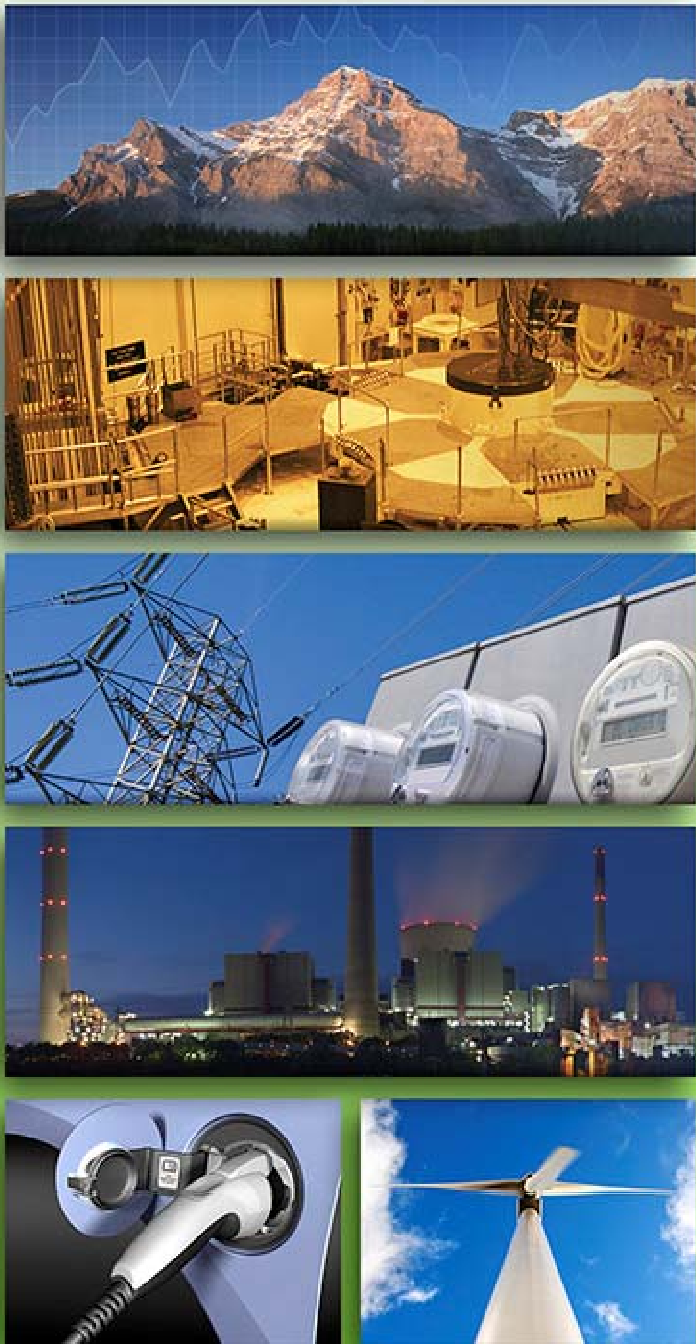

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Materials Degradation Matrix and Issue Management Tables Overview - LTO Update

Robin Dyle

Technical Executive, EPRI

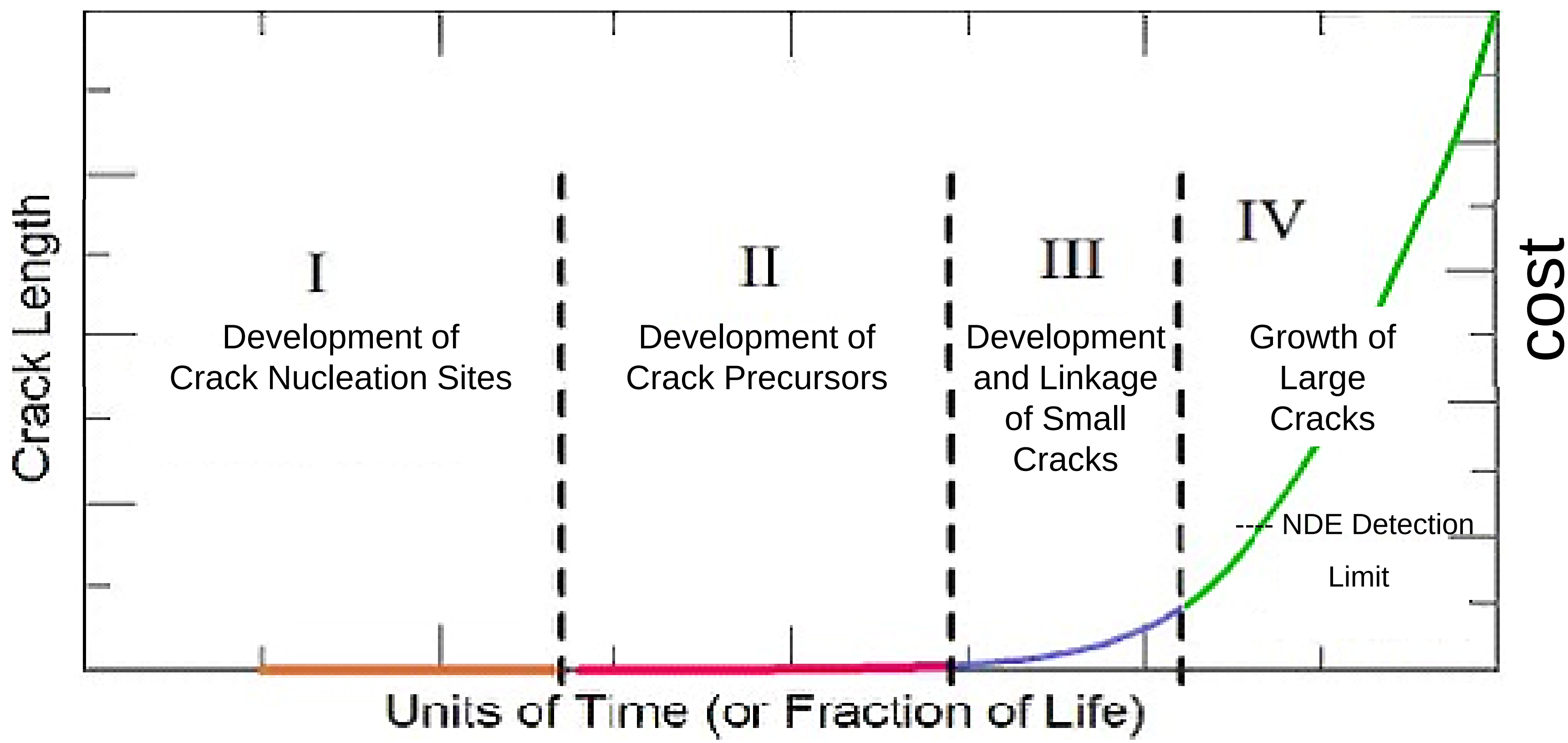
LB60 Workshop

February 23, 2011

Introduction

- Materials Aging Management is Critical to Long Term Operation
- Affects Almost All Nuclear Systems
- Must be Addressed Proactively
- Major Focus of EPRI Programs
  - **Primary Pressure Boundary (metallic)**
  - Nondestructive Examination – early detection
  - Cables
  - Concrete

Stages of Environmentally-Assisted Cracking



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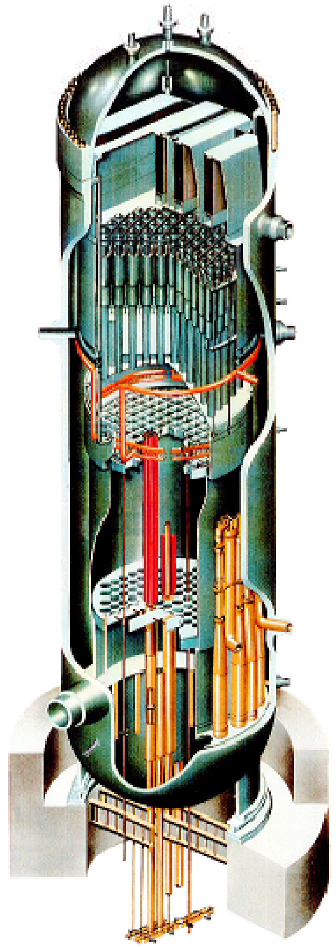
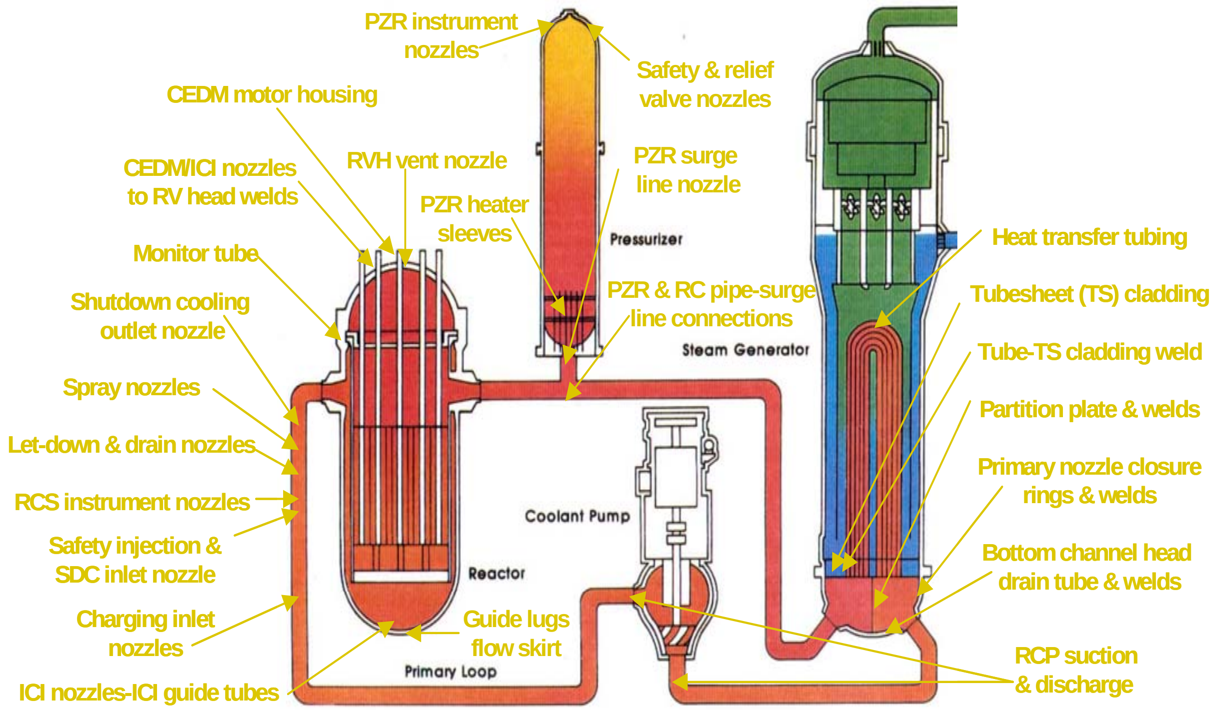
BWR and PWR, Materials Program Focus





