EPRI MRP Low Alloy Steel Research for LTO

NRC LTO Conference

Elliot J. Long – EPRI MRP
Senior Principal Technical Leader IV

NRC LTO Meeting
Rockville, MD
October 1, 2024

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Outline

- EPRI MRP Low Alloy Steel Research for LTO
  - Who We Are?
  - Time-Limited Aging Analyses (TLAAs)
    - RPV Integrity Approach for Life Extension
  - *Potentially* OPEN Long-Term Operation (LTO) Gap in Reactor Pressure Vessel Integrity
  - Current and Ongoing Research
    - PSSP Capsules
  - New Proposed Program
    - ASTM E900-15 Improvements and Enhancements

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Who We are?

MRP Member Utilities for 2024

North America

- Ameren Services Company
- American Electric Power, Inc.
- Constellation Energy Corp.
- Dominion Energy, Inc.
- Duke Energy Corp.
- Energy Harbor Corp.
- Entergy Services, LLC
- Evergy Services (Wolf Creek)
- NextEra Energy, Inc.
- Pacific Gas & Electric Co.
- Palisades Energy [NEW]
- Pinnacle West Capital Corp.
- PSEG
- Southern Nuclear
- STP Nuclear Operating Co.
- Tennessee Valley Authority
- Vistra Energy/Comanche Peak
- Xcel Energy Services, Inc.

Europe

- Axpo (Switzerland)
- EDF Energy (UK)
- Foro-CEN (Spain)
- NEK (Slovenia) [NEW]
- Rolls-Royce SMR (UK)
- Rolls-Royce Submarines (UK)
- Vattenfall (Sweden)



Asia

- CGN Power [NEW]
- China National Nuclear Power
- Emirates Nuclear Energy Corp.
- Japan Atomic Power Company
- Kansai Electric Power Company
- Korea Hydro & Nuclear Power
- Kyushu Electric Power
- Shandong Nuclear Power Company
- Shikoku Electric Power Company

South America

- Eletronuclear S.A.

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MRP Team, Organization, and Advisory Structure for 2024

THE MRP TEAM



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Research Integration Committee

Provides TAC oversight and makes project funding

Chair: Pål Efsing, Vattenfall

Vice Chair OPEN

MRP RIC PM: Bob McGill

Technical Advisory Committees

Internals & Integrity

Chair - Corey Thomas, Southern

Vice Chair OPEN

MRP TAC PM - Elliot Long

All technical issues related to reactor pressure vessel internals assessment, stainless steel alloys, and reactor pressure vessel integrity

Pressure Boundary

Chair - Lora Drenth, Constellation

Vice Chair - John Robinson, Entergy

MRP TAC PM - Heather Malikowski

All technical issues related to nickel-based alloys and thermal, vibration, and environmentally-assisted fatigue

Inspection

Chair - Dale Brown, Southern

Vice Chair - Todd Davis, Constellation

MRP TAC PM - Bob Grizzi

All technical issues related to inspection technique, available equipment, and reliability of results

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Time-Limited Aging Analyses (TLAAs)

Time-Limited Aging Analyses (TLAAs)

- Per 10 CFR 54.3*, TLAAs are:
  - Involve systems, structures, and components {SSCs} within the scope of license renewal, as delineated in § 54.4(a);
  - Consider the effects of aging;
  - Involve time-limited assumptions defined by the current operating term, for example, 40 years;
  - Were determine to be relevant by the licensee in making a safety determination;
  - Involve conclusions or provide the basis for conclusions related to the capability of the system, structure, and component to perform its intended functions, as delineated in § 54.4(b); and
  - Are contained or incorporated by reference in the CLB {Current Licensing Basis}

*Code of Federal Regulations, 10 CFR 54.3, "Definitions," U.S. Nuclear Regulatory Commission, Washington, D.C., Federal Register, Volume 72, dated August 28, 2007.

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Time-Limited Aging Analyses (TLAAs)

Time-Limited Aging Analysis	Calculated Fluence	Pressurized Thermal Shock (PTS)	Upper-Shelf Energy (USE)	Pressure-Temperature (P-T) Limits for Heatup and Cooldown
Considers the Effects of Aging	YES	YES	YES	YES
Involves Time-Limited Assumptions Defined by the Current Operating Term	YES	YES	YES	YES
Involves SSC Within the Scope of License Renewal	YES	YES	YES	YES
Involves Conclusions or Provides the Basis for Conclusions Related to the Capability of SSC to Perform Its Intended Function	YES	YES	YES	YES
Determined to be Relevant by the Licensee in Making a Safety Determination	YES	YES	YES	YES
Contained or Incorporated by Reference in the CLB	YES	YES	YES	YES

