US Nuclear Electric Power Generation Industry Management of Age Related Degradation

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Underlying Premise and Challenge for Materials Programs

Primary system materials integrity vital to plant performance and reliability

Reactor components operate in a harsh environment (temperature, stress, radiation, etc.)

Aging of plant system materials is complex and not always fully understood

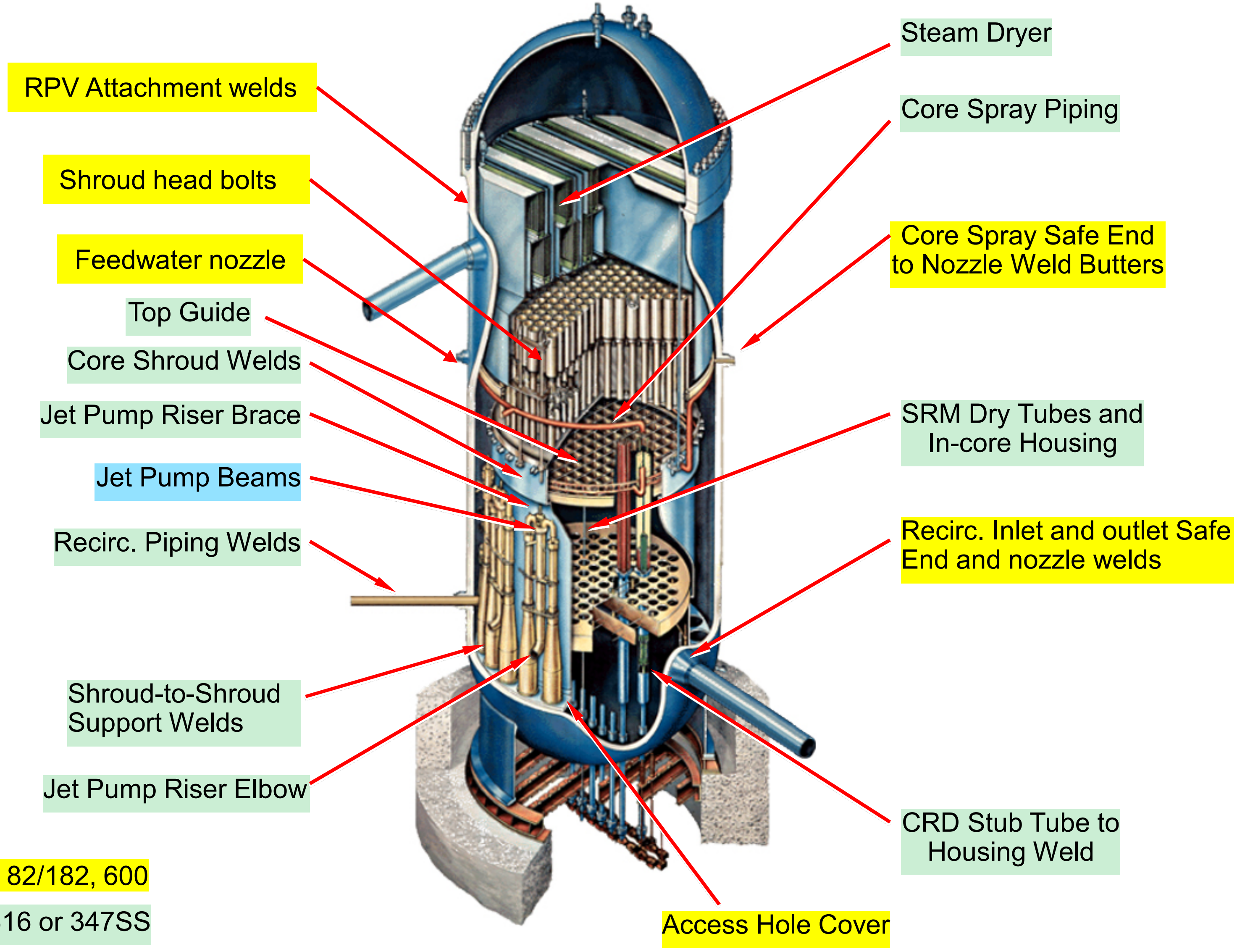
Routine surveillances can mitigate some of these factors; however, some failures can be expected

<u>Challenge</u>: Find the next material vulnerability and address it before any failures occur

Operating Experience through 2002

- Reactor Internals components:
  - Core shrouds
  - Core spray piping
  - Jet pump beams
  - Jet pump inlet piping
  - Top guides
  - Steam dryers
  - BWR fuel support castings
  - PWR baffle bolts and split pins
- Pressure boundary items:
  - BWR recirculation piping
  - BWR CRD stub tubes
  - Pressurizer heater sleeves
  - Primary system full penetration butt welds
  - PWR reactor vessel bottom mounted nozzles
  - PWR CRDM head penetrations