NEI 03-08 Materials Initiative Expectations

- The body of materials work conducted across the industry will be *forward-looking* and *coordinated*, resulting in *fewer unanticipated issues* that could consume an inordinate level of resources and divert focus from an *orderly approach to managing materials*

- This initiative will enhance the issue programs' ability to rapidly identify, react and effectively respond to emerging issues

- **Every utility** will fully participate in the implementation of the materials management activities applicable to its plants

Integrated Materials Issues Strategic Plan

- Provides Systematic Approach to Managing Materials Issues
  - Identify vulnerabilities
  - Assess condition (inspect & evaluate)
  - Mitigate degradation initiation and propagation mechanism
  - Repair or replace as required
- Approach Used:
  - Degradation Matrix and Issue Management Tables
    - Degradation Matrix and Issues Management Tables to be maintained as living documents

Industry Materials Degradation and Issue Management Table Approach

MDM

- **Develop a fundamental understanding of the degradation phenomena/mechanisms**

IMTs

- **Perform operability and safety assessments**
- **Develop Inspection and evaluation guideline**
- **Evaluate available mitigation options**
- **Develop repair & replace options**
- **Monitor and assess plant operation experience**
- **Obtain regulatory acceptance**

Materials Degradation Matrix (MDM) and Issue Management Tables (IMT) are effective materials aging management tools in support of industry's Materials Degradation and Issue Management Initiative

Materials Degradation Matrix (MDM)

Materials Degradation Matrix (MDM) Revision 1

- MDM provides a comprehensive listing of potential degradation mechanisms for existing LWR primary system components
- Assesses the extent to which applicable degradation mechanisms are understood
- Evaluates the state of industry knowledge worldwide associated with mitigation of applicable degradation mechanisms
- Documents the results of an expert elicitation process
- Proactively identifies potential challenges to avoid surprises

MDM Revision 1 Strategic Issues

- Environmental Effects on Fracture Resistance
- Environmental Effects on Fatigue Life
- SCC of Ni-Base Alloys
- SCC of Stainless Steels
- Effect of Fluence on SCC Susceptibility and SCC Crack Growth Rates

NRC PMDA reached the same conclusions

2010 MDM Revisions

2010 Revisions of the MDM (Rev. 2) address:

- 80-year operations (Long-Term Operations or “LTO”)
- Updates on identifying degradation mechanisms
- Recent operating experience
- Industry progress in addressing LWR materials issues
- Most Gaps revised to keep contents up to date

Expert Elicitation

- **2010 MDM expert panel meeting held in Feb at EPRI - Palo Alto offices. Focus Included:**
  - Long-Term Operations - “LTO” (*2^{nd} 20-year license renewal term)*
  - Recent research program results

