Topics

• Integrated Industry Approach, Processes and Tools
• Materials Applications
• Fleet-wide Implementation
Integrated Industry Approach, Processes, and Tools

Glenn Gardner,
PWROG Reactor Internals Core Planning Team Chair
PWROG Implementation Process for RV Internals Aging Management Program

Industry-wide Coordination of Plant-Specific Reactor Internals Aging Management

- Plant Aging Management (AMP)
- NRC Requests for Additional Information (RAIs)
- Plant Responses to RAIs
- Plant Pre-Inspection Engineering Plan
- Outage Scheduled Inspections
- Extended Plant Operations

Coordinated Industry Documentation

- Validated databases
- Inspection approaches
- Plan development approaches – templates
- I&E Guidelines
  - Inspection Hierarchy
  - Primary Components
  - Expansion Components
PWROG Implementation Process for RV Internals Aging Management - Overview

- **Focus:** Safety, Dose, Reliability
- **Approach:** Define a systematic strategy for internals aligned with the generic elements of license renewal
  - MRP-227-A I&E Guideline provides *what and when* is to be inspected
  - MRP-228 is an inspection standard that describes *how* to inspect
  - WCAP-17096-NP is a guideline for acceptance criteria methodology
  - MRP-318 gives mitigation and contingency repair planning options for PWR internals
  - WCAP-17436 provides consensus results for the reactor internals inspection planning and contingencies
  - Separate but coordinated fulfillment of ASME XI requirements

*NEI 03-08 implementation requirements apply*
Component Categorization
- Aging mechanism
- Likelihood and severity of safety
- Economic consequences

Primary and Expansion
- Examination method
- Coverage
- Examination frequency
- Inspection acceptance criteria
- Primary-Expansion link

NEI-03-08 Implementation Requirements
- Mandatory category requirement
- Needed category requirements
4-Step Process for Plant-Specific Implementation of MRP-227-A

1. Aging Management Program (AMP) Scope Definition
2. AMP Development
3. Program Development and Implementation
   – Pre-Inspection Engineering
   – Field Inspection
4. Industry Reporting, Response, and Follow

- MRP-227 is a “living program”
- MRP-227 & 4-Step Process provide the basis for consistent plant specific implementations
4-Step Process Flow Chart for Development & Implementation

1. Proprietary Design Information → AMP
2. AMP → Component Inspection Details
3. Component Inspection Details → Inspections
4. Inspections → Are Inspection Indications Discovered?
   - Yes → Apply Acceptance Criteria
   - No → Contingency (Utility-specific)
5. Contingency (Utility-specific) → Record Result & Send Operating Experience
6. Record Result & Send Operating Experience → End
Step 1 and Step 2:
Aging Management Program Plan

Steps 1 & 2 provide direction for developing a plant-specific program for implementing MRP-227-A

- **AMP Scope Definition**
  Must meet the requirements of the generic guidance while considering the plant-specific situations

- **AMP Development**
  Couples the plant-specific scope definition with:
  - Regulatory plan requirements as defined in the 10 GALL elements,
  - MRP guidelines,
  - Regulatory applicant/licensee action items, and
  - Plant-specific design variants, commitments and outage planning
Step 3 Program Development & Implementation

- **Elements:**
  - **Pre-Inspection Engineering**
    - Component Inspection Details, CID
    - Acceptance Criteria, AC
    - Inspection Response Plan, IRP (Mitigate, Repair, Replace, Inspect)
  - **Field Inspection**
    - Proprietary and Non-proprietary documents suitable for use by utility, regulator and third parties

- **Alignment with:**
  - Guidelines: MRP-227-A
  - Regulatory or plant-specific requirements and commitments
  - Inspection Requirements: MRP-228, ASME Section XI
  - Acceptance Criteria: WCAP-17096-NP Revision 2

- **Nuclear safety related**

Step 3 focuses on plant-specific preparations and field execution of guidelines (MRP-227-A/MRP-228)
Step 3 Development of Component Inspection Details (CIDs)

- Provide a visual reference for the location of components to be inspected
- Indicate specific area of the component to be inspected
- Show surrounding area to provide perspective of clearances and potential obstacles
- Provide consistent industry naming conventions for the component and any observed flaws
Step 3 Development of Acceptance Criteria: Inspection and Engineering Evaluation

- Define limiting parameters (including margin) and determine the allowable criteria (e.g., maximum crack length, number of failed components, loss of material) that will permit the plant to return to service for the entire inspection cycle (typically 10 years).
- Alternate is to provide acceptance criteria to allow a return to power for 1 fuel cycle:
  - This prevents an impact to the current outage and allows the utility time to assess and develop a safe and responsible plan to manage observed aging.

Focus on Safety and Reliability
Step 3 Inspection Response Plan (IRP)

Plan and prepare:
• Build on sharing of plant experiences
• Identify options for responding to observed material degradation or unknowns
• Manage impacts on existing plant activities
• Define limits or bounding risks for outage impacts
• Identify utility-specific decision triggers
• Bring together key stakeholders to ensure consensus
  ➢ Utilities, research, OEM, vendors, regulators
Step 4 - Reporting Results and Follow – Utilization of Results of Field Inspections

Inspection results initiate plant responses per IRP…

…and under the Needed NEI 03-08 requirements provide feedback to the industry:

- Collaborate
- Communicate
- Peer Check

Baffle-former Assembly
Baffle-former Bolt
Baffle-edge Bolt
Lower Flange Weld
Hold Down Spring
Thermal Shield Flexure
Overall - Reactor Internals Aging Management
Inspect, Evaluate, Adjust

Goal: Successful Execution & Effective Aging Management

- Inspection Guidelines
  - What to inspect
  - When to inspect
- Evaluation Guidelines
  - What is acceptable
  - Actions
    - Mitigate
    - Repair
    - Replace
    - Inspect
- Lessons Learned
- Communicate

Knowledge sharing is key

- PA-MSC-0350 B&W RV Internals Structural Bolt Evaluations
- PA-MSC-0473 - RI Acceptance Criteria Methodology and Data Requirements (WCAP-17096-P)
- PA-MSC-0568 - Reactor Internals Operating Experience Review, Risk Ranking and Response Planning (WCAP-17435-NP, Rev. 1 & WCAP-17436-P)
- PA-MSC-0573 B&W PWR Internals Fabrication Records for MRP-227
- PA-MSC-0688 – Westinghouse Guide Tube Card Wear (WCAP-17451-P)
- PA-MSC-0692 B&W Functionality Criteria Core Barrel Assembly
- PA-MSC-0784 - Generic Flaw Acceptance Criteria Core Barrel Welds (WCAP-17684-P)
- PA-MSC-0835 - B&W-Plant Reactor Internals Functional Acceptance Criteria & Technical Justifications
- PA-MSC-0983 - Support for A/LAI 1, 2, 7 & Cold Work & Fluence (WCAP-17638-P, MRP 2013-025)
- PA-MSC-0984 - Acceptance Criteria for Measurement of CE Internals
- PA-MSC-1103 - Functionality Analysis Lower Support Columns (PWROG-14048-P)
- PA-MSC-1198 - Clevis Insert Bolting
- PA-MSC-1288 - PWR Materials Assessment
Coordinated Industry Analyses of Reactor Vessel Internals  CASS Aging Issues

Mike Burke, Westinghouse
Topics

• CASS issues in reactor vessel internals
• CASS embrittlement screening threshold development and issues
• Appropriateness of High Mo data use in developing thresholds for low Mo CASS screening
• Need for improved determination of CASS ferrite content in plant relicensing
• Statistical approach to predicting CASS ferrite content – Approach, Results
Cast Austenitic Stainless Steels (CASS) in Light Water Reactors

- CASS materials have been used in both pressure boundary components (Class 1 piping, elbows, etc.) and reactor internals
  - High Mo grades (CF-8M, CF-3M) are used in piping etc.
  - RV Internals components rarely used high Mo CASS - almost exclusively low Mo grades, CF-3 & CF-8
- CASS components are ductile in the as-cast or heat treated condition, with ductility approaching that of wrought materials, but ...
- Changes in mechanical properties of CASS are associated with exposure to nuclear plant operating conditions
  - Thermal embrittlement (TE)
  - Irradiation embrittlement (IE)
- Concern that embrittlement of CASS may be a significant factor for RV Internals components
- Threshold levels are used for screening of RV internals CASS in I&E planning
Threshold for CASS for Internals I & E in Plant Relicensing

- TE for ferrite content >20%, IE for fluence > 1x 10^{17} n/cm^2
- Fluence threshold recognized as being too low, discussion on combine TE + IE Effects