BWR IGSCC

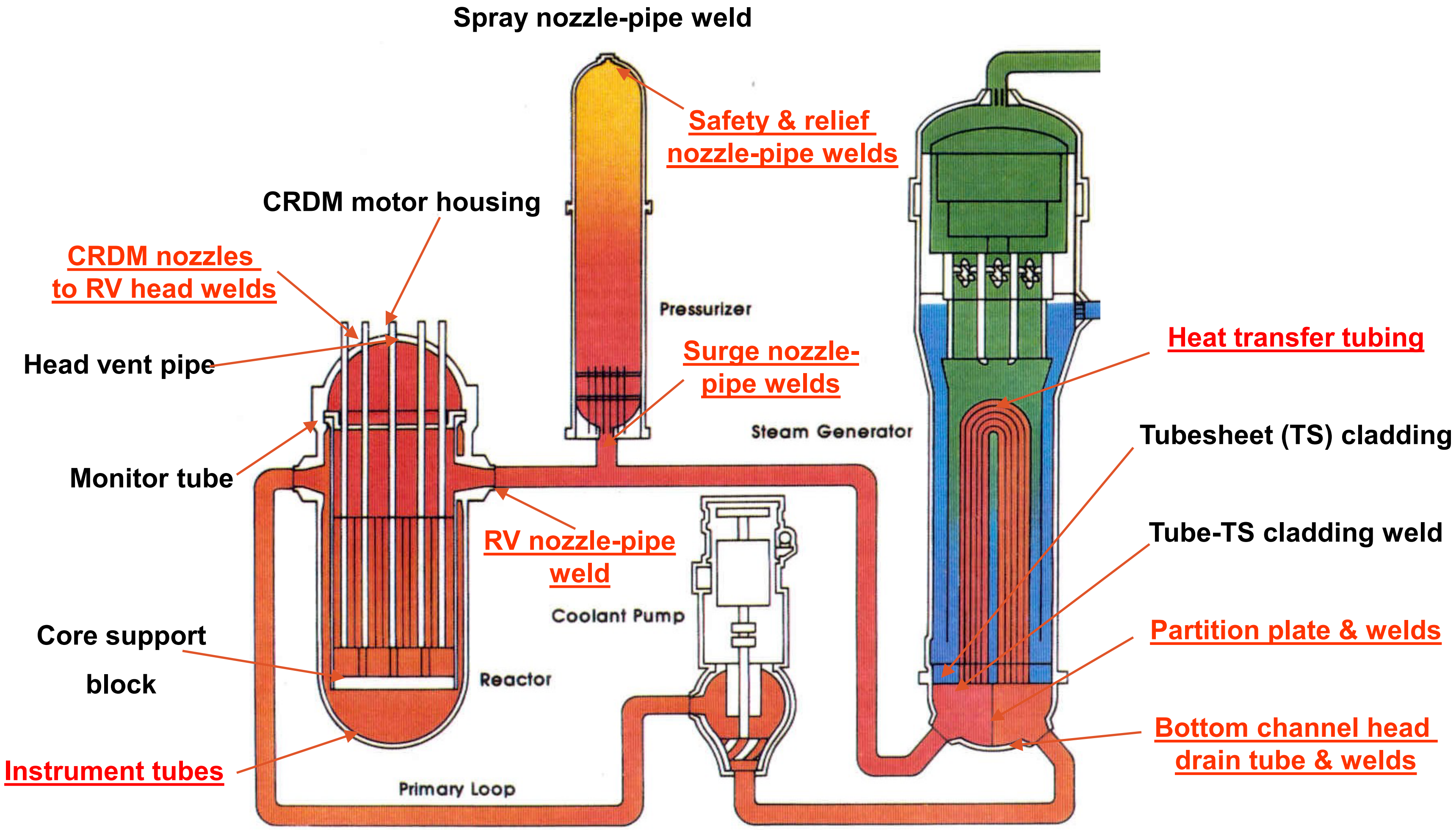


Alloy 82/182, 600

304, 304L, 316 or 347SS

X-718, X-750

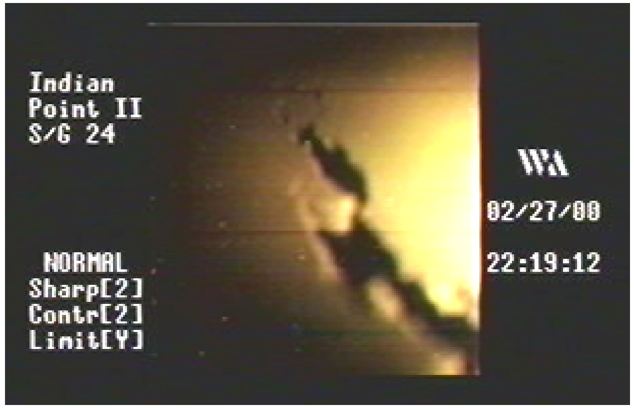
PWR PWSCC



Locations that have experienced cracking and or leakage are highlighted in red.