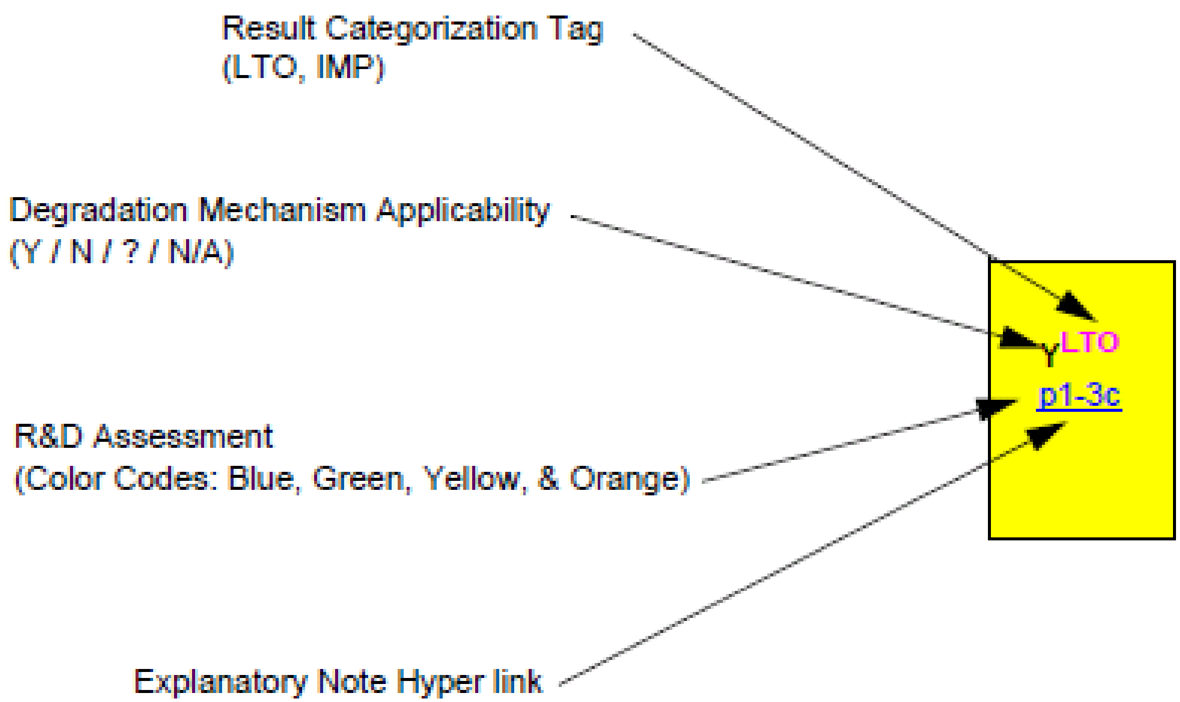
<u>Expert panel</u>:

  - Vendors/Industry Experts
    - Scott, Andresen, Sandusky, Fyfitch, Lott, Horn, Lunceford
  - Utilities
    - Armson, Covill, Kammerdeiner, Shaw, Whitaker, Wirtz,
  - NRC and DOE observers
  - EPRI PMs & Contractors (Marks, Eaker)

Identify Strategic Issues in Materials Degradation

- **Major LTO issues:**
  - Increased EOL Neutron Fluence
    (*RPV integrity, high fluence effects on austenitic SS, expanded regions of neutron effects*)
  - Increased Fatigue Cycles (*with focus on environmental effects*)
  - Late-Life SCC Initiation and Stress Improvement Technique Stability
  - Steam Generator Fouling / Corrosion / Long-Term Management
- **Other major issues:**
  - Effect of environment on fracture properties
  - SCC initiation factors (*cold work, welding effects, PWR system oxygen ingress*)

Color Chart Presentation of MDM Results



Blue	lack of data to establish degradation applicability
Green	well characterized, little or no additional research is needed
Yellow	ongoing R&D efforts to resolve uncertainties in near-term time frame
Orange	insufficient R&D to resolve uncertainties in a near-term time frame

MDM Results---- PWR Reactor Internals

Table 3-2 PWR Reactor Vessel Internals

	DEGRADATION MODE													
	SCC		Corrosion				Wear	Fatigue		Reduction in Fract Properties		Irradiation Effects		
MATERIAL	IG/TG	IA	Wstg.	Pitting	FAC	Foul	Wear	HC	LC-Env.	Th.	Env.	Emb.	VS	IC / SR
SS: 300 Series Base Metal	Y^{LTO} p2-1a	Y^{LTO} p2-2a	N	N	N	N	Y^{IMP} p2-7a	Y^{LTO} p2-8a	Y^{LTO} p2-9a	N	Y^{LTO} p2-11a	Y^{LTO} p2-12a	Y^{LTO} p2-13a	Y^{LTO} p2-14a
SS: 300 Series Welds & Clad	Y^{LTO} p2-1b	Y^{LTO} p2-2b	N	N	N	N	N	Y^{LTO} p2-8b	Y^{LTO} p2-9b	Y^{LTO} p2-10b	Y^{LTO} p2-11b	Y^{LTO} p2-12b	Y^{LTO} p2-13b	Y^{LTO} p2-14b
CASS	Y^{LTO} p2-1c	$?^{LTO}$ p2-2c	N	N	N	N	N	Y p2-8c	Y^{LTO} p2-9c	Y^{IMP} p2-10c	Y^{LTO} p2-11c	Y^{LTO} p2-12c	N .	N .
Ni-Alloy: Base Metal (A600)	Y^{IMP} p2-1d	N	N	N	N	N	Y^{IMP} p2-7d	Y p2-8d	Y^{LTO} p2-9d	N	Y p2-11d	N .	N .	N .
Ni-Alloy: X-750	Y^{LTO} p2-1f	$?^{LTO}$ p2-2f	N	N	N	N	Y p2-7f	Y^{LTO} p2-8f	Y^{LTO} p2-9f	N	Y^{LTO} p2-11f	$?^{LTO}$ p2-12f	N .	N .
SS: Precip. Hardened (A-286)	Y^{LTO} p2-1g	Y^{LTO} p2-2g	N	N	N	N	Y^{LTO} p2-7g	Y^{LTO} p2-8g	Y^{LTO} p2-9g	Y^{LTO} p2-10g	$?^{LTO}$ p2-11g	Y^{LTO} p2-12g	N	Y^{LTO} p2-14g
SS: Martensitic	Y^{LTO} p2-1h	N	N	N	N	N	Y p2-7h	Y p2-8h	Y^{LTO} p2-9h	Y^{LTO} p2-10h	? p2-11h	N	N	N

