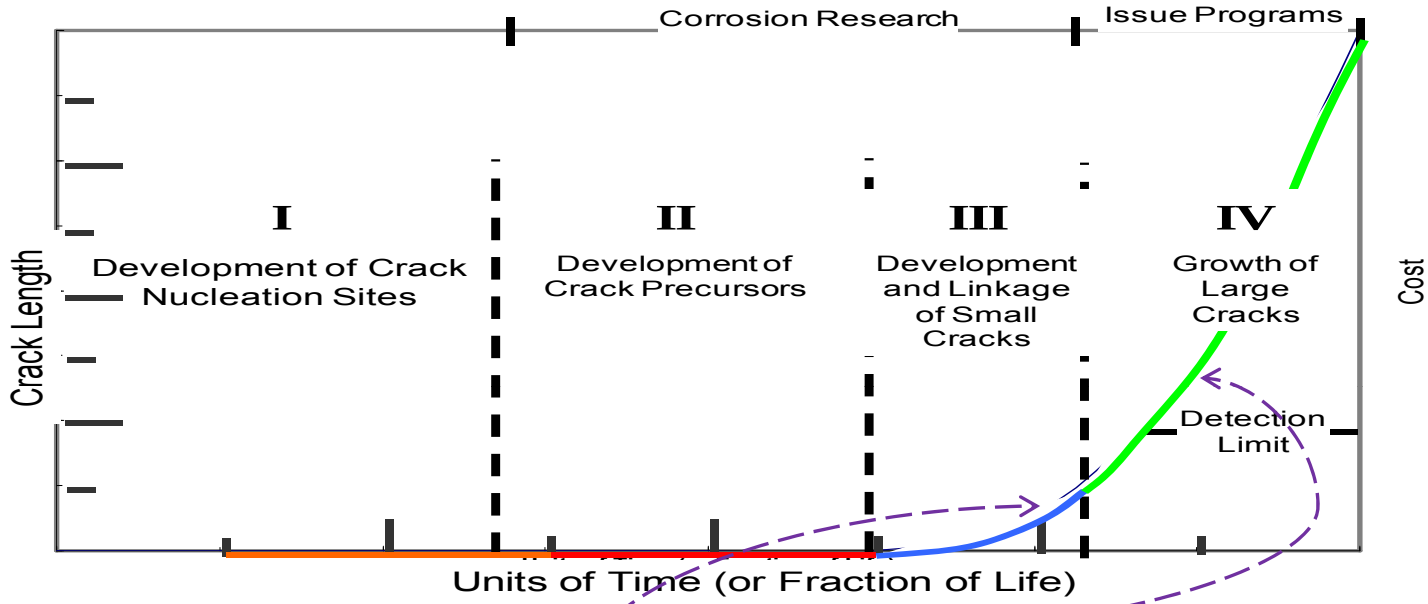
RISMC (DOE):
Passives reliability related to long-term NPP safety margins