**Industry Developed Thresholds**
- MRP-227 Process
- Threshold based on
  - Grimes TE approach
  - Industry test data for CF-3 and CF-8 low ferrite content irradiated materials
  - Focus on low Mo materials
  - Discounting IE threshold from wrought stainless steels value (1.5dpa → 1.0dpa)
- Thresholds identified in MRP-175
  - TE Threshold at 20%
  - IE Threshold at 1dpa
  - No TE + IE interaction
- Initial TE & IE assessments based on this approach

**Regulator Developed Thresholds**
- NRC guidance development process
- Thresholds based on
  - Review of NUREG test database - CF-3, CF-8, CF-8M and welds
  - Testing of ferrite contents above 20%
  - Inclusion of high Mo materials in database
  - Consideration of “synergy” of TE & IE
- Thresholds identified in 2014 guidance
  - TE alone – 20% threshold
  - Retain higher 1.5 dpa threshold for IE alone
  - Consider IE + TE combined effect
- Reduced IE threshold of 0.45 dpa for low Mo CASS with 16%<ferrite content <20%
- Plant CASS RAIs call for assessments to use these criteria

*NRC guidelines penalizes low Mo CASS materials and leads to unnecessary inspections*
## Implications of Implementation of Regulatory Guidance vs Existing Industry Guidance for CF-3 and CF-8 (low Mo) Materials

<table>
<thead>
<tr>
<th>Ferrite Content</th>
<th>Industry TE</th>
<th>Industry IE</th>
<th>Regulator TE</th>
<th>Regulator TE+IE</th>
<th>Regulator IE</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤15%</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 1.0 dpa</td>
<td></td>
<td></td>
<td>&gt;1.5 dpa</td>
</tr>
<tr>
<td>16% &lt; X ≤20%</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 1.0 dpa</td>
<td></td>
<td>&gt;0.45 dpa</td>
<td>&gt;0.45 dpa</td>
</tr>
<tr>
<td>&gt;20%</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>IE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;1.0 dpa</td>
<td></td>
<td></td>
<td>&gt;0.45 dpa</td>
</tr>
</tbody>
</table>

- Industry process “screens in” sequentially for TE then IE
- Utilizes MRP-175 categorizations of component fluence (<0.15dpa, 0.15→1dpa, 1→1.5dpa, >1.5dpa etc.)
- Simply identifies component TE susceptibility
- Aligns with available plant specific data
- Regulator guidance requires additional screening steps for TE + IE
- May require detailed component fluence remapping – to determine local fluence vs 0.45dpa threshold
- Introduces unwarranted conservatism for low Mo CASS in use in almost all plants
Rationale for Use of High Mo Data and Concern for Combined TE + IE Effect for CF-3 and CF-8 (low Mo) Materials are Not Understood by Industry

- Industry concern is that CF3 and CF8 properties are under-represented by CF-8M properties
- Clear difference in TE limiting toughnesses for low Mo and high Mo variants
- NUREG database of sequential TE and IE shows
  - Significant effect of either TE or IE but…
  - Small Δ for TE + IE over TE alone or IE alone
- Industry data based on LWR exposure (simultaneous IE & TE exposures) and sequential exposures (TE then IE)
- Low Mo compositions, 16%-20% ferrite content show
  - Significant toughness retained to several dpa
  - Expected toughness at 1dpa screening threshold is significantly above 255kJ/m²

<table>
<thead>
<tr>
<th>CASS</th>
<th>J-values at 2.5 mm of Crack Growth (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF-3</td>
<td>364 to 478</td>
</tr>
<tr>
<td>CF-8</td>
<td>343 to 451</td>
</tr>
<tr>
<td>CF-8M</td>
<td>161 to 259</td>
</tr>
</tbody>
</table>

Neutron Exposure Required to Reduce Toughness to 255kJ/m² is ~3.3 dpa

Lower Bound
Toughness at 1 dpa is ~435 kJ/m²
Need for Improved Determination of RV Internals Component CASS Compositions and Ferrite Content

• Determination of CASS Thermal Embrittlement (TE) calls for component specific CASS information (ferrite content and remaining toughness)

• Records were not originally required to be retained in such detail
  – Records were most often administratively retained and stored in mass, often as part of purchasing records
  – Record retention for aging plants uses older technology and is not automated
  – Reasonable due diligence plant record searches cannot be expected to recover 100% of needed data

• For components without CMTRs bounding assumption has been to assume maximum ferrite content → Effectively mandates screening-in all such CF-3 and CF-8 for TE

• Clear need for alternative method of determining CASS parameters in the absence of cast article specific data
Basis for Improved Statistically-based CASS Predictions in RV Internals Aging Management

• Searches conducted to date have resulted in:
  - Sometimes 100% data found
  - More often less than 100% of required detailed data found
  - Data shows consistent CASS composition distributions
  - Only in isolated instances does calculated ferrite content exceed 20%

• Analysis of existing data provides the ability to confidently predict ferrite content in future assessments of components in the absence of specific data
  - Predictions of the ferrite contents within a single plant for CASS can be generated from data for CASS components in that same plant
  - Predictions of the ferrite content of components in one plant can be generated from CASS components’ data from similar plants (e.g. same manufacturer).
Approach for Statistical Evaluation of RV Internals CASS Data

- CASS components’ chemical compositions taken from certified material test reports (CMTRs) to date
  - Over 40% of plants information has been searched
  - CMTRs confirmed for the majority of components to date
  - 100% CMTR retrieval for some specific plant/specific component sets

- Key Input Parameters
  - Plant ID
  - Component
  - Heat number

- Key Output Parameters
  - Ferrite content – calculated using Hull’s equivalent factors
    - Use for establishing statistics of the process and for going forward predictions
  - “Saturation” remaining toughness estimations – calculated using NUREG/CR-4513 formulas
    - Use for identifying saturation toughness and statistical margin versus identified acceptable minimum toughness
Results of Analysis of CASS Ferrite Content Statistical Data

- Ferrite content distributions approximate a normal distribution for a given manufacturer
  - To be expected from plant statistical process controls
  - Components with unrecovered CMTRs expected to be produced under similar conditions
  - Ferrite content of components with unrecovered CMTRs expected to be within the same characteristic distribution
- Results show that the probability of finding a component with estimated ferrite greater than 20% is very low

- Assuming maximum ferrite content in the absence of data is excessively conservative
- ALARA implications of imposing inspections with little to no improvement in the level of quality or safety
Results of Analysis of Remaining Toughness of CASS after Thermal Exposure

- Prediction of remaining toughness from equations given in NUREG/CR-4513
- Confidence intervals of data are determined by established statistics of distribution
- Measured distributions give high confidence in remaining toughness predictions very rarely encroaching on reasonable toughness screening thresholds

- Results demonstrate several $\sigma$ between distribution mean and screening threshold value
- Results better demonstrate available margin measured based on ferrite content

![Graph showing resistance to fracture at 2.5 mm crack extension versus heat quantity. The graph displays two distributions with a mean of 255 kJ/m².](image)
Summary and Conclusions for CASS in RV Internals

• Exposure to service is acknowledged to potentially induce embrittlement (TE and IE) in RV Internals CASS components
• Thresholding values for embrittlement assessments of CASS are crucial for effectively and safely preparing Inspection and Evaluation plans for plant relicensing.
• Differences in screening thresholds between industry developed approach and 2014 regulator guidelines have implications for the complexity of the required analyses
• Industry believes that low Mo CASS (CF-3 and CF-8) used in LWR RV Internals is inappropriately penalized in regulator screening guidelines due to inclusion of high Mo data
• Lack of 100% availability of CASS certification data calls for improved method of predicting CASS characteristics (vs threshold values)
• A statistics based approach can account for missing CASS certification data
• Implementation of statistics approach in responses to future RAIs provides for timely resolution of RV Internals aging management concerns and has generic applicability
Fleet-wide Implementation

Heather Malikowski, PWROG Materials Committee Vice Chair
PWROG PA’s Address Common Material Aging Questions

- Concerns on multiple material and fabrication issues resulting in RAIs
- Call for significant and, repetitive, efforts by utilities, OEMs, and the regulator
- Generic fleet or consistent resolutions developed for:
  - Training
  - Implementation
  - Knowledge sharing
  - CASS
  - Cold work
  - Fluence
- Coordinated resolution led by Owners Group projects not only expedited responses but also minimizes labor efforts and individual plant and regulatory review costs
- Partnered with other industry stakeholders to achieve a consensus on managing aging
RAI Questions Relate to Thresholds for Aging Management I&E Planning

- Based on established data and expert review of materials behavior and controlling effects on identified damage mechanisms
- Operating parameters:
  - neutron fluence, temperature, time
- Material parameters:
  - alloy chemistry, heat treatment, cold work
- If operating and material parameters are projected to exceed the threshold value a component must be considered for inspection and evaluation
CASS – Current Initiatives (Recap)