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MDM Results for PWR: – Neutron Irradiation Effects

Low Alloy Steels

2008	2010	LTO
Irradiation embrittlement	Irradiation embrittlement	Irradiation embrittlement

Austenitic Stainless Steels

2008	2010	LTO
–IASCC –Irradiation embrittlement –Void swelling	–IASCC –Irradiation embrittlement –Void swelling	–IASCC –Irradiation embrittlement –Void swelling

High Strength Stainless Steels and Alloy X-750

	2008	2010	LTO
A-286	–IASCC –Irradiation embrittlement	–IASCC –Irradiation embrittlement	–IASCC –Irradiation embrittlement
X-750			–IASCC –Irradiation embrittlement

MDM Results for PWR: – Environmental Effects on Fatigue Life and Fracture Toughness, Thermal Aging

Environmental Effects on Fatigue Life

2008	2010	LTO
Environmental fatigue	Environmental fatigue	Environmental fatigue

Embrittlement due to Thermal Aging

Materials	2008	2010	LTO
690/52/152	Thermal aging	Thermal aging	
CASS	Thermal aging	Thermal aging	

Environmental Effects on Fracture Property

Materials	2008	2010	LTO
SS Base Metal	Loss Fracture Resistance	Loss Fracture Resistance	Loss Fracture Resistance
SS Weld & Clad	Loss Fracture Resistance	Loss Fracture Resistance	Loss Fracture Resistance
CASS	Loss Fracture Resistance	Loss Fracture Resistance	Loss Fracture Resistance
Ni-Alloys	Loss Fracture Resistance	Loss Fracture Resistance	

MDM Results---- BWR Reactor Internals

Table 4-2 BWR Reactor Vessel Internals

MATERIAL	DEGRADATION MODE													
	SCC		Corrosion				Wear	Fatigue		Reduction in Fract Properties		Irradiation Effects		
	IG/TG	IA	Wstg.	Pitting	FAC	Foul	Wear	HC	LC-Env.	Th.	Env.	Emb.	VS	IC / SR
SS: Wrought / Forged	Y^{LTO} b2-1a	Y^{LTO} b2-2a	N	N	N	Y b2-6a	Y^{IMP} b2-7a	Y^{IMP} b2-8a	Y^{LTO} b2-9a	N	Y^{LTO} b2-11a	Y^{LTO} b2-12a	N	Y^{IMP} b2-14a
SS: Welds & Clad	Y^{LTO} b2-1b	Y^{LTO} b2-2b	N	N	N	Y b2-6b	Y^{IMP} b2-7b	Y^{IMP} b2-8b	Y^{LTO} b2-9b	Y b2-10b	$?^{LTO}$ b2-11b	Y^{LTO} b2-12b	N	Y b2-14b
CASS	Y^{LTO} b2-1c	Y^{LTO} b2-2c	N	N	N	N	N	Y^{IMP} b2-8c	Y^{LTO} b2-9c	Y^{IMP} b2-10c	$?^{LTO}$ b2-11c	Y^{LTO} b2-12c	N	N
Ni-Alloy: Wrought (A600)	Y^{LTO} b2-1d	N	N	N	N	N	N	Y^{IMP} b2-8d	Y^{LTO} b2-9d	N	Y b2-11d	N	N	N
Ni-Alloy: Welds & Clad (A82/182)	Y^{LTO} b2-1e	N^{LTO}	N	N	N	N	N	Y^{IMP} b2-8e	Y^{LTO} b2-9e	N	Y^{LTO} b2-11e	N	N	N
X-750	Y^{LTO} b2-1f	Y^{LTO} b2-2f	N	N	N	N	N	Y^{IMP} b2-8f	Y^{LTO} b2-9f	N	Y^{LTO} b2-11f	Y^{LTO} b2-12f	N	Y^{LTO} b2-14f
XM-19	Y^{LTO} b2-1g	Y^{LTO} b2-2g	N	N	N	N	N	Y^{IMP} b2-8g	Y^{LTO} b2-9g	N	$?^{LTO}$ b2-11g	Y^{LTO} b2-12g	N	Y^{LTO} b2-14g