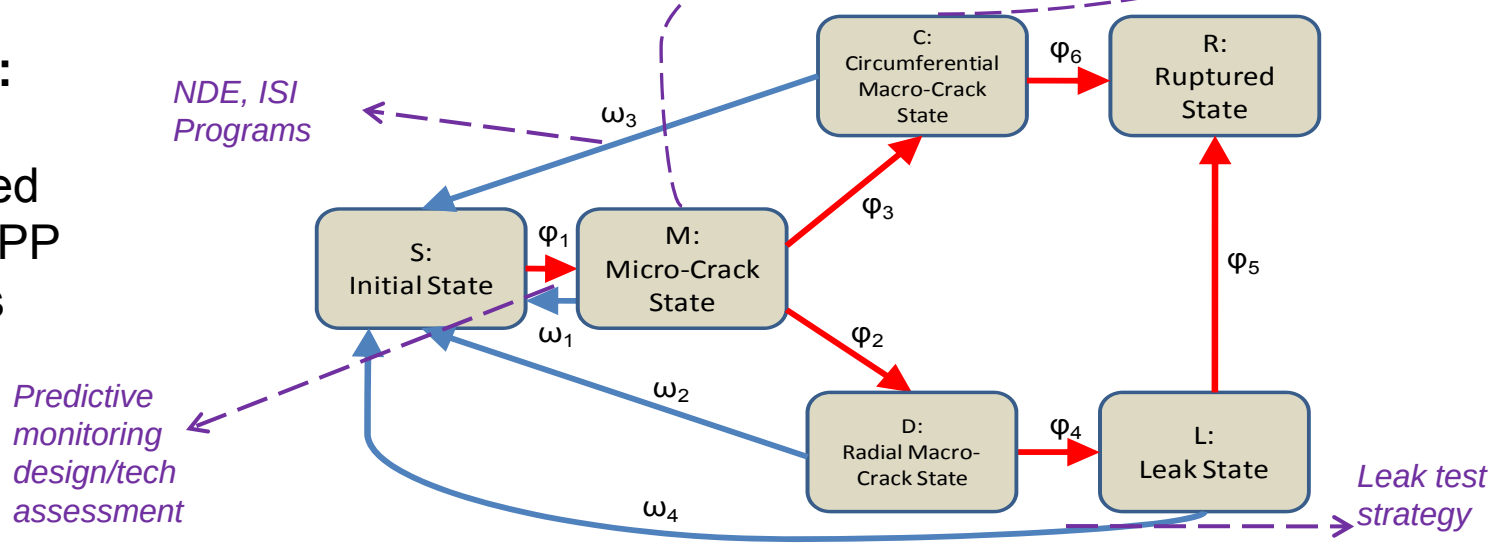


Complementarity of RISMC and NRC Proactive Management of Materials Degradation (PMMD) Program

PMMD (NRC):
Methods and technologies for materials flaw precursor detection and proactive intervention

RISMC (DOE):
Passives reliability related to long-term NPP safety margins





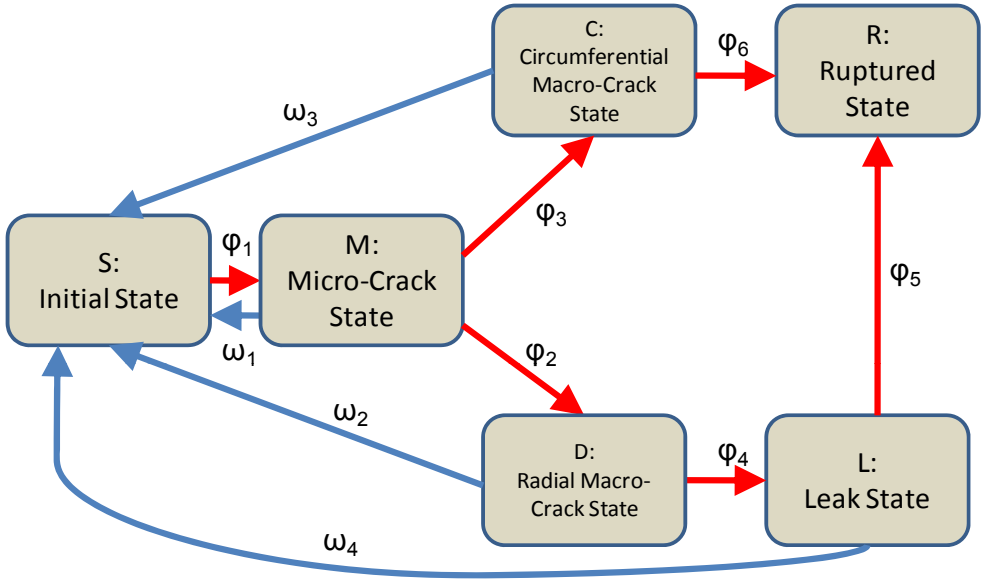
Summary: RISMC as Decision Framework for NPP Materials Management

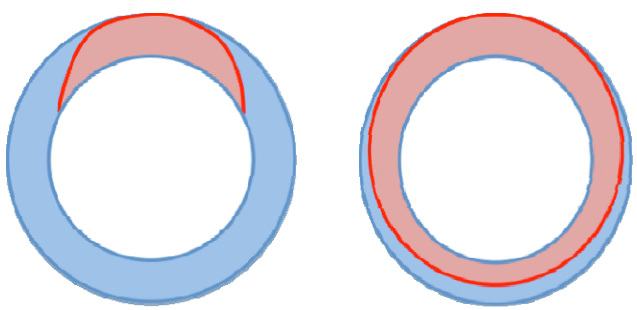
- Physics-driven models of component/materials reliability
  - Multiple-mechanism materials degradation models
  - Monitoring, flaw detection, and intervention strategies modeled
- R7 environment predicts lifetime physical stressors on materials
  - Key uncertainties
  - Feedback of materials/component performance on physical environment
- RISMC framework relates materials performance to long-term safety margins
  - Safety margin acceptability
  - Cost-benefit analysis of proactive management of materials degradation

BACKUP SLIDES

BACKUPS

RISMC: Initial Physics-Based Passives Multi-State Model – Stress Corrosion Cracking

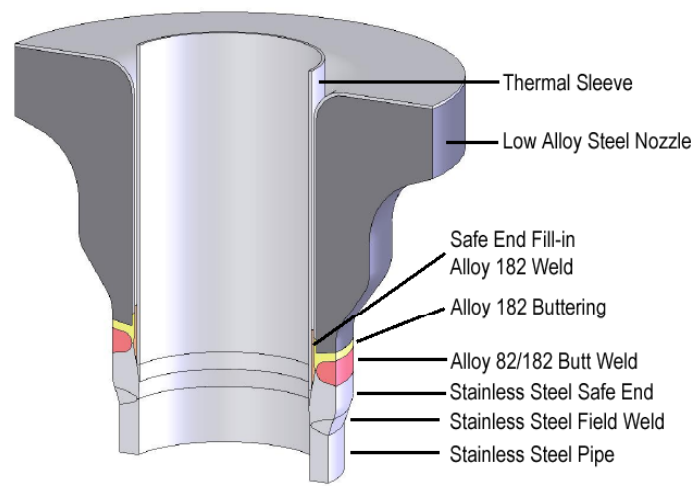




Crack Morphologies

<u>Pipe Component States</u>

S – success
M – micro-crack
C – circumferential macro-crack
D – radial macro-crack
L – leak
R – rupture



PWR surge line nozzle connection to the pressurizer (Courtesy of Westinghouse)

Initial Physics Models – Crack Initiation

- Weibull model of crack initiation
  - $P(t) = 1 - \exp[-(t/\tau)^b]$
    - t is time from last repair
    - T and b are physics-based Weibull parameters

$$\tau = A\sigma^n e^{\left(\frac{Q}{RT}\right)}$$

    - σ = stress factor, Q = activation energy, T= absolute temperature
  - EPRI TR-104030; NUREG/CR-6737

- Effective state transition rate to crack initiation:

$$\Phi_1 = \int (b/\tau) \cdot (t/\tau)^{b-1} \cdot \Pi(\tau, b)\, d\tau . db.$$

  - Π represents aleatory probability density

Initial Physics Models – Crack Growth

- Crack growth
  - EPRI MRP-115 model

$$\dot{a} = \alpha\, f_{alloy}\, f_{orient} K^{\beta}\, e^{\left[-\left(\frac{Q}{R}\right)\left(T^{-1} - T_{ref}^{-1}\right)\right]}$$

  - Relates rate of crack growth to crack tip stress intensity factor(K), thermal activation energy for crack growth (Q), operating temperature (T), and fitting factors