Call to Action – Early 2000's

Series of Events in PWRs Motivated Industry Executives to Take Broad Generic Action



Indian Point (February 2000):
SG tube leak hidden by noise in NDE signal

V.C. Summer (Fall 2000):
Crack in a hot leg nozzle to pipe weld

Leaking PWR CRDM Head Penetrations

Davis Besse (March 2002):
CRDM penetration and head wastage

Impact of Unexpected Operating Experience (OE)

- Unanticipated Impacts
  - Events costly and impact reliability, safety, and performance
    - Davis-Besse – more than $500M
    - Unplanned head replacement ~ $60M to $100M and up
    - Unanticipated RPV penetration repairs ~$65M
    - Lost generation daily replacement power
    - Increased dose exposure
  - Increased regulatory involvement and oversight
  - Quality of life of utility work force
- Something had to be done

1st Step - Self-Assessment

- In August 2002 Executive Committee directed industry to:
  - Proactively address material issues
  - Assess the industry's materials programs to identify strengths, weaknesses, and make recommendations
  - Scope
    - Primary pressure boundary components in BWRs and PWRs
    - Material issues related to nuclear fuels
    - NDE
    - Chemistry/corrosion control programs
- A Materials Assessment Working Group (MAWG) was formed with representatives from all industry groups dealing with materials issues

MAWG Issue Statement

The corrosion of the base metal in the Davis-Besse reactor pressure vessel head, increased occurrences of control rod drive mechanism nozzle cracking in pressurized water reactors (PWRs), and the V. C. Summer hot leg dissimilar metal weld defect represent issues that have threatened nuclear plant asset value and raised questions regarding the ability of the industry to detect degraded conditions in reactor coolant system components and piping. Other plant events over the last three years involving steam generator tubes, boiling water reactor (BWR) vessel internals and other pressure boundary, vessel internals, and fuel materials suggest that the nuclear industry has not been able to consistently anticipate and manage materials problems as well as it could. These events also suggest the need for better integration of existing PWR and BWR materials programs, as well as underlying technical support programs in the areas of plant chemistry, NDE, cracking/corrosion research, etc. Lessons from programs that are working well need to be transferred. Finally, the industry must continue to monitor and manage the impacts of materials issues prevention and mitigation strategies on fuel reliability and performance.

Key Conclusions from Self Assessment

- Industry lacked a unified strategic focus and direction
- Limited coordination of industry efforts on materials issues
- Budget and funding challenges
- Unable to enforce and to verify implementation of industry guidance
- Oversight of industry materials efforts was inconsistent
- Industry participation in materials issue programs lacking
- Implementation of materials tools inconsistent

- Recommendation: Define an NSIAC Initiative to address materials aging management

What is an NSIAC Initiative?

- Formal agreement among the utility Chief Nuclear Officers (CNOs) that form the Nuclear Strategic Issues Advisory Committee (NSIAC) to follow a defined policy

- Requires 80% vote of the NSIAC for approval

- Binding industry commitment at CNO level for full implementation

NEI 03-08 – Guideline for the Management of Materials

- Documents the Materials Initiative and defines the scope
- Established the policy - *Each licensee will endorse, support and meet the intent of NEI 03-08*
- Approved unanimously by Nuclear Strategic Issues Advisory Committee (NSIAC) in May 2003
- Defines roles, and responsibilities
  - Executive / Management oversight
  - Issue Programs (IPs)
  - Utilities
- Initiative was effective January 2, 2004
- Current version is Revision 3, effective March, 2017

Materials Management Policy Statement

"… the industry will ensure that its management of materials degradation and aging is ***forward-looking and coordinated*** to the maximum extent practical. Additionally, the industry will ***continue to*** rapidly identify, react and ***effectively respond to emerging issues***. The associated work will be managed to emphasize safety and operational risk significance as the first priority, appropriately balancing long term aging management and cost as additional considerations. To that end, as issues are identified and as work is planned, the groups involved in funding, managing and providing program oversight will ensure that the ***safety and operational risk significance of each issue is fully established prior to final disposition***."

Materials Initiative

- The objective is to assure safe, reliable and efficient operation of the U.S. nuclear power plants in the management of materials issues.
- The purpose of this Initiative is to:
  - Provide a consistent management process
  - Provide for prioritization of materials issues
  - Provide for proactive approaches
  - Provide for integrated and coordinated approaches to materials issues
- Utility actions required by this Initiative include:
  - Commitment of executive leadership and technical personnel
  - Commitment of funds for materials issues within the scope of this Initiative
  - Commitment to implement applicable guidance documents
  - Provide for oversight of implementation

NEI 03-08 Scope and Issue Programs

- Scope
  - Reactor internals
  - Primary system pressure boundary components
  - Related NDE, chemistry and corrosion controls
  - Other as directed by NSIAC
- Issue Programs (IPs)
  - EPRI
    - BWR Vessel & Internals Project (BWRVIP)
    - Materials Reliability Program (MRP)
    - Steam Generator Management Program (SGMP)
    - Nondestructive Evaluation (NDE)
    - Primary Systems Corrosion Research (PSCR)
    - Water Chemistry Control (WCC)
  - PWR Owners Group Materials Subcommittee

NEI 03-08 Expectations for Owners

- Utility responsibilities (shall)
  - Maintain a RCS Materials Degradation Management Program
  - Implement “Mandatory” and “Needed” IP guidance (see next slide)
  - Participate in IPs
  - Apply appropriate focus on materials issues
  - Communicate materials OE

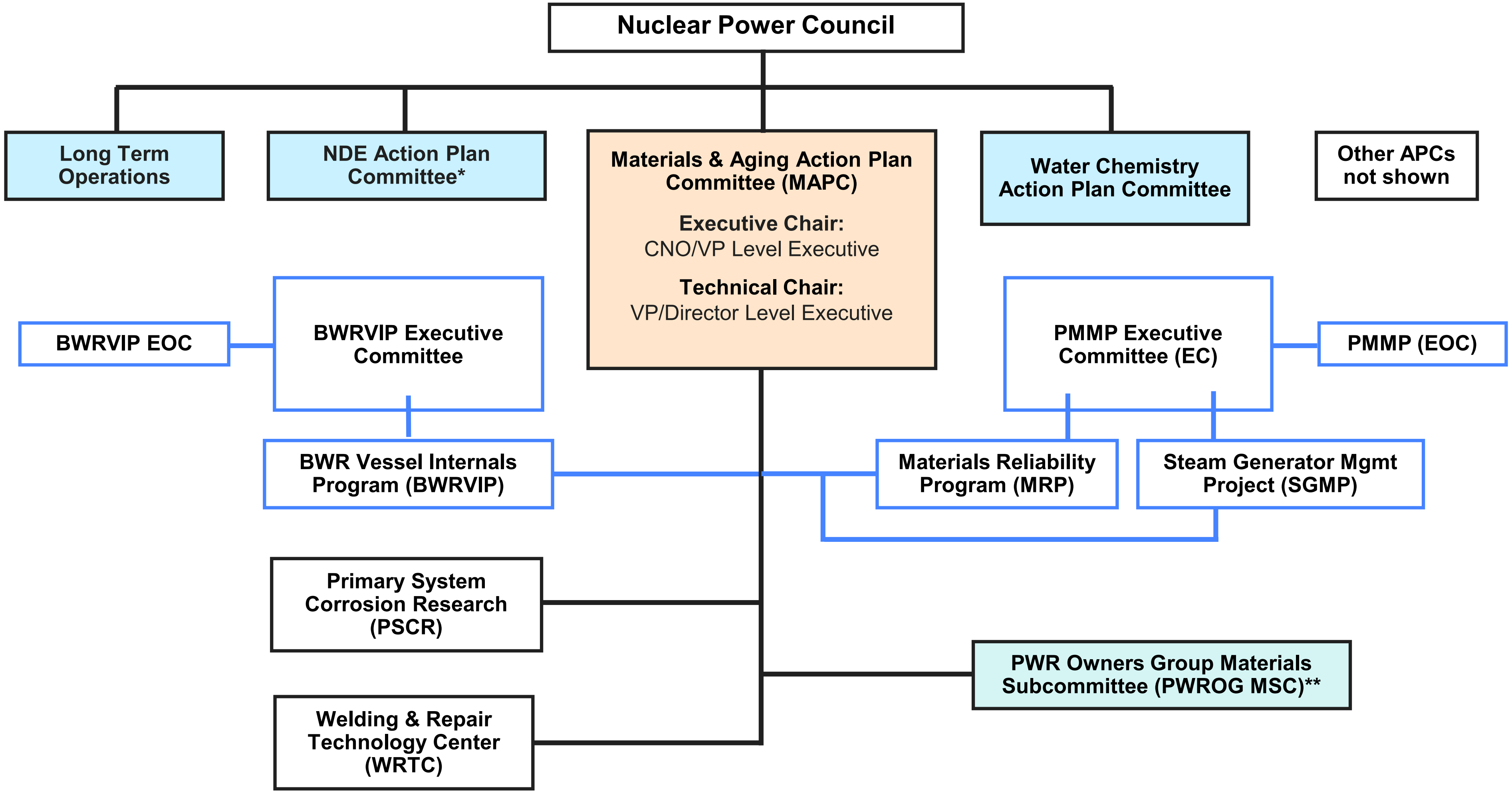
NEI 03-08 Expectations for Materials Programs