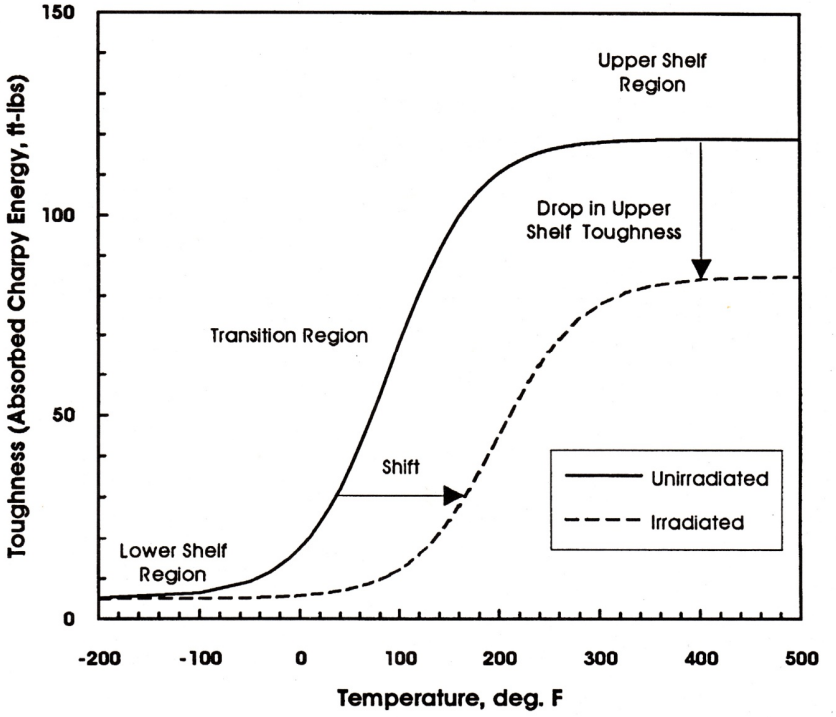
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Reactor Pressure Vessel (RPV) Integrity Approach

RPV Life Extension Analyses

What is Reactor Vessel Integrity?

Charpy V-notch Curves



Primary Reactor Vessel Integrity Regulations

Low Upper Shelf Toughness	Pressure-Temperature Limits	Reactor Vessel Material Surveillance	Pressurized Thermal Shock
10CFR50 Appendix G	10CFR50 Appendix G	10CFR50 Appendix H	10CFR50.61, PTS Rule
Reg. Guide 1.99 Rev. 2 (for calculating embrittlement effects) Reg. Guide 1.161 (for Equivalent Margins Analysis [EMA]) Reg. Guide 1.190 (Calculation & Dosimetry Methods for Determining RPV Neutron Fluence)	Reg. Guide 1.99 Rev. 2 (for calculating embrittlement effects) Reg. Guide 1.190 (Calculation & Dosimetry Methods for Determining RPV Neutron Fluence)	Reg. Guide 1.190 (Calculation of Capsule Fluence) NUREG-1801 Rev. 2 and NUREG-2191 (re: Surveillance Requirements in License Renewal and Subsequent License Renewal, respectively)	10CFR50.61a, Alternate PTS Rule Reg. Guide 1.230 for implementation of 10CFR50.61a Reg. Guide 1.190 (Calculation & Dosimetry Methods for Determining RPV Neutron Fluence)
ASME Section XI Appendix K (for Equivalent Margins Analysis [EMA])	ASME Section XI Appendices G & E	ASTM E185 (-73, -79, -82) (Testing & reporting per ASTM E185-82)	

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What Do I Do When…My plant goes for License Extension (40→60 years)?

- Key License Extension Point – NEW end-of-life (EOL) EFPY with projected fluence values thus being higher
- Report will be titled **T**ime-**L**imit **A**ging **A**nalysis (TLAA)
- Requires reassessment or update to *ALL* RPV Evaluations
  - New USE, ART and PTS values are developed
  - May need to withdraw and test another Surveillance Capsule to provide data for 60 or 80 years of operation
    - For example, if the new projected EOL fluence is greater than the highest tested capsule
  - Typically, only check existing P-T curves, new ones for a plant's SLR EFPY term can be developed later per 10 CFR 50, Appendix G
  - This is a good time to update or fully confirm material properties
    - May need to include extended beltline materials and/or RPV nozzles per NRC RIS 2014-011
- Inputs from this report will be provided to the NRC via a License Renewal Application (LRA) → See Section 4.2 for RPV Integrity of a standard LRA ←

None of these required reassessments are NEW for SLR (60→80 years) *and* beyond

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Appendix G to 10 CFR 50

- Upper Shelf Energy (USE):
  - Fracture toughness requirements for protection against ductile failure
  - RPV beltline materials at the 1/4 thickness (1/4T) location must have Charpy upper-shelf energy of no less than 75 ft-lb (102 J) and must maintain upper-shelf energy throughout the life of the vessel of no less than 50 ft-lb (68 J), unless equivalent margins of safety are shown
  - If the minimum USE requirement at end of life is not met, an Equivalent Margins Analysis (EMA) is required. To date, no plant has ever failed to demonstrate equivalent margins.
- Pressure-Temperature (P-T) Limits
  - Fracture toughness requirements for protection against brittle failure
  - Utilize Adjusted Reference Temperature (ART) values calculated at 1/4T and 3/4T
  - Provides Minimum Temperature Requirements and invokes ASME Section XI, Appendix G
    - Minimum temperatures for performing any hydrostatic test involving pressurization of the reactor vessel after installation in the system
    - Minimum temperatures for all leak and hydrostatic tests performed after the plant is in service
    - Maximum pressure-minimum temperature curves for operation, including startup, upset, and cooldown conditions
    - Maximum pressure-minimum temperature curves for core operation