- Effective state transition rate to radial macro-crack formation:

$$\Phi_2 = \frac{(a_D/u^2)\,.\,\Pi\left(\frac{a_D}{u}\right).\,P_D}{P_C\left(1 - \int_{\frac{a_C}{u}}^{\infty} \Pi(\dot{a})\,.\,d\dot{a}\right) + P_D\left(1 - \int_{\frac{a_D}{u}}^{\infty} \Pi(\dot{a})\,.\,d\dot{a}\right)}$$

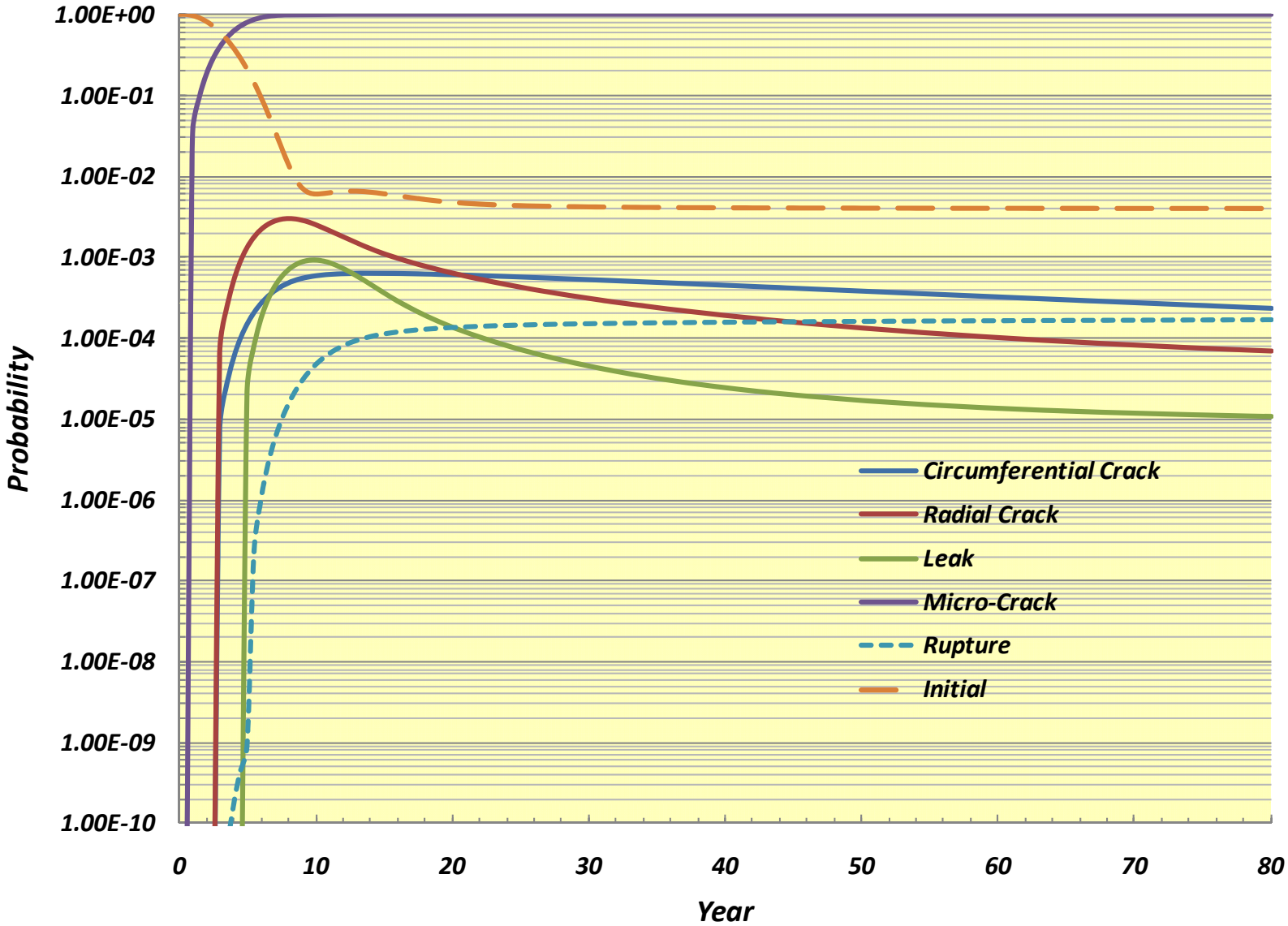
  - a_D , a_C = threshold macro-crack lengths (D=radial, C=circumferential), u is time from crack initiation, P_D , P_C = probabilities of given crack morphologies, and Π = aleatory distribution over crack growth rate