MDM Results for BWR: – SCC & Neutron Irradiation Effects

SCC of Low Alloy RPV Steels

2008	2010	LTO
IG/TG	IG/TG	IG/TG

SCC of Austenitic Stainless Steels

2008	2010	LTO
IG/TG	IG/TG	IG/TG

Irradiation effects on Low Alloy Steels

2008	2010	LTO
IASCC	IASCC	IASCC
Irradiation embrittlement	Irradiation embrittlement	Irradiation embrittlement

Irradiation effects on Austenitic Stainless Steels

2008	2010	LTO
IASCC	IASCC	IASCC
Irradiation embrittlement	Irradiation embrittlement	Irradiation embrittlement

Irradiation effects on X-750 & X-19 (High Strength)

2008	2010	LTO
IASCC	IASCC	IASCC
Irradiation embrittlement	Irradiation embrittlement	Irradiation embrittlement

MDM Results for BWR: – Fatigue & Fracture Toughness

Fatigue

Environmental Effects on Fatigue Life

2008	2010	LTO
Lo-C Env.	Lo-C Env.	Lo-C Env.

High-C Thermal Fatigue of BWR Piping

2008	2010	LTO
Hi-C Fat.	Hi-C Fat.[IMP]	

Reduction in Fracture Properties

Thermal Aging of CASS

2008	2010	LTO
Thermal aging	Thermal aging	

Environmental effects on Fracture Toughness

	2008	2010	LTO
SS	RiFP-Env	RiFP-Env	RiFP-Env
Ni-Alloys	RiFP-Env	RiFP-Env	

Issue
Management Tables

Issue Management Table(s)

- Failure Consequences Evaluation Basis
  - Component failures considered in the IMT may be beyond current design or licensing basis. All reasonably postulated events will be considered, solely to establish relative importance of postulated failures. No new design bases will be implied by the failures considered.
- An adverse consequence is failure of a component that results in one or more of the following:
    - Inability to come to safe shutdown
    - Precludes maintenance of coolable core geometry
    - Loss of core cooling effectiveness
    - Loss of reactivity control
    - Reduction/elimination of critical Instrumentation availability
    - Causes a design basis accident
    - Significant economic impact
    - Significant on-site/off-site radiation release
    - Jeopardy to personnel safety
    - Breach of the reactor coolant system pressure boundary
    - Breach of the fuel cladding

PWR IMT Update

- **Product issued as MRP-205, Rev 2 (1021024)**
- 76 Currently Open Gaps (total same as for Rev 1)
  - 16 new R&D gaps identified
    - Majority tied to consideration of longer service life (>60 years)
    - 1 High Priority, 5 Medium Priority, and 10 Low Priority
      - High Priority = P-I&E-22 – "Appendix VIII Compliance"
  - 16 previous R&D gaps closed
  - 30 High Priority Items (7 elevated from Medium plus 1 new)

Example IMT – PWR

Table A-1
Issue Management Table: PWR Reactor Pressure Vessel

Component & ID No.	Material	Degradation Mechanism[1]	Conseq. of Failure	Mitigation[2]	Repair / Replace	I & E Guidance	Gaps
1.1 Upper Shell Assembly							
1.1-1 Upper Shell Flange (Vessel Flange)	C&LAS/ SS Clad *(SA-336 or A/SA-508, Cl 2 or 3)*	SCC: IG, IA, TG, LTCP, PW C&W: Wstg, Wear Fat: LC/Th, Env RiT: Th, Emb, Fl	A, B, E, F, G	**Water Chemistry** TR-105714, *Primary Water Chemistry*	**ASME Sect. XI** IWA-4000	**Boric Acid Corrosion Control** EPRI: 1000975, *BAC Handbook* Vendor: WCAP-15988-NP, *BAC Prog.* NRC: GL 88-05 **LC / Env. Fatigue Management** EPRI: MRP-148, *Fatigue Mgmnt.* MRP-149, *Lic. Basis Mon.* MRP-47, *Fatigue Env. Effects* NRC: GALL X.M1, *Fatigue Mon.* NUREGs 6260 & 6583 **ASME Code Sect. XI** IWB-2500-1: *B-A (Vol)–R.G. 1.150* *B-P (VT-2)*	DM-01 DM-02 AS-02 AS-27

Example Gap Description – PWR

Table 3-2
Degradation Mechanism Understanding Gaps

R&D Gap Description	Applicable Components
DM-01 - Environmentally Assisted Cracking: LAS Develop an improved understanding regarding the potential for environmentally assisted cracking of clad LAS materials (IGSCC, TGSCC, PWSCC) in the primary water environment. Some of the concern is related to cracking of LAS materials exposed to the CANDU reactor heavy water environment, but to date there have been no documented instances of environmentally assisted cracking of any domestic PWR. Currently, there is wide scatter in the laboratory data for stress corrosion crack propagation in low alloy steels, likely due to differences in the experiment assumptions and structure. Basis: MDM: e002, e003 EPRI: TR-103160 (BWR Environment), NP-7473-L, TR-102796, TR-102692	RESULTS DATA: Priority: LOW Resp. Program: To be determined per NEI 03-08 Summary Level Applicability: RPV Pressurizer SG Shell ASME Class 1 Ppg., Vlvs., Fittings