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Appendix H to 10 CFR 50

- Establishes requirement for comprehensive surveillance programs
  - Prior to the introduction of Appendix H in 1973, plants had installed irradiation test samples using the guidance of the 1961 (tentative), 1962, 1966, 1970 or the then-emerging 1973 version of ASTM E-185
- RPVs that exceed 10^{17} n/cm^2 (E > 1 MeV) at the end-of-license are required to have an RPV material surveillance program
- The intent of surveillance programs is to monitor changes in the fracture toughness properties of ferritic materials in the RPV beltline that result from exposure to neutron irradiation and the thermal environment
- Augmented with License Renewal NUREGs (NUREG-2191, and -2192)
  - Withdraw one capsule that receives a neutron fluence of between one and two times the peak reactor vessel wall neutron fluence at the end of the period of extended (60-years, then 80-years) operation
  - Can necessitate additional capsule withdrawal and testing and/or capsule reinsertion for further irradiation and/or new capsule fabrication, etc.

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10 CFR 50.61 – PTS Rule

- Fracture toughness requirements for protection against pressurized thermal shock events
- RT_{PTS} is determined for all RPV beltline plates and/or forgings, and axial and circumferential welds
  - RT_{PTS} is ART at the vessel ID surface (not the 1/4T as for P-T curves)
  - Based on end of license (EOL) fluence
  - Screening limits:
    - 270°F (132°C) for plates, forgings, and axial welds
    - 300°F (149°C) for circumferential welds
- If RT_{PTS} exceeds these screening limits, most common actions required:
  - Implement flux reduction programs, where reasonably practicable
  - Or apply for licensing under the Alternative PTS Rule, 10 CFR 50.61a

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Consideration of Extended Beltline in RPV Evaluations

- For developing P-T limits and evaluating other aspects of RPV integrity, it is important to know which portions of the RPV are located within the projected extended beltline region
  - Based on the applicable fluence limit
  - Based on the end of the operating period, i.e., the time when the fluence will be greatest (so the beltline region will be largest)
- This may include components that were not evaluated for embrittlement effects as a part of the original RPV design
  - Other components may require embrittlement evaluation for longer term operation (e.g., 60 years compared to original 40-year design)
- Definition has evolved over-time, most recently clarified in RIS 2014-11*
  - "…the beltline definition in 10 CFR Part 50, Appendix G is applicable to all reactor vessel ferritic materials with projected neutron fluence values greater than 1 x 10^{17} n/cm^2 (E > 1 MeV)"

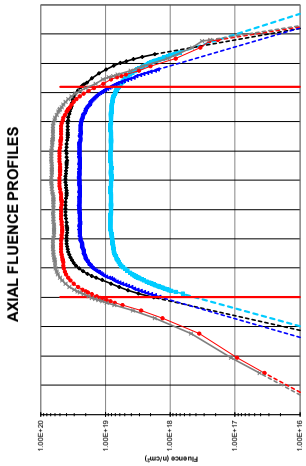
***U.S. NRC Regulatory Issue Summary (RIS) 2014-11, "*Information on Licensing Applications for Fracture Toughness Requirements for Ferritic Reactor Coolant Pressure Boundary Components*" October 2014 (ML14149A165)**

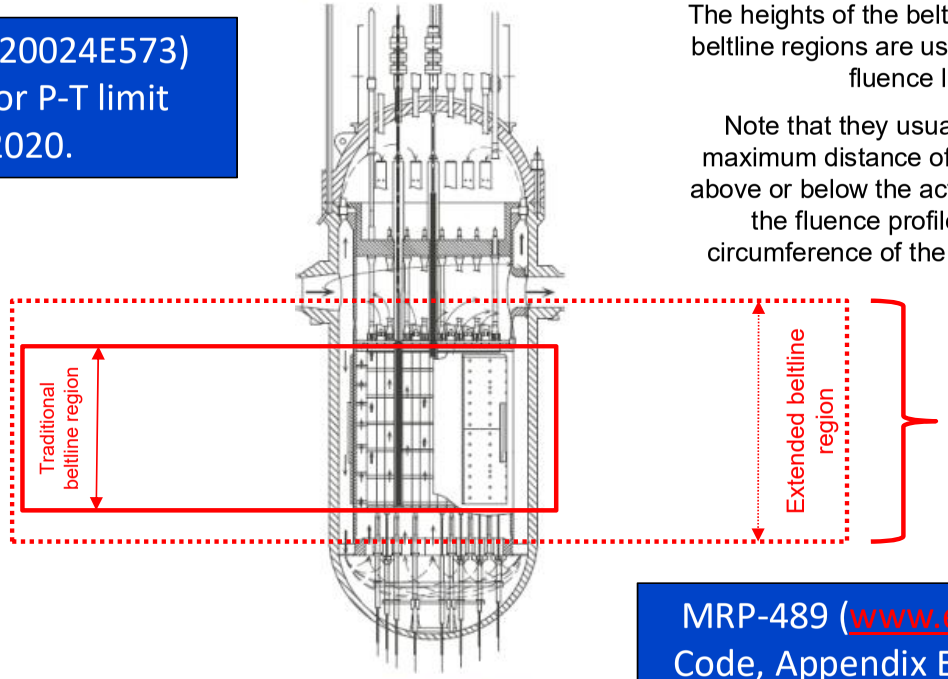
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Extended Beltline Definition continued

- As plants operate for longer periods, the beltline region can “grow”
- This is sometimes referred to as the “extended beltline” region
- Despite the different terminology, these definitions are intended to define the region where embrittlement effects are significant and must be evaluated

PWROG-15109-NP-A, R0 (ML20024E573) dispositioned RPV Nozzles for P-T limit curves generically in 2020.