- Simplified models of other phenomenology

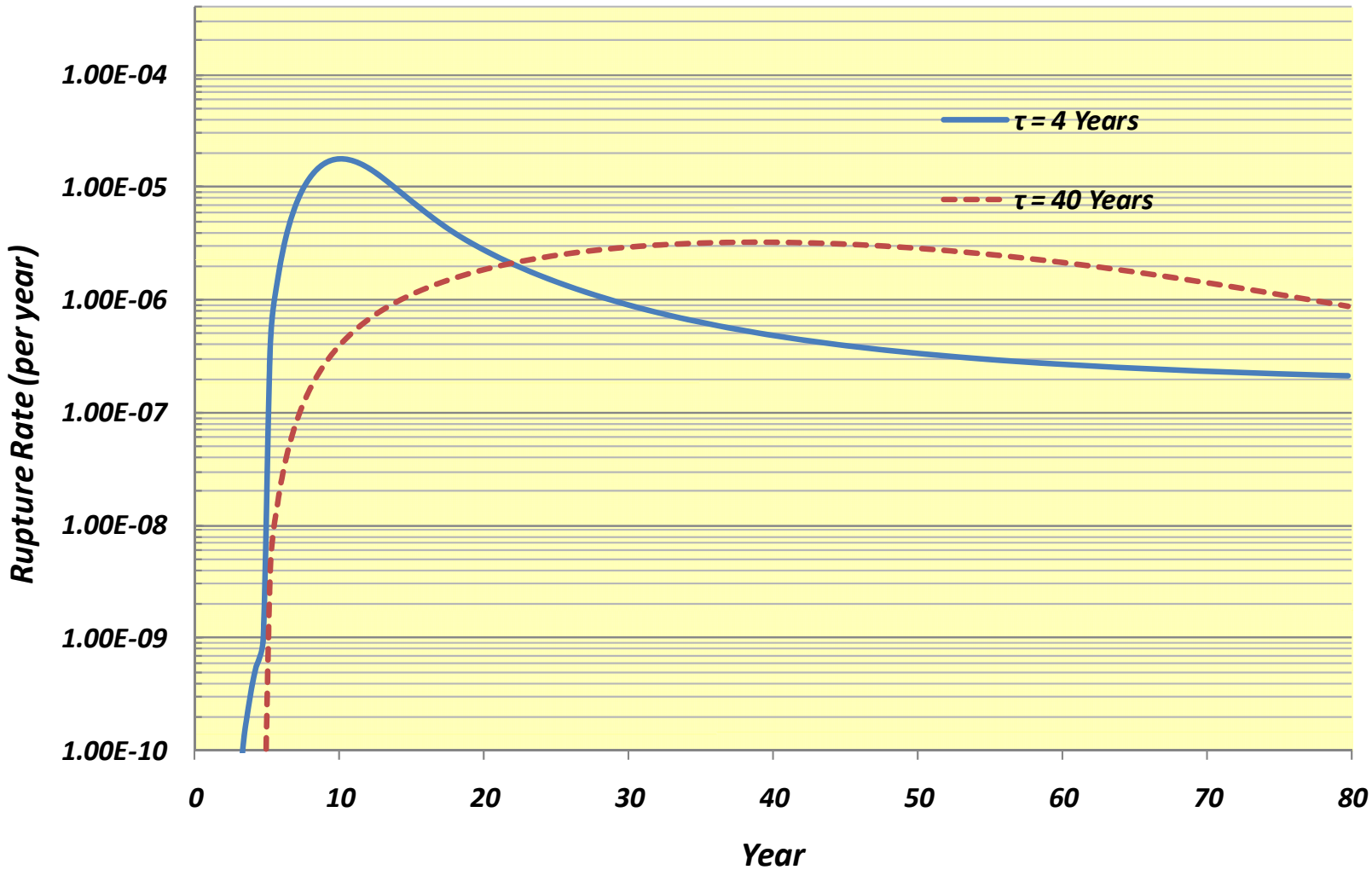
Solution Algorithms

- We have stochastic, time-inhomogeneous transition rates $\underline{\Phi}$
  - Not a Markov process
  - Not a semi-Markov process
- Use of *proportional hazards methodology*
  - Embed stochastic non-Markov process in stochastic Markov process
- State-space enrichment
  - Number of states in enriched space = original number (6) x number of discrete time steps (6 months per step)
  - Process becomes a Markov chain – solved numerically
- Solutions re-integrated in original 6-state space

Results – State Probabilities (τ = 4 years)



Results – Component Rupture Rates

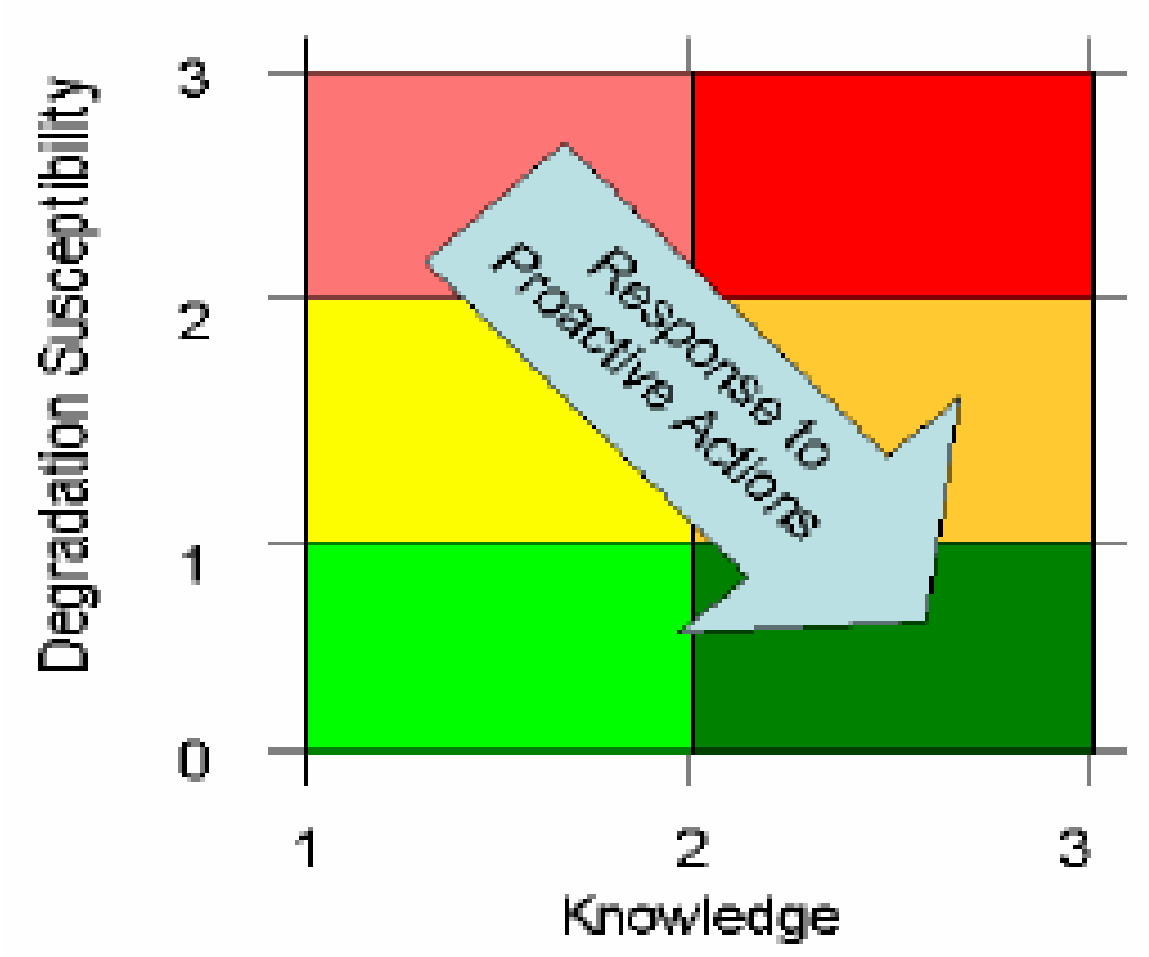


NRC PMMD: Degradation Modes

Abbreviation	Degradation Mechanism
BAC	Boric Acid Corrosion
CREEP	Thermal Creep
CREV	Crevice Corrosion (including denting)
DEBOND	De-bonding
EC	Erosion Corrosion Including Steam Cutting and Cavitation
FAC	Flow-accelerated Corrosion
FAT	Fatigue (corrosion/thermal/mechanical)
FR	Reduction of Fracture Resistance
GALV	Galvanic Corrosion
GC	General Corrosion
IC	Irradiation Creep
MIC	Microbially Induced Corrosion
PIT	Pitting Corrosion
SCC	Stress Corrosion Cracking (intergranular, transgranular, irradiation-assisted, strain-induced, hydrogen-embrittlement) and Intergranular Attack
SW	Swelling
WEAR	Fretting/Wear

From Carpenter, Hull, Shalik, 2008

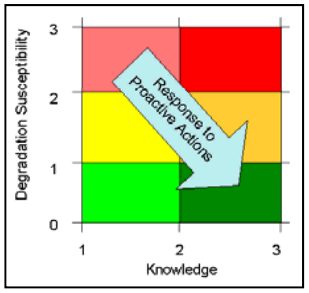
Color-Coding of Aggregate Scores



Proactive Materials Degradation Assessment – PIRT Expert Elicitation

Phase 3

Allow for identification of components for PMDM programs



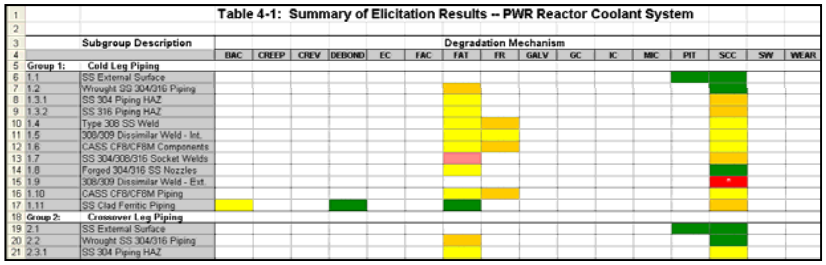
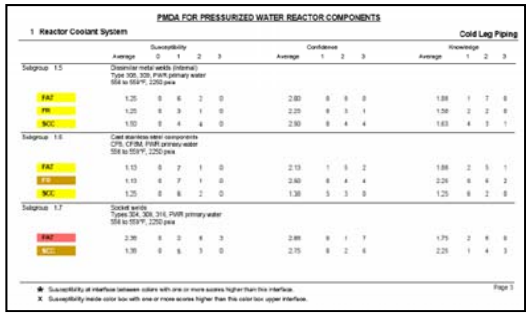


Table 4-1: Summary of Elicitation Results -- PWR Reactor Coolant System

		Subgroup Description	Degradation Mechanism														
			BAC	CREEP	CREV	DEBOND	EC	FAC	FAT	FR	GALV	GC	IC	MIC	PIT	SCC	SW	WEAR
5	Group 1:	Cold Leg Piping																
6	1.1	SS External Surface																
7	1.2	Wrought SS 304/316 Piping																
8	1.3.1	SS 304 Piping HAZ																
9	1.3.2	SS 316 Piping HAZ																
10	1.4	Type 308 SS Weld																
11	1.5	308/309 Dissimilar Weld - Int.																
12	1.6	CASS CF8/CF8M Components																
13	1.7	SS 304/308/316 Socket Welds																
14	1.8	Forged 304/316 SS Nozzles																
16	1.9	308/309 Dissimilar Weld - Ext.																
15	1.10	CASS CF8/CF8M Piping																
17	1.11	SS Clad Ferritic Piping																
18	Group 2:	Crossover Leg Piping																
19	2.1	SS External Surface																
20	2.2	Wrought SS 304/316 Piping																
21	2.3.1	SS 304 Piping HAZ																



PMDA FOR PRESSURIZED WATER REACTOR COMPONENTS

1 Reactor Coolant System — Cold Leg Piping

	Subgroup	Susceptibility Average	Susceptibility 0	Susceptibility 1	Susceptibility 2	Susceptibility 3	Confidence Average	Confidence 1	Confidence 2	Confidence 3	Knowledge Average	Knowledge 1	Knowledge 2	Knowledge 3
	1.5 Dissimilar metal welds (internal) Type 308, 309, PWR primary water 554 to 559°F, 2250 psia													
FAT		1.25	0	6	2	0	2.80	0	0	0	1.88	1	7	0
FR		1.25	0	3	1	0	2.25	0	3	1	1.50	2	2	0
SCC		1.50	0	4	4	0	2.50	0	4	4	1.63	4	3	1
	1.6 Cast stainless steel components CF8, CF8M, PWR primary water 554 to 559°F, 2250 psia													
FAT		1.13	0	7	1	0	2.13	1	5	2	1.88	2	5	1
[illegible]		1.13	0	7	1	0	2.50	0	4	4	2.25	0	6	2
SCC		1.25	0	6	2	0	1.38	5	3	0	1.25	0	2	0
	1.7 Socket welds Types 304, 308, 316, PWR primary water 554 to 559°F, 2250 psia													
FAT		2.38	0	3	0	3	2.88	0	1	7	1.75	2	0	0
SCC		1.38	0	5	3	0	2.75	0	2	6	2.25	1	4	3

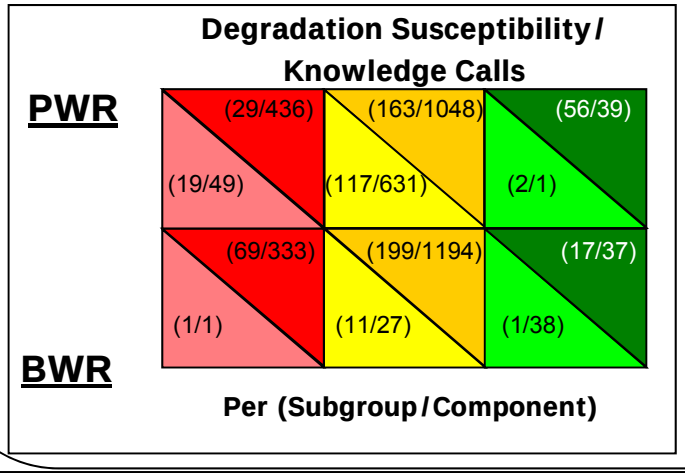
★ Susceptibility at interface between colors with one or more scores higher than this interface.
X Susceptibility inside color box with one or more scores higher than this color box upper interface.

Page 1

Phase 4

Identify Research Needs to Allow for PMDM

- Generic
- Component Specific



For **PWR** Evaluation:

- Started with 48 subsystems containing 2203 components
- Agglomerated into 392 subgroups
- Conducted 1222 assessments (per expert) for various mechanisms and subgroups

For **BWR** Evaluation:

- Started with 28 subsystems containing 1660 components
- Agglomerated into 297 subgroups
- Conducted 1322 assessments (per expert) for various mechanisms and subgroups

From G. Carpenter et al., 2008