- Identifying, prioritizing, and resolving issues
- Communicating
- Managing regulatory interface
- Developing guidance
- Reviewing deviations
- Self assessments and performance metrics
- Process for addressing emergent materials issues

MAPC Structure

- EPRI Materials Action Plan Committee (MAPC) provides strategic direction for materials programs including:
  - EPRI materials programs: BWRVIP, MRP, SGMP, PSCR, WCC, NDE
  - PWROG MSC (Materials Committee)
- BWRVIP and PWR executive committees report to MAPC for strategic coordination
- MAPC members to include:
  - CNO as chair to coordinate with NSIAC
  - Executive and Technical chairs of the Materials Programs
  - At-large members for fleet representation
  - INPO and NEI representatives
- Effective January 1, 2010

Materials Organizational Structure



**NDE APC coordinates with Materials APC and PWR Owners Group*
***Materials Subcommittee has a representative on Materials APC*

NEI 03-08 Integrated Materials Issues Strategic Plan

- A Systematic Approach to Managing Materials Issues
  - Identify degradation modes (DM)
  - Assessment of the extent of degradation and implications (AS)
  - Identify methods to inspect & evaluate evidence of degradations (I&E)
  - Opportunities and methods to Mitigate degradation (MT)
  - Repair or Replacement methods as available (RR)
  - Listing of Regulatory driven issues (RG)
- Approach :
  - Collection and Updating of Operating Experience
    - MRP Meetings – Operating Experience updates from plants, 3 times per year
    - EPRI Emerging Issues – as arising
  - Documentation
    - Materials Degradation Matrix (MDM) and Issues Management Tables (IMT) maintained as living documents with regular updates

EPRI Systematic Approach to Materials and Components' Aging Management

Materials Degradation Matrix

3002013781

MDM

Every component, every material, every potential degradation mechanism

- Mapped to 80 years of operation
- Covering BWR, PWR, CANDU and VVER

Issue Management Tables

PWR: 3002000634
BWR: 3002000690
CANDU: In Progress

IMTs

Every issue to resolve identified and prioritized

- Covers BWRs and PWRs
- CANDU in progress

A key objective is to help coordinate the global industry

Materials Degradation Matrix (MDM)

- Comprehensive listing of potential degradation mechanisms for existing LWR primary system components
- Documents how well applicable degradation mechanisms are understood
- Identifies the industry knowledge worldwide for mitigation of applicable degradation mechanisms
- Documents the results of an expert elicitation process
- Proactively identifies potential challenges to avoid surprises
- Identifies Strategic Long Term Operation Issues
- Current Revision 4, 2018 (EPRI document **3002013781**)

MDM Results---- PWR Reactor Internals

- For groups of components…
- Matrices of materials used vs potential (standard set of) degradation modes
- Expert panel elicitation to define applicability (Y, N, ?... N/A)
- R&D status –
  - Green = sufficiently well characterized, reasonable understanding
  - Yellow = near term gaps in characterization but relevant research is in progress
  - Orange = near term gaps in characterization but relevant research is in progress
  - Blue = for all ?... = lack of data
- Notes – clarify the applicability of the mechanism and research determination

Table 4-2
PWR Reactor Vessel Internals

	DEGRADATION MODE													
	Corrosion				Wear	SCC		Fatigue		Reduction in Fract Properties		Irradiation Effects		
MATERIAL	Wstg.	Pitting	FAC	Foul	Wear	IG / TG	IA	HCF	EAF	Th	Env	Emb	VS	IC / SR
STRUCTURAL COMPONENTS & WELDS														
SS: 300 Series SS Base Metal & HAZ	N	N	N	N	Y p2-5a	Y p2-6a	Y p2-7a	Y p2-8a	Y p2-9a	N	Y p2-11a	Y p2-12a	Y p2-13a	Y p2-14a
SS: 300 Series SS Welds & Clad	N	N	N	N	N	Y p2-6b	Y p2-7b	Y p2-8b	Y p2-9b	Y p2-10b	Y p2-11b	Y p2-12b	Y p2-13b	Y p2-14b
Cast Austenitic Stainless Steel:	N	N	N	N	N	Y p2-6c	? p2-7c	Y p2-8c	Y p2-9c	Y p2-10c	Y p2-11c	Y p2-12c	N	N
Ni-Alloy: A600 Base Metal	N	N	N	N	Y p2-5d	Y p2-6d	N	Y p2-8d	Y p2-9d	N	Y p2-11d	N	N	N
FASTENERS & HARDWARE														
SS: 300 Series (304, 347, 316CW)	N	N	N	N	N	Y p2-6e	Y p2-7e	Y p2-8e	Y p2-9e	N	Y p2-11e	Y p2-12e	Y p2-13e	Y p2-14e
SS: A-286 Precip. Hardened SS	N	N	N	N	Y p2-5f	Y p2-6f	Y p2-7f	Y p2-8f	Y p2-9f	N	Y p2-11f	Y p2-12f	N	Y p2-14f
SS: Martensitic (Tp. 403, 410, 431, 17-4PH, 15-5PH)	N	N	N	N	Y p2-5g	Y p2-6g	N	Y p2-8g	Y p2-9g	Y p2-10g	Y p2-11g	N	N	N
Ni-Alloy: X-750	N	N	N	N	Y p2-5h	Y p2-6h	Y p2-7h	Y p2-8h	Y p2-9h	N	Y p2-11h	Y p2-12h	N	Y p2-14h

MDM Notes

Table 4-7 (continued)
PWR Systems Explanatory Notes

NOTE ID	EXPLANATORY NOTE
p2-6h	There has been substantial field experience with SCC of prior generation Alloy X-750 components due to sub-optimal heat treatment and designs that included high stress concentrations and poor surface finish. However, extensive laboratory testing indicates that new Alloy X-750 parts will perform satisfactorily if they meet current specification requirements with regard to chemical composition, optimized heat treatment (HTH condition), fabrication sequence, stress / strain limits, and surface finish. Older Alloy X-750 designs are being managed through inspection and replacement, sometimes with the optimized Alloy X-750 parts and sometimes with strain-hardened Type 316 stainless steel. During a routine ISI of the reactor vessel, one plant reported that seven of forty-eight Alloy X-750 clevis insert bolts showed evidence of separation between the head and the shank. Clevis insert bolt head / shank failures were evidenced by wearing of the lock bars which retain the torque of the clevis insert bolts. At one location, the clevis insert dowel pin tack welds were fractured and the dowel pin was slightly rotated and displaced deeper into the clevis insert. While not confirmed at this time, the known susceptibility of non-optimized Alloy X-750 to stress corrosion cracking and low temperature crack propagation (LTCP) is expected to be a contributor to the observed degradation. Westinghouse performed engineering evaluations of the as-found conditions and was able to justify that the system would function as required for two cycles of operation without immediate repair. At present, no additional research is considered to be needed. Screening criteria for SCC based on stress are contained in MRP-175. [R&D Status = GREEN] **References:** EPRI: MRP-88, MRP-175R1, 3002012420 (Materials Handbook) Other: [4-31]

- Defined by and pertains to the applicable matrix table cell
- Assessment of the status of the issue
- Summary of the relevant research in progress
- Hyperlinked from applicable matrix table

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Issue Management Tables

- Assesses the consequences of failure
- Identifies gaps in inspection, mitigation, repair, and replacement guidance
- Prioritizes IMT gaps to direct R&D project plans of the Issue Programs
- Requires utility members engagement
- Updated 2013
  - BWRVIP-167, Rev. 3; EPRI Report 30020000690
  - MRP-205, Rev. 3; EPRI Report 3002000634

Component-Based Issue Management Tables

Components & ID No.	Material	Degradation Mechanisms	Conseq. of Failure	Mitigation	Repair / Replace	I & E Guidance	Gaps
2.1 Control Rod Guide Tube Assembly							
2.1-1 Control Rod Guide Tube Assembly *(Sleeve, Base, Alignment Lugs)*	SS *(304, 316L)*	SCC: IG/TG RiFP: Env	B, F	**Water Chemistry** BWRVIP-190 BWRVIP-225 **HWC Technology** BWRVIP-62R1 BWRVIP-156 BWRVIP-159 BWRVIP-219 BWRVIP-245 BWRVIP-248	**EPRI BWRVIP** BWRVIP-55-A BWRVIP-84R2	**EPRI BWRVIP** BWRVIP-47-A	B-DM-06 B-DM-09 B-AS-31 B-MT-02 B-MT-04 B-RG-05
2.1-2 Control Rod Guide Tube Assembly *(Cast Body)*	CASS *(CF3 / CF8)*	SCC: IG/TG RiFP: Env IE: Emb	B, F	**None**	**EPRI BWRVIP** BWRVIP-55-A BWRVIP-84R2	**EPRI BWRVIP** BWRVIP-47-A No Inspection Required	B-DM-06 B-DM-09 B-AS-31 B-MT-05
2.1-3 Guide Tube & Fuel Support Alignment Pin	SS *(304 typ.)*	SCC: IG/TG RiFP: Env	B, F	**Water Chemistry** BWRVIP-190 BWRVIP-225 **HWC Technology** BWRVIP-62R1 BWRVIP-156 BWRVIP-159 BWRVIP-219 BWRVIP-245 BWRVIP-248	**EPRI BWRVIP** BWRVIP-55-A BWRVIP-84R2	**EPRI BWRVIP** BWRVIP-47-A	B-DM-06 B-DM-09 B-AS-31 B-MT-02 B-MT-04

Background – R&D Gap Categories

- Degradation Mechanism Understanding (DM) – Fundamental materials knowledge gaps (*understanding the degradation mechanisms affecting primary systems components*)
- Assessment (AS) – Gaps related to understanding the detrimental impacts of degradation on component performance and managing these effects to support continued safe and reliable operation
- Mitigation (MT) – Technology gaps related to preventing or mitigating the occurrence or progression of degradation mechanisms (*encompasses not only water chemistry based mitigation, but other methods as well – e.g., surface stress improvement*)
- Inspection & Evaluation (I&E) – Technology gaps related to inspection / NDE capabilities and uncertainties
- Repair / Replacement (RR) – Technology gaps related to repair / replacement capabilities
- Regulatory (RG) – Issues driven by regulatory requirements or by regulator imposed requirements

Issue Management Gap Tables

- Builds on Materials Degradation Matrix
- Combine with evaluations of Consequences of Failure of Components (e.g. MRP-156 & MRP-157)
- Identify gaps in
  - Understanding of the degradation method
  - Assessment methods and capabilities
  - Mitigation methods
  - Inspection and evaluation methods and capabilities
  - Repair and replacement availability
  - Ability to respond to regulatory issues
- Prioritize the gaps
  - ***High, Medium, Low***
- Work projects based on issues' priorities
- Update the tables in cycles
  - Close gaps as knowledge and capabilities are developed
  - New gaps as OE, licensing, regulatory questions arise

Table 3-1 R&D Gap Priority Results

Gap ID No.	Gap Description
Degradation Mechanism Understanding Gaps (Table 3-2)	
P-DM-09	Environmental Effects on Fracture Resistance
P-DM-10	Thermal Embrittlement of Low-Alloy Pressure Vessel Steels
P-DM-11	SCC (and Thermal Aging) of CASS Pressure Boundary Components
P-DM-12	Increased Fastener SCC Susceptibility due to Long-Term Aging
P-DM-13	Long-Term SCC Susceptibility (Late Life SCC Initiation)
P-DM-14	Long-Term Stability of Surface Stress Improvement Mitigations
P-DM-15	Thermal Embrittlement of Martensitic Stainless Steels
P-DM-16	Thermal Embrittlement of Martensitic Stainless Steels (SG Tube Support Plates)

Issue Management Gap Tables – Open Gaps

Table 3-2 Degradation Mechanism Understanding Gaps (Continued)

R&D Gap Description	Results Data
P-DM-13 - Long-Term SCC Susceptibility (Late Life SCC Initiation) **Issue:** Long-term exposure of materials to environments conducive to SCC may lead to additional incidents of initiation or initiation in materials or components where it has not previously been observed. **Description:** The MDM panel continues to express concern that a late life upward trend in degradation events related to aging is possible and should be monitored. Aging may be metallurgical in origin and / or due to some slow accumulation of a degrading environmental reaction. Deterioration of the surface condition could lead to crack initiation at progressively lower levels of stress intensity, potentially leading to cracking in locations or components not previously experiencing SCC. Closure of this gap involves substantial advances in industry understanding regarding the SCC initiation risk at long service times. This work would appear to be challenging given current industry limitations relative to modeling and predicting SCC initiation. **References:** MDM (Note p1-6c, 1-6d, 1-6e, 1-6f, 1-6h, 1-6i)	**Status:** Open **Priority:** R3 (2013): Low R2 (2010): Low **Responsibility:** MRP PSCR **LTO Impact:** Indirect

- Clear statement of the gap and consequence
- Description of the issues related to the gap
- References to MDM notes
- Priority – ***Low, Medium, or High***
- History of revisions previous priority, newly opened
- (Closed items also identified in EPRI documents for completeness)

PWR Issue Management Gap Tables

- Identifies and prioritizes “gaps” by reviewing impact at a subcomponent level
- Focuses efforts where most needed
- Used to set priorities and funding (High, Medium & Low) for research projects
- Used to inform stakeholders of key areas that require efforts
  - EPRI Program Members
  - Collaborators – MAI, CRIEPI, US-DoE & National Labs
  - Regulatory Agencies – US-NRC, ENSI, IAEA

Current IMT PWR High Priority Gaps (1 of 2)

Including Updates

Gap ID	Description	Comment
P-AS-02	Environmental Effects on Fatigue Resistance of Pressure Boundary Components	LTO
P-AS-09	SCC of Stainless Steel Exposed to Primary Water	LTO
P-AS-11	PWSCC Crack Growth Rates for Alloys 600, 82 and 182	LTO C/O
P-AS-12	PWSCC Crack Growth Rates for Alloys 690, 52 and 152	
P-AS-13a	Thermal and Irradiation Synergistic Effects on CASS	LTO
P-AS-13b	Thermal and Irradiation Synergistic Effects on SS Welds	LTO
P-AS-14a	IASCC Characterization : Generic Data Needs	LTO
P-AS-14b	IASCC Characterization : Baffle Bolting	LTO
P-AS-17	Flow Induced Vibration and Wear of Reactor Internals	LTO C/O
P-AS-19	PWSCC Management for Ni-base Reactor Internals	LTO

Current IMT PWR High Priority Gaps (2 of 2)

Including Updates

Gap ID	Description	Comment
P-AS-38	Fluence Impact on Stainless Steel Mechanical Properties (Fracture Toughness, Tensile Strength)	LTO
P-AS-46	CASS Piping Component Thermal Aging Embrittlement and Long Term Integrity Assessment	New / LTO
P-AS-47	Fracture Toughness Properties of Low Alloy Pressure Vessel Steels (Plates and Forgings)	New in 2015
P-AS-49	Impact of Small Surface Flaws on ASME XI Appendix G P-T Limit Methodologies	New in 2015
P-AS-50	Improved Technology for Predicting Piping Thermal Fatigue	New in 2016
P-MT-14	Develop Recommendations for Mitigating Fatigue Failures at Piping	New in 2016
P-I&E-03	NDE Technology for J-Groove Weld Locations	
P-I&E-12	NDE Technology for Examination of CASS	
P-RG-06	NDE Qualification for Reactor Internals Inspection (VT Evaluation)	
P-RG-09	Pipe Rupture Probability Re-Assessment (xLPR)	

Ongoing EPRI Research Programs Address Issue Gaps – Just some of the current projects

- SCC of stainless steels in off-chemistry environments
- Mechanistic understanding of SCC in stainless steels
- IASCC of irradiated stainless steels in elevated LiOH and KOH balanced PWR coolant
- Re-examination of irradiation effects and void swelling in irradiated stainless steels
- Fluence impact on fracture toughness of irradiated stainless steels
- Crack growth testing of irradiated stainless steels
- Updating of reactor internals guidelines (MRP-227 process) documentation
- Tracking and correlation of RV internals I&E guidelines
- Assessment of long time thermal effects on embrittlement of low alloy steels
- Assessment of C segregation effects on fracture resistance of low alloy steels
- PWR Supplementary Surveillance Program to re-irradiated pre-exposed surveillance materials
- Improved reactor vessel degradation modeling – use of master curve approach
- Assessment of environmental effects on fatigue
- PWSCC crack initiation and crack growth data correlations in Alloy 600 and Alloy 690
- Potential LRO and its effects on PWSCC of Alloy 690
- Effect of cold work and welding on PWSCC of Alloy 690
- Risk based pipe rupture methodology, xLPR

Initiative Accomplishments

- Integrated industry strategic plan for materials
- Achieved a high level of industry integration, coordination, alignment, and communication on material issues
- Established a process for prioritizing projects, budgets, and planning
- Predictable funding for materials R&D – clear definition of ***NEEDED*** projects
- Engaged INPO as an active participant
- Defined expectations and protocols for industry actions upon discovery of an emergent issue
- Established consistent process for deviations and communication with NRC
- Executive level interactions between industry and senior NRC management
- Successful at closing materials issues and gaps
- Fewer unexpected materials related transients

Summary

- NEI 03-08 set an expectation for proactive materials aging and degradation management
- The strategic approach utilizes the MDM and IMTs
- Based on significant and continually updated plant OE inputs
- EPRI’s MDM and IMTs are living documents that reflect:
  - Operating experience
  - Updates from research programs
  - Status and priority of issues
- The MDM and IMTs are effective tools for the MRP and other programs to use in development of strategic plans to address needed knowledge generation.
- IMT prioritized gaps drive the EPRI funded research programs.

Questions

Together…Shaping the Future of Electricity