The heights of the beltline and extended beltline regions are usually defined by a fluence limit.

Note that they usually indicate the maximum distance of the fluence limit above or below the active fuel (because the fluence profile around the circumference of the RPV is not flat).

Height expands with increased length of plant operation

MRP-489 (www.epri.com) is updating ASME Code, Appendix E to account for RPV Nozzles

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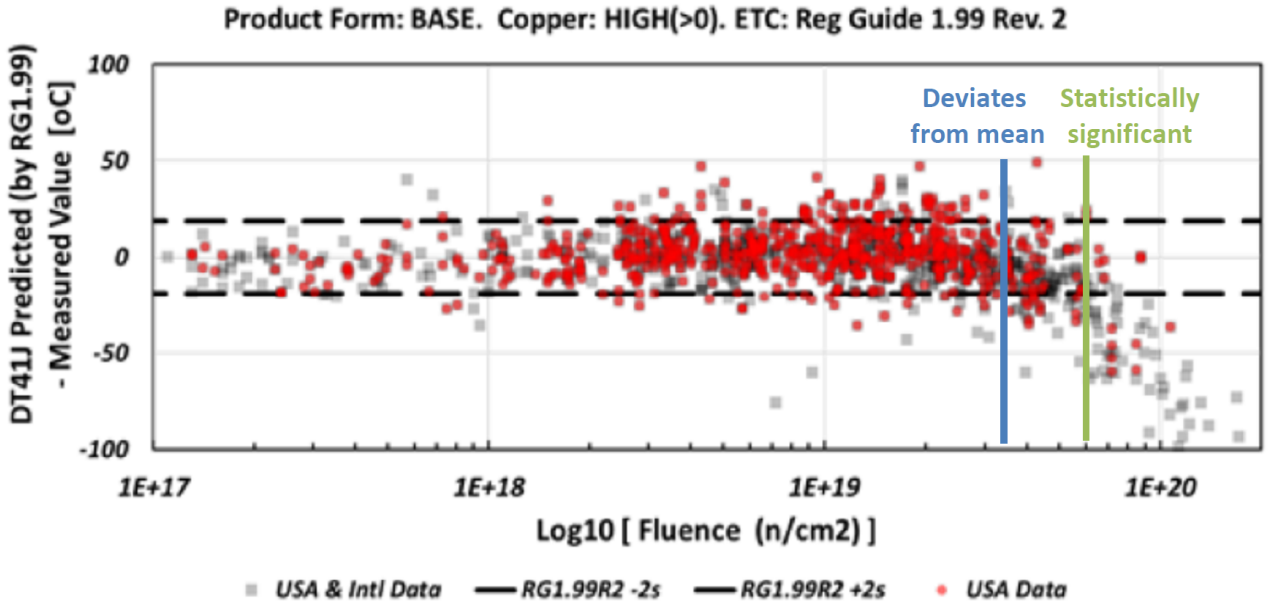
Potentially OPEN Long-Term Operation (LTO) Gap in Reactor Pressure Vessel Integrity

Embrittlement Trend Curves

- May 1988, NRC published RG 1.99, which contained an improved embrittlement trend curve (ETC)
  - Fit based on 177 datapoints, mainly at fluence values below 3.5 n/cm^2
- June 1991, NRC updated 10 CFR 50.61 to include the ETC from RG 1.99
- This ETC was re-evaluated for continued adequacy in 2014 (ML13346A003) and in more detail in 2019 (ML19203A089)
- The 2019 re-evaluation uncovered a loss of accuracy for the ETC at high fluence levels (for plate materials) – *See next Slide*
- Much effort by industry and NRC Staff, and many public meetings from 2019 – 2022, lead to the generation of SECY 22-0019 requesting the Commissioners to approve a Rulemaking plan for a potential revision to the ETC contained in RG1.99R2

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RG1.99R2 ETC at High-Fluence for Base Metal



- There remains high confidence that currently operating plants are safe
- As of 2022, there exists 10-years for PTS and 23-years for P-T limits before the first plants are projected to cross the statistically significant threshold
- More data at high fluence is needed to confirm conclusions drawn in ML19203A089