- Screening hierarchy – process to assure all concerns (TE, IE) are screened-in
- Appropriateness of screening thresholds
- Conservatism of screening approach when missing information
- Assessment of consequences of potentially degraded items in an assembly (e.g. lower support columns)
- Provides reasonable confidence in safety margin when less than 100% inspectable
PWROG Industry-wide Coordination to Resolve Cold Work Issues in RV Internals

- Cold Work consideration needed to address SCC and IASCC in aging management of RV Internals components
- 20% cold work limitation was already recognized at the time of plant construction, i.e. from 1970’s
- Plant fabricators quality programs were in place to adhere to limitations in cold work in austenitic stainless steels in these times
- Plant specific assessments conducted to date confirm that no non-fastener materials contain cold work greater than 20%
- Correlation of data based on searches to date demonstrates consistency across the PWR fleet - B&W, CE and, W show no cold worked non-fastener materials used in reactor vessel internals
Current Method of Resolution of Plant Specific "No Cold Work > 20%" RAI’s

- Extensive work required to identify all plant internals drawings
- Identify components’ materials allowed by plant drawings
- Determine plant specific CW from plant records
  - Material Designation
  - Specific restrictions on e.g. hardness
- Owners group program has correlated and analyzed data from individual plants
  - For each plant summary tables of information gathered extends for 70+ pages
  - Each component drawing/material set has been individually identified and resolved
  - Conducted for over 50% of plants so far

Data to date provide reasonable assurance that cold worked items do not present a concern for RV Internals aging management
Plant Specific Fluence – NRC Concern

- RAIs request confirmation that plant operation has been within the constraints identified in the analysis supporting the MRP-227 process.
- MRP-227 process considered:
  - 30 Years of operation with high leakage core loading pattern
  - Subsequent years with low-leakage core loading pattern
- Concern that different operating conditions would impact on internals’ materials degradation via effects of:
  - Fluence
  - Temperature
- Effects on degradation mechanisms
  - IASCC
  - Irradiation Embrittlement
  - Void Swelling
  - Thermal Embrittlement
  - Creep/Stress Relaxation
Industry Generalized Response to Plant Specific Fluence Considerations

- No intention to conduct a bounding analysis or define limiting values.
- Defined simple parameters to demonstrate that assumptions of MRP-227-A are representative of the plant.
- Examined the sensitivity of dpa and heat generation rate to differences in reactor geometry and core operating characteristics:
  - Internals Geometry
  - Core Geometry
  - Fuel Assembly Geometry
  - Core Loading Patterns
- Establish a range of variability for the Westinghouse/CE fleet relative to the models used in the MRP-227 functionality analysis.
- Demonstrated that stress, fluence, temperature and material assumptions used as inputs to the MRP-227 process are broad enough to support fleet wide recommendations.
Analysis of Generalized Effects of Core Loading on RV Internals Irradiation - Overall Impacts

- Fluence is a matter of geometry – distance from the core is key
- Operating experience to data does not show sensitivity to these (effectively small) variations in fluence exposures
  - Components located above the upper core plate should remain below the threshold for radiation embrittlement
  - Some, but not all, plants may exceed the MRP-227 screening threshold for radiation embrittlement of the upper core plate either in current operation or moving into the future.
    - The upper core plate was not considered to be a candidate for inspection as a result of the original generic industry evaluation, however the NRC included the upper core plate as an expansion category component as part of their safety evaluation.
- It is therefore concluded that the effects of IE and IASCC as a result of the marginally higher fluence value following the uprate are adequately managed by the implementation of the MRP-227-A inspection strategy

Generalized analysis has provided a consistent flexible approach for demonstration of long term operational compliance
Summary

- RV Internals Aging Management
  - Developed processes are in place
  - Consistent implementation of fleet-wide approaches
  - Feedback and updating of documentation
- Material Questions in RV Internals Aging Management
  - CASS
  - Cold working
  - Fluence modeling
- Fleet-wide approach to issue resolution
  - Reduced risks
  - Reduced uncertainty
  - Industry technical consensus
  - Continued learning
- PWROG initiatives continually engage industry stakeholders on a fleet wide basis …

- MRP-227 is a “living program”
- MRP-227 & 4-Step Process provide the basis for consistent plant specific implementations
Questions?