PWR LTO Summary

- Neutron Fluence Effects
  - RPV embrittlement
  - SS materials data for >60 years
    - Threshold stress
    - Reduction in toughness
    - Void swelling
  - Impact on core periphery materials
- Fatigue Usage
- Steam Generator Corrosion Limits
  - FAC impact
  - Number of cleaning cycles

BWR IMT Update

- **Product issued as BWRVIP-167NP, Rev 2 (1020995)**
- 45 Currently Open Gaps (3 less than for Rev 1)
  - 10 new R&D gaps identified
    - Majority tied to consideration of longer service life (>60 years)
    - 3 High Priority, 4 Medium Priority, and 3 Low Priority
      - High Priority = B-AS-29 “Steam Dryer Evaluation Methodology”
  - 13 previous R&D gaps closed
- 18 High Priority Items (4 elevated from Medium plus 3 new)

Example IMT – BWR

Table A-2 (continued)
Reactor Vessel Internals

Component & ID No.	Material	Degradation Mechanism[1]	Conseq. of Failure	Mitigation[2]	Repair / Replace	I & E Guidance	Gaps & Priority
2.9 Shroud							
2.9–1 Shroud Cylinders *(Includes Welds H1–H7 and Shroud Vertical Welds)*	SS *(304, 304L)*	IGSCC *(e103)* IASCC / Neutron Emb. *(e045, e116)* TGSCC *(e104)* Env. Fatigue *(e014)*	Loss of Support / Orientation Loss of Flow Distribution	**Chemistry Control** BWRVIP–130 *(BWRVIP 2005–168)* **HWC / NMCA** BWRVIP–62 *(Some locations not mitigated by HWC / NMCA)*	**EPRI BWRVIP** BWRVIP–02–A *(RDC)*	**EPRI BWRVIP** BWRVIP–76	DM-02: *SCC of "Resistant" SS* AS-01: *RAMA Code* AS-09: *Fluence Impact on CGR/Fract Tough* AS-10: *HWC / NMCA Impact on CGRs* AS-11: *Assess Fast Reactor Data* AS-14: *Fat. Environ. Eff.* MT-01: *Alt. Mitigation Technology* MT-02: *ECP Model* MT-03: *High Fluence Eff. on NMCA / HWC* MT-04: *On-Line NMCA* MT-05: *Startup & Shutdown Chem.* MT-06: *NMCA Durab. & Long Term Effect* RR-02: *Weld Process for Irrad. Matl*

Example Gap Description – BWR

AS-09 - Assess Impact of High Fluence & NMCA/HWC on CGRs & Fracture Toughness	
BWRVIP-99 provides correlations to determine the crack growth rates for irradiated stainless steel. Data used to develop these crack growth rate correlations for irradiated stainless steels is based on research conducted prior to the early 1990s. There are gaps in the data. In some cases it is not possible to determine if the correlations are overly conservative or non-conservative. As BWR internals continue to accumulate radiation damage, data at high fluence is needed to ensure that the predictions are appropriate and accurate for structural integrity assessments. Without this information, NRC may impose very conservative criteria for evaluation of flaws which can result in premature installation of repairs. Furthermore, the effect of HWC / NMCA on crack growth rates at high fluences (>$3x10^{20}$ n/cm^2) are not well understood because of limited data. Additional investigations and data are needed to better understand the effect of high fluence and HWC / NMCA on crack growth rates. The NRC SER on the BWRVIP-14 crack growth model limits its application to a fluence of < $5x10^{20}$ n/cm^2. H4 welds in some plants will exceed this limit before end of life. Additional data is needed to demonstrate that HWC or NMCA will effectively mitigate cracking in highly irradiated material. In the absence of additional data, the NRC may not allow inspection relief for highly irradiated welds which are currently not covered by BWRVIP-62. Ongoing work to resolve this gap includes crack growth rate and fracture toughness tests performed under both NWC and HWC conditions. Post test fractography will be conducted to determine the fracture mode. Microstructure and micro-chemical evaluation will be performed to analyze grain boundary profiles and chemical compositions. Basis: BWRVIP: BWRVIP-62, BWRVIP-99, BWRVIP-14, 2006 Work Plan (Tasks 2.9 & 2.10) MDM: a045	RESULTS DATA: Priority: HIGH Resp. Program BWRVIP Assessment BWRVIP Mitigation Summary Level Applicability: RVI (A-2)

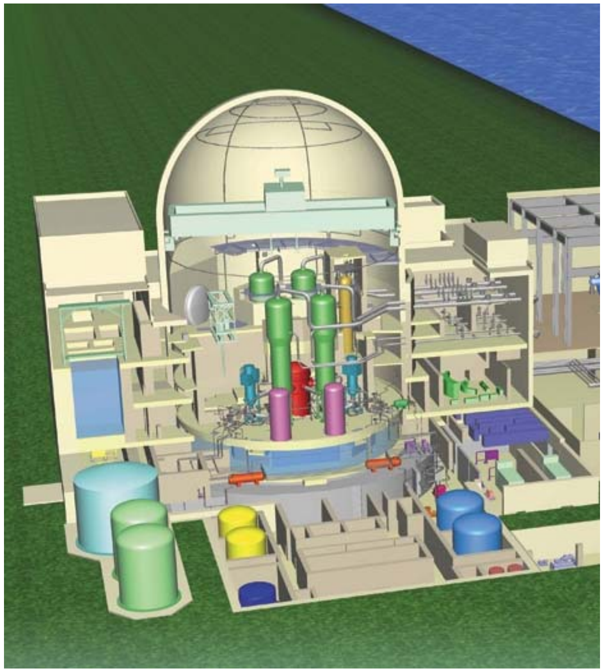
BWR LTO Summary

- Neutron Fluence Effects
  - RPV embrittlement
  - Irradiation effects on LAS resistance to environmetally assisted cracking
  - SS materials data for >60 years
  - Impact on CASS reactor internals
  - Impact on nickel alloys
  - Irradiated material welding
- Fatigue Usage
- Late-life SCC Initiation
  - Impact of oxide formation/environment exposure

Examples

Presentation on Industry Strategic Plan for Primary Metals Research

- Environmentally Assisted Stress Corrosion Cracking (EASCC)
- Irradiation Assisted Stress Corrosion Cracking (IASCC)
- Reactor Pressure Vessel (RPV) Embrittlement

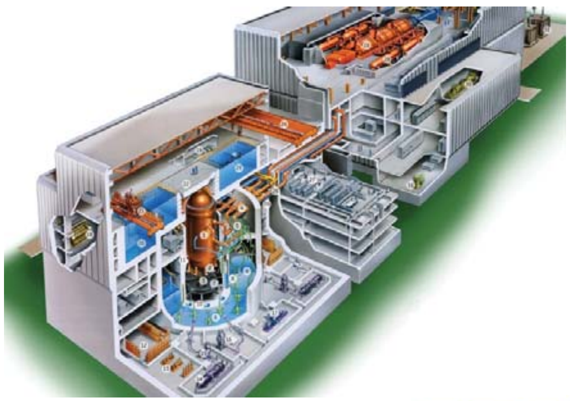


Environmentally-Assisted Stress Corrosion Cracking (EASCC)

- Evaluation of Crack Initiation and Propagation Mechanisms in LWR Components
  - EASCC Knowledge Base for Long-Term Operations (periodic, 2012-2020)
  - Crack Growth Prediction Model (target 2016)
  - Mitigation Strategies for EA Crack Initiation and Growth (target 2017)
  - Crack Initiation Prediction Model (target 2019)

Irradiation Assisted Stress Corrosion Cracking (IASCC)

- Identifying Mechanisms and Mitigation Strategies for Irradiation Assisted Stress Corrosion Cracking of Austenitic Steels in LWR Core Components
  - IASCC Knowledge Base for Long Term Operations (target 2014 and then periodic)
  - Parametric Correlations for Crack Initiation and Growth and Mitigation Strategies (target 2014)
  - Report on IASCC Resistant Materials for Repair and Replacement (target 2018)



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Reactor Pressure Vessel Embrittlement

- Reactor Pressure Vessel Embrittlement
  - Report on Revisions to Embrittlement Trend Correlation (target 2014)
  - Ongoing Material Testing and Evaluations
    - Late-blooming Effects (target 2016)
  - Support for Demonstration Project Deliverables:
    - Draft Reactor Embrittlement Analysis and Validation Plan to 80 Years (target 2012)
    - Gap Analysis and Feasibility Study of Plan for Ginna and Nine Mile Point Unit 1 (target 2012)
    - Demonstration of Plan Elements for Ginna and Nine Mile Point Unit 1 (target 2013)

Summary (1)

- MDM Revision-2 has updated the understanding of the potential materials degradation mechanisms for primary circuit components, in the context of 80-year operation
- The identified major LTO degradation mechanisms in primary system materials include: the increased end-of-life neutron fluence, increased fatigue cycles, late-in-life SCC initiation, long-term stress stability, and steam generator fouling/corrosion
- Both PWR and BWR Issue Management Tables (IMTs) have incorporated the MDM results at a component level and from an operational significance perspective

Summary (2)

- Primary Metals Research is In Progress to Address LTO Issues for EASCC, IASCC and RPV Embrittlement

- Research Efforts Encompass Worldwide Organizations

- Formal Periodic Reporting Expected to Frame Results and Support Decision Making

Publication of EPRI MDM and IMTs

- EPRI MDM Rev-2, EPRI Report # 1020987
- BWR and PWR IMTs have been updated to reflect MDM extension to 80 years
  - BWR-167NP, Rev-2, EPRI Report # 1020995
  - MRP-205, Rev-2, EPRI Report # 1021024
- Available at www.epri.com

Contact: *TG Lian, tlian@epri.com; (650) 855-2405*
Robin Dyle, rdyle@epri.com; (205) 426-5371

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