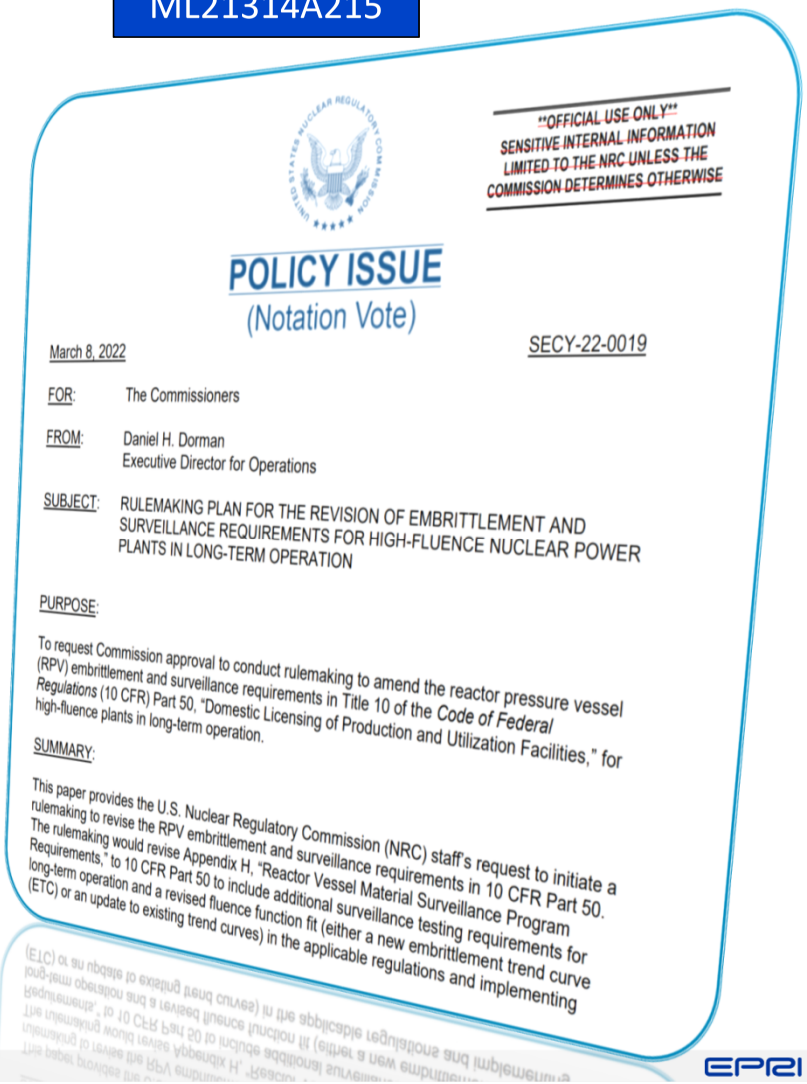
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Rulemaking Plan: SECY-22-0019

- Identified need to generate high fluence data to confirm long-term embrittlement of RPV steels
- Confirmed
  - 6 x 10^{19} n/cm^2 is the critical fluence threshold when the current ETC presented in RG1.99R2 loses accuracy
  - The preferred model for long-term, high fluence operation is ASTM E900-15
- Recommends Alternate 2 – Focused Solution
  - "A revised fluence function fit (e.g., a new ETC or an update to existing ETCs) would be developed for only RPV materials that will experience high neutron fluence levels and would be appropriately implemented in a manner to be determined in the applicable regulations and guidance."

EPRI started a project to *gather high fluence surveillance data* supporting this 2022 SECY Position back in 2012 – the PSSP!

ML21314A215



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COMMISSION DETERMINES OTHERWISE

POLICY ISSUE
(Notation Vote)

March 8, 2022 SECY-22-0019

FOR: The Commissioners

FROM: Daniel H. Dorman
Executive Director for Operations

SUBJECT: RULEMAKING PLAN FOR THE REVISION OF EMBRITTLEMENT AND SURVEILLANCE REQUIREMENTS FOR HIGH-FLUENCE NUCLEAR POWER PLANTS IN LONG-TERM OPERATION

PURPOSE:

To request Commission approval to conduct rulemaking to amend the reactor pressure vessel (RPV) embrittlement and surveillance requirements in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities," for high-fluence plants in long-term operation.

SUMMARY:

This paper provides the U.S. Nuclear Regulatory Commission (NRC) staff's request to initiate a rulemaking to revise the RPV embrittlement and surveillance requirements in 10 CFR Part 50. The rulemaking would revise Appendix H, "Reactor Vessel Material Surveillance Program Requirements," to 10 CFR Part 50 to include additional surveillance testing requirements for long-term operation and a revised fluence function fit (either a new embrittlement trend curve (ETC) or an update to existing trend curves) in the applicable regulations and implementing

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MRFA 4.1.3 PWR Supplemental Surveillance Program (PSSP)

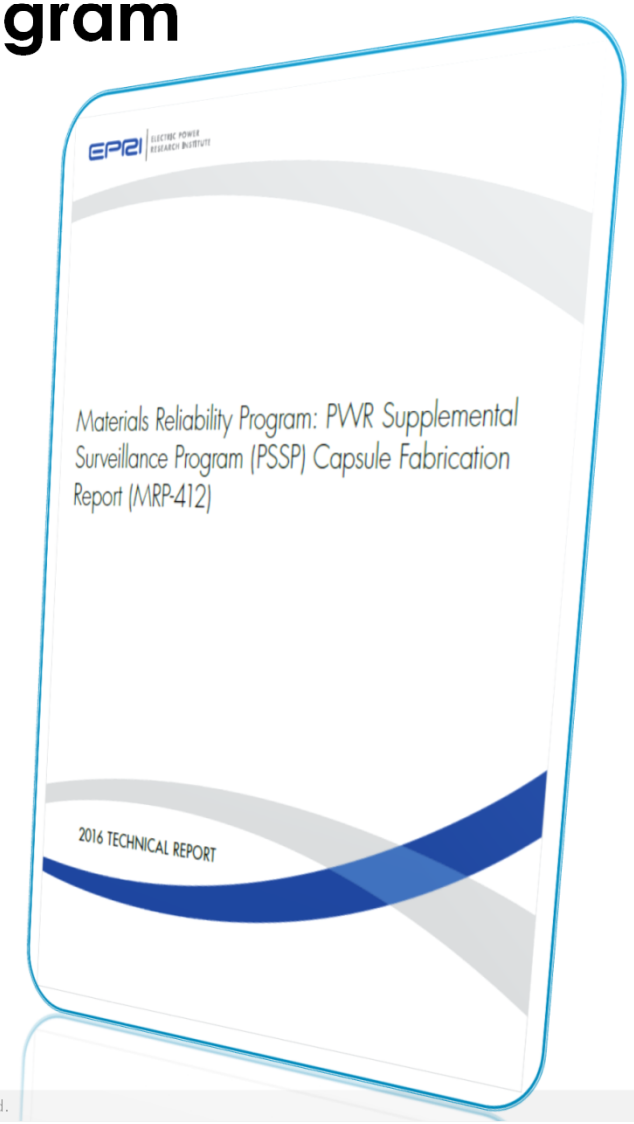
PWR Supplemental Surveillance Program (PSSP)

- Materials Issue Being Addressed:
  - Additional high-fluence ($f > 5.0 \times 10^{19}$ n/cm^2) surveillance data is needed to inform development of embrittlement trend correlations (ETCs) applicable for RPV operation to high fluence (60+ years)
- Objectives of the Project:
  - Fill projected gaps in the tested surveillance capsule database
  - Inform future ETCs using actual RPV surveillance materials from commercial PWRs (not test reactor data)
- Project Goal: Irradiate two supplemental surveillance capsules for ~10 total years before withdrawal, testing, evaluation, and publication of capsule test reports
  - These two surveillance capsules have 288 Charpy Specimens from 27 unique plates, forgings and welds
  - The data generated from these capsules will ultimately yield 24 new transition temperature shift results and 3 additional upper shelf energy results
    - Fluence levels of the to be evaluated specimens will range from ~4.5E+19 up to ~1.2E+20 (n/cm^2)

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PWR Supplemental Surveillance Program

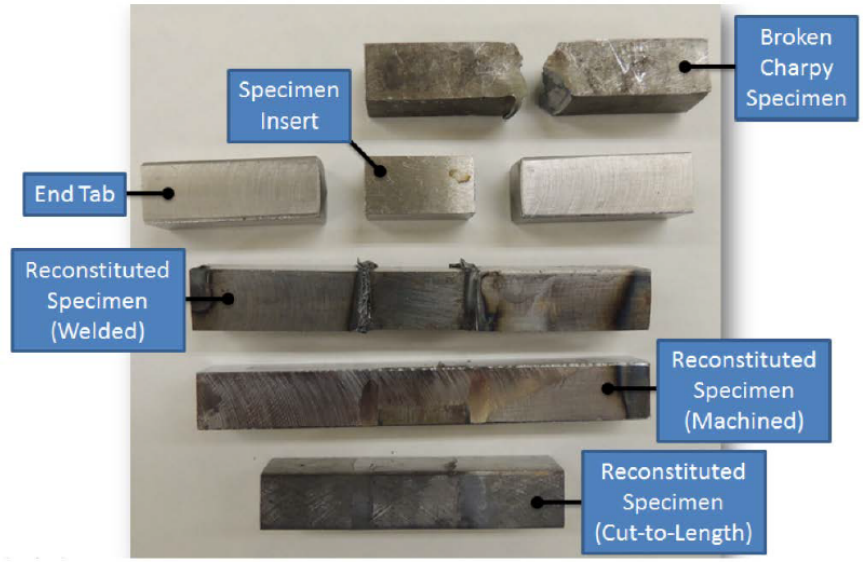
- Project History (2012 – 2024 and counting)
  - Program designed and fabricated 2 supplemental surveillance capsules containing previously-irradiated, reconstituted PWR materials
  - EPRI MRP sponsored the fabrication of these 2 surveillance capsules:
    - ALA-P; 14 materials (Host: Farley 1), inserted October 2016
    - CQL-P; 13 materials (Host: Shearon Harris), inserted April 2018
  - MRP-412 (PSSP Capsule Fabrication report) was published in 2016

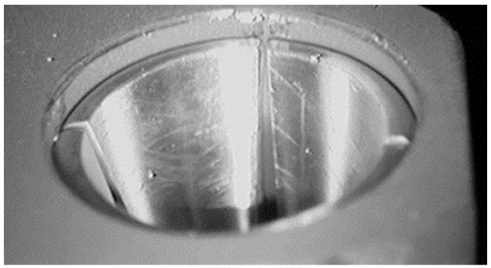


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PWR Supplemental Surveillance Program

- Project Status and Future Timeline
  - White paper evaluation of current status of PSSP Program – underway in 2024
  - Farley 1 Capsule P to be withdrawn in Spring 2027; Shearon Harris Capsule P in Fall 2028 per MRP-326, R1
  - Testing of surveillance capsules and data evaluation in 2028-2030
  - Anticipated Project Deliverable Date:
    - Capsule report within ~18 months of each capsules' withdrawal date (2 reports total)
  - Data evaluation and impact on future ETCs in 2030-2032 (Report No. 3?)
- Data can be used to confirm and support conclusions of SECY-22-0019
  - Provide inputs to develop the best possible ETC into 80-years of life (and potentially beyond).





PSSP Capsule seated in its holder

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PWR Supplemental Surveillance Program (PSSP)

- The flux for the irradiation locations in Farley and Harris is about 1.2 x 10^{11} n/cm^2/s
  - This amounts to a fluence of about 3.5 x 10^{19} n/cm^2 over 10 years.
- Ten years was originally selected as a reasonable time frame that will produce sufficiently high fluence applicable to extended operation
- Fluence level and planning time-frame is consistent with the horizon for the Coordination PWR Reactor Vessel Surveillance Program (CRVSP, MRP-326, Revision 1)
- EPRI and Industry have been reviewing options to confirm capsule pull schedule
  - Options included:
    - No change to the original ten-year plan?
    - Let one capsule irradiate longer, and test the other as planned? → If so, which one?
    - Let them both capsules irradiate longer? If so, how long or until when, etc.?

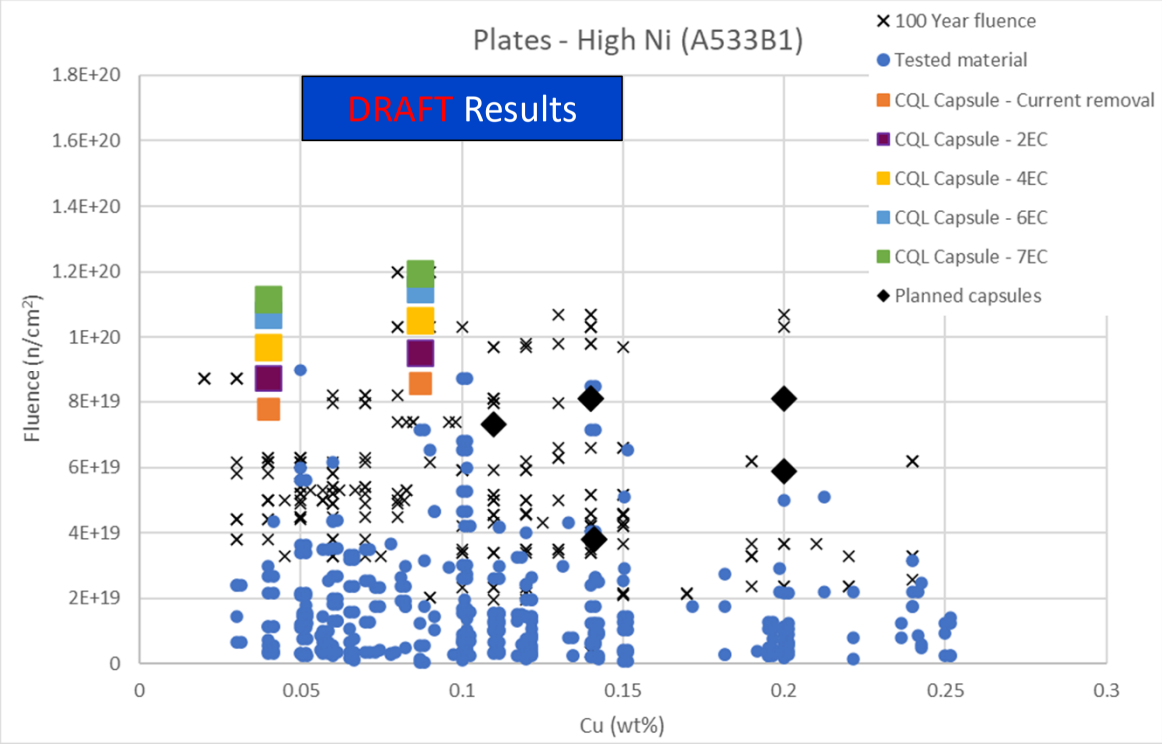
Farley Capsule P			
Range	Material	Fluence (n/cm^2)	
		Initial	Final
Max	Plate and Weld	8.72E+19	1.22E+20
Min	Weld	1.04E+19	4.54E+19

Harris Capsule P			
Range	Material	Fluence (n/cm^2)	
		Initial	Final
Max	Weld	6.53E+19	1.00E+20
Min	Forging	9.84E+18	4.48E+19

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PSSP White Paper

- The two capsules contain previous irradiated, reconstituted materials from several sources inserted in Farley Unit 1 RPV and in Shearon Harris RPV
  - Aim is to evaluate if one or both capsule withdrawal should be delayed to achieve fluences levels to inform 100 years operation to provide data to better understand embrittlement trend correlations at the these high fluence levels
- The graph is a draft example of the data being explored in the paper
  - For the CQL capsule, it *might* make sense to delay withdrawal to obtain ~100-year fluence
  - However, all 13 materials in this capsule must be considered



- Fluence as function of Cu content for RPV plates. The graph shows:
  - Updated to expected 100-year fluence for operating plant RPV plate materials
  - Materials that have already been tested
  - Capsules that are planned to be tested in the future.
  - Peak fluence for the materials in the PSSP CQL capsule, based on possible retrieval dates: 2EC = 2 added exposure cycles

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PSSP White Paper

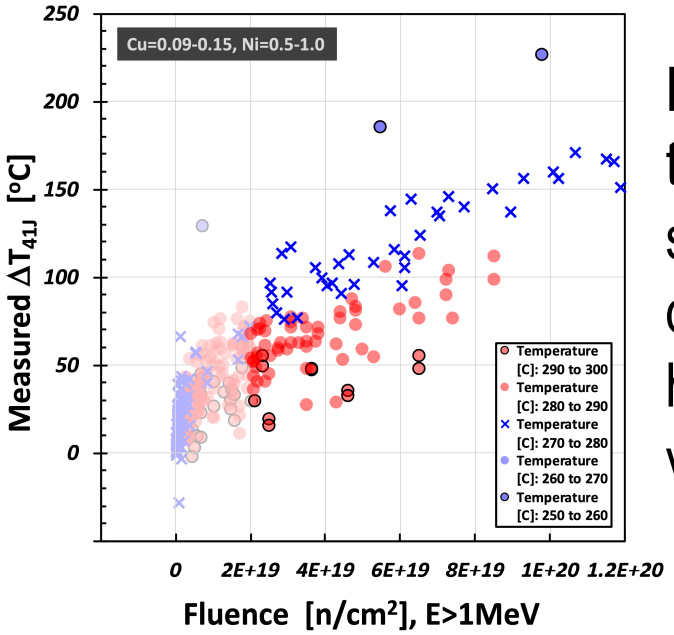
- The PSSP white paper is the in-depth plan for these materials.
- The plan includes
  - Update on tested capsule data and future planned testing
  - Update on plant RPV fluence for 100 years
  - Fluence projection for several cycles
    - Farley Unit 1 Spring 2027 and Harris Fall 2028 (delay to produce higher fluence?)
  - Detailed experimental plan for the materials including combined Charpy and T_0 testing (using mini-CTs), if practical and beneficial
  - Budgets and timing associated with each step of the project
- Draft Report from Vendor expected in September
  - Further discussion at the November TAC meetings in Los Angelos

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ASTM E900 Improvements and Enhancements

Proposed Program: ASTM E900 Improvements and Enhancements

- ASTM E900 ΔT_{41J} ETC
  - Adopted in 2015
  - Re-affirmed by ASTM in 2022
  - Evaluated in MRP-484 in 2023
- These efforts show that while E900 is acceptable
  - Improvements to fluence and nickel representation are possible
  - These improvements may become more important when high-fluence data becomes available (PSSP)
- Objectives
  - Proactively address fluence and nickel lack of fit before PSSP data become available
  - Provide alternative methods for high-fluence ΔT_{41J} prediction for use during license renewal



Embrittlement trends are simpler to describe at higher fluence values

- Benefits
  - PSSP data will validate E900-future rather than call it into question
  - Potentially simpler options for high-fluence ΔT_{41J} predictions

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Wrap-up

So, what Do I Do When…My plant goes for *Second* License Extension *(60→80 years)?*

- The Key License Extension Point *still* holds – NEW end-of-life (EOL) EFPY with projected fluence values thus being higher
  - Report will *still* be titled **T**ime-**L**imit **A**ging **A**nalysis (TLAA)
- Secondly, remember our common theme for RPV Integrity
  - There is a well established & successful framework of what to do to go from 40 – 60 years of operation, and now 60 – 80 years.
  - Any given licensing period with a +20-year extension is no different.
- In support of SECY-22-0019, EPRI is pro-actively
  - Collecting additional high fluence data (PSSP)
  - Assessing the applicability of ASTM E900 and, if needed, providing alternatives/updates

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Questions / Discussion





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Back-up Slides

2024 MRFA 4 Ongoing Deliverables

Deliverables for MRFA #4: Low Alloy Steels

- 2024
  1. MRP-489 – Technical Basis Report for Application of ASME XI Appendix E to Vessel Nozzles <COMPLETE>
  2. MRP-491 – Summary of Testing Completed on Harvested Low-Alloy Pressurizer Steel from Indian Point Unit 2
- 2025
  1. MRP-490 - Technical Basis Document on 100°F/hour Heat-up and Cooldown Rates in RPV P-T Limit Curves
  2. MRP-462, Revision 1 – Methods to Address the Effects of Irradiation Embrittlement in Section XI of the ASME Code
  3. MRP-418, Revision 2: Technical Basis for ASME Code CC N-830-2
  4. MRP-TBD – Development of T_0-based Embrittlement Trend Curve
  5. MRP-TBD – Development of a Revised E900-15 Embrittlement Trend Curve <NEW>

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