Addressing Reactor Pressure Vessel Integrity for LTO

International Conference on Long-Term Operation (LTO) of Nuclear Power Plants

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Outline

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- RPV Material Surveillance
- Extended Beltline
- Update to ASME Section XI Appendix E
- Upper Shelf Energy – ASME Section XI Appendix K
- Summary and Conclusions

Background

- As nuclear LWRs operate longer, the low-alloy steel reactor pressure vessel (RPV) is exposed to higher total accumulated neutron fluence and subjected to increased irradiation embrittlement.
- Regulations around the world regarding reactor vessel integrity for LWRs require:
  - Protection of ferritic steel from brittle fracture. In the U.S. ➔ 10 CFR 50 Appendix G
  - A reactor vessel material surveillance program to monitor irradiation embrittlement and inform the prediction of embrittlement. In the U.S. ➔ 10 CFR 50 Appendix H
- Replacement of the RPV has not been attempted in the worldwide reactor fleet and compliance with reactor vessel integrity regulations has the potential to be a limiting consideration for LTO.
- This presentation will discuss several recent initiatives relative to addressing RPV integrity challenges for LTO.

RPV Material Surveillance

RPV Material Surveillance

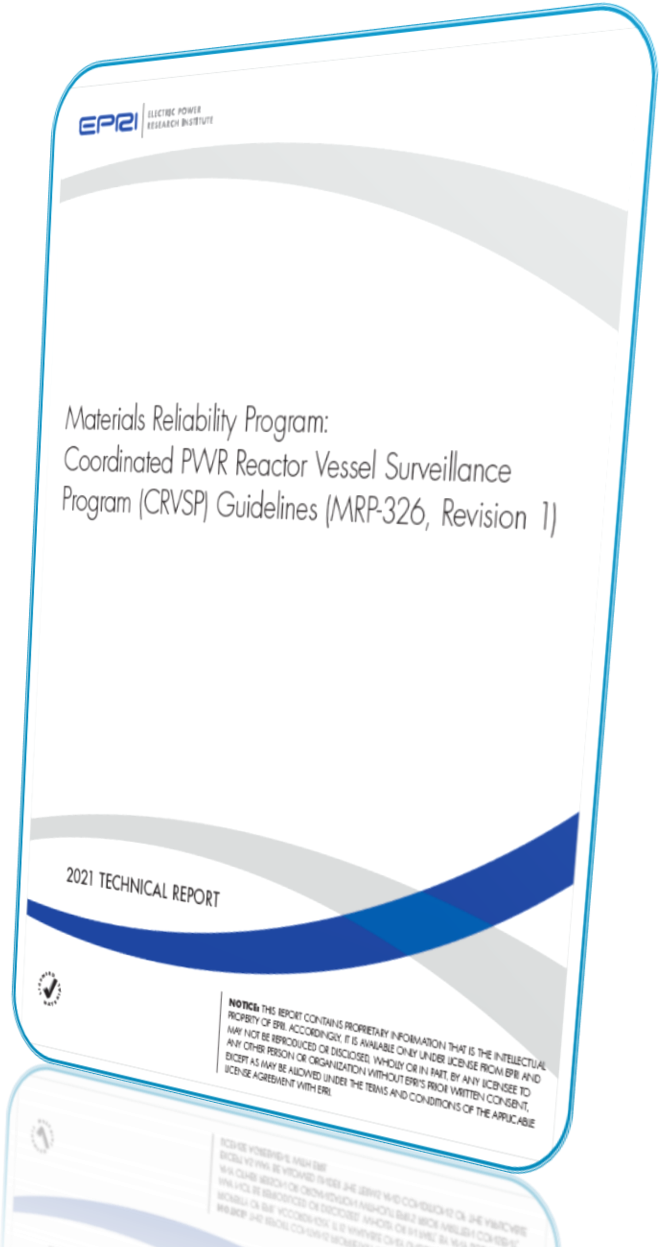
- Long Term Operation presents two main issues for RPV material surveillance:
  - Regulations typically require additional surveillance data that is enveloping of RPV fluence exposures at the end of the plant's extended operating license
  - Higher fluence surveillance data may be needed to substantiate the accuracy of embrittlement trend curves (ETCs) at the higher RPV fluences
    - In the U.S., NRC noted a need to generate high fluence data in SECY-22-0019 to confirm long-term embrittlement of RPV steels
    - RG 1.99 R2 observed to lose accuracy at a fluence of 6 x 10^{19} n/cm^2
- Addressing these issues can be challenging because:
  - Surveillance specimens are limited
  - Locations for insertion of specimens in the RPV are limited
  - Obtaining the needed fluence exposure can take a long time

Coordinated PWR Reactor Vessel Surveillance Program (CRVSP)

- Materials Issue Being Addressed:
  - Optimize the U.S. PWR surveillance capsule withdrawal schedules to increase the amount of high-fluence ($f > 3.0 \times 10^{19}$ n/cm^2) surveillance data which can be used to inform development of embrittlement trend correlations (ETCs) applicable for RPV operation to high fluence (60+ years).
- Objectives of the Project
  - Revision 0 (2011): Review the reactor vessel surveillance programs (RVSPs) of the operating U.S. PWR fleet and recommend changes to selected RVSP withdrawal schedules in order to increase the amount of high fluence surveillance data by 2025.
  - Revision 1 (2021): Review of how we did, what has occurred, what's left to do, and when it is most likely to happen across the US fleet
- Updates to the evaluation include
  - Evaluated capsules withdrawn since 2011
  - Future capsule pull schedules
  - Capsule fluence values
  - Analysis of closed (or to be closed) plants

Update to the CRVSP, MRP-326, Revision 1

- Current high fluence capsule withdrawal results
  - 16 out of 30 CRVSP Capsules are tested or planned to be tested
  - There are 14 remaining CRVSP Capsules
    - Half of these are not planned to be tested (i.e., due to plant shutdown) or will be delayed beyond 2025
- Summary of available high fluence data
  - 48 U.S. capsules have been tested at f > 3.0 x 10^{19} n/cm^2
    - 4 of these are f > 8.0 x 10^{19} n/cm^2
  - By 2025, the remaining 7 planned CRVSP capsules will be tested at f > 3.0 x 10^{19} n/cm^2
    - 2 of these are predicted to be f > 8.0 x 10^{19} n/cm^2

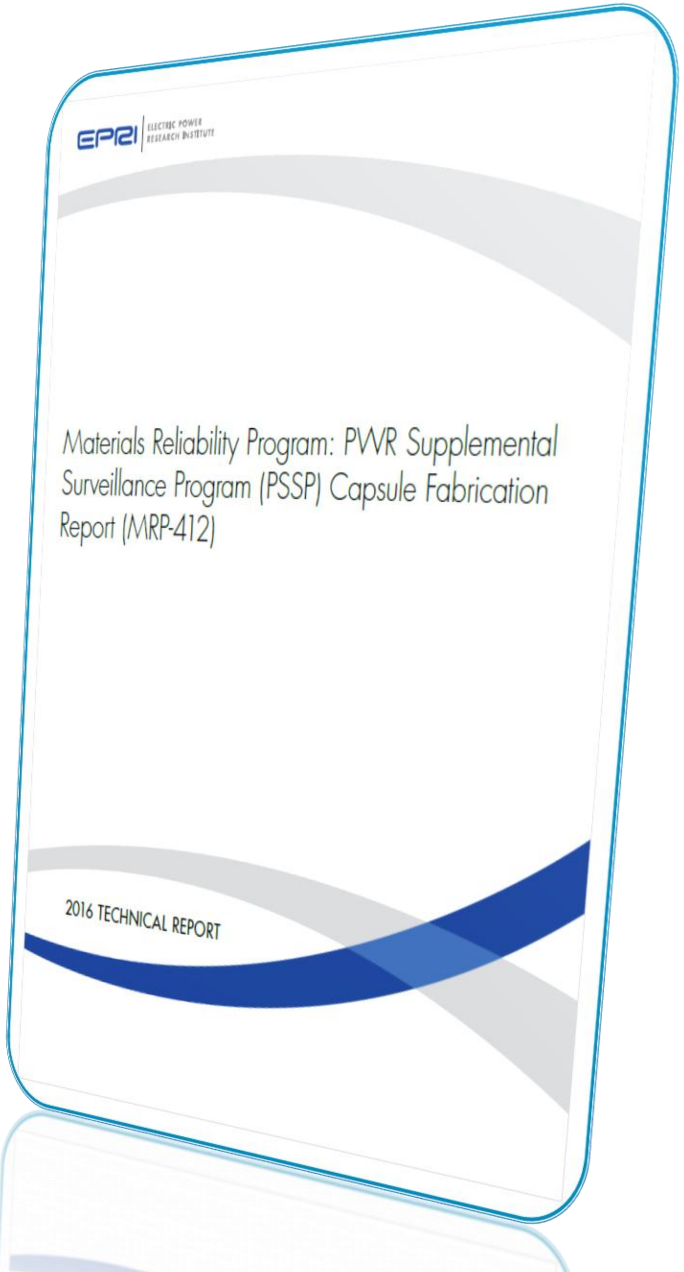


PWR Supplemental Surveillance Program (PSSP)

- 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)
- End game: 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
    - Fluences levels of the to be evaluated specimens will range from ~4.5E+19 up to ~1.2E+20 (n/cm^2)

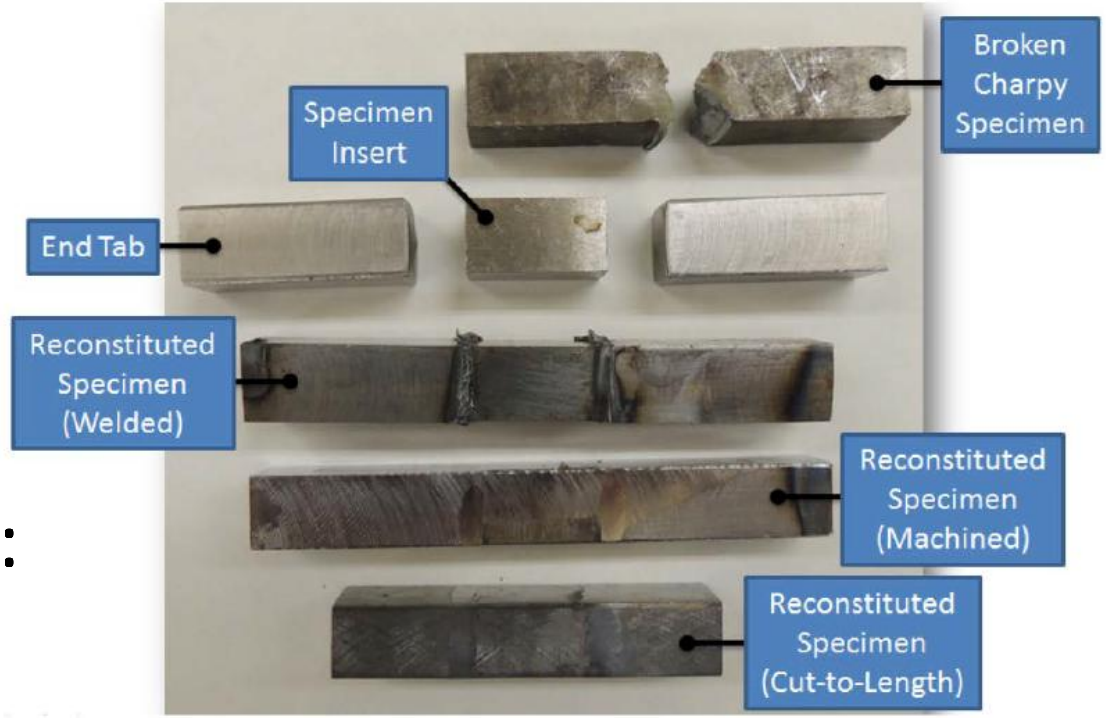
PSSP Project History

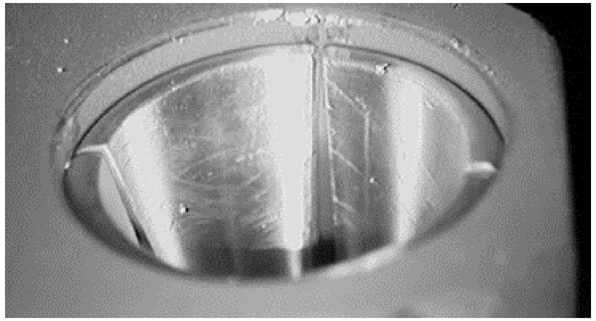
- Program designed and fabricated 2 supplemental surveillance capsules containing previously-irradiated, reconstituted PWR materials
- MRP-364 (Materials Selection report) was published in 2013
- EPRI MRP sponsored the fabrication of these 2 surveillance capsules:
  - ALA-P; 14 materials (Host: Farley 1), inserted October 2016
  - CQL-P; 13 materials (Host: Shearon Harris), inserted April 2018
- MRP-412 (PSSP Capsule Fabrication report) was published in 2016



PSSP Current Project Status and Timeline

- Farley 1 Capsule P to be withdrawn in Spring 2027; Shearon Harris in ~2035
- 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

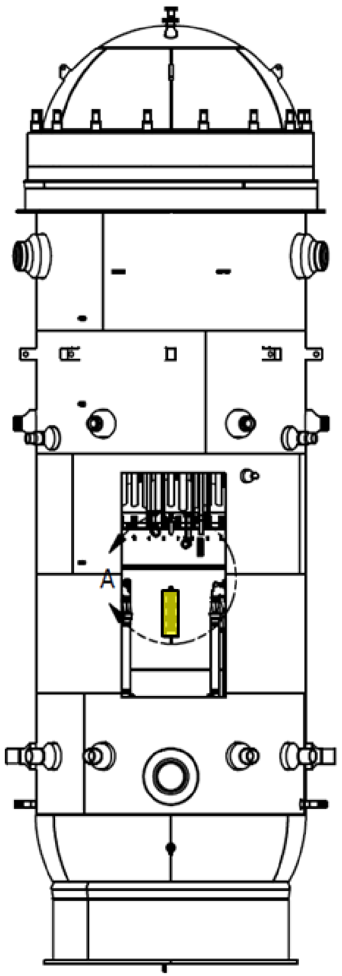




PSSP Capsule seated in its holder

BWRVIP Integrated Surveillance Program for 80 years

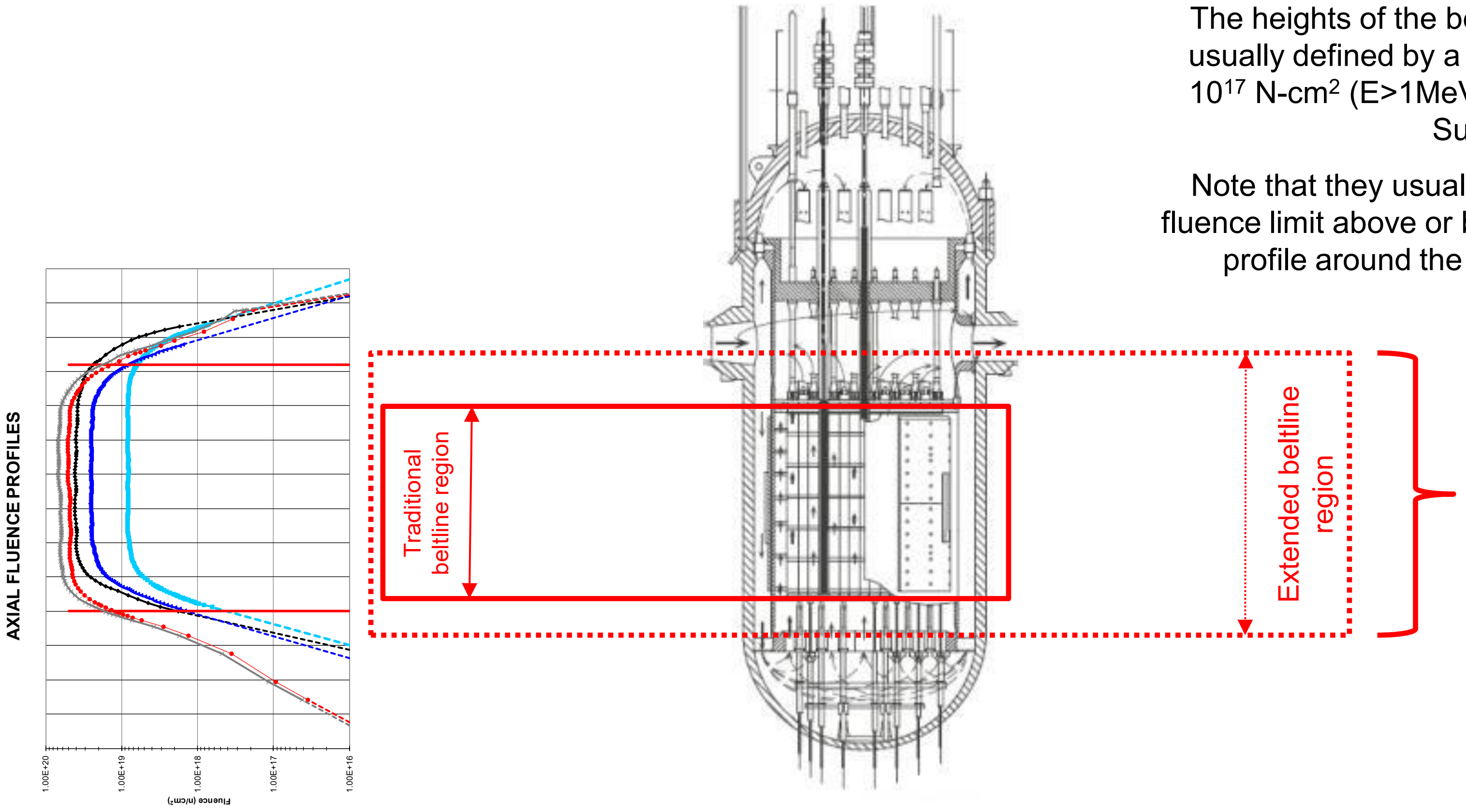
- Materials Issue Being Addressed:
  - The U.S. BWR fleet uses an integrated surveillance program (ISP) which withdraws capsules from 13 host plants to provide representative surveillance data for the entire fleet.
  - After 60 years, most of the host plants will have no surveillance capsules remaining.
- Objectives of the Project:
  - Provide additional surveillance data for the U.S. BWR fleet that has a total accumulated fluence that is enveloping of 80-year RPV fluence values
- Current Status:
  - Extension to ISP program plan approved by U.S. NRC (BWRVIP-321, Rev. 1-A)
  - Specialized surveillance capsule installed in a single host plant in 2023
    - Contains 322 specimens comprising 23 different RPV materials
    - Attached directly to the core shroud to increase flux and decrease needed exposure time
  - Capsule is scheduled for withdrawal and testing in 2035



Extended Beltline

Extended Beltline Definition

- Historically, the RPV beltline was defined as the region immediately adjacent to the reactor core
- 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



The heights of the beltline and extended beltline regions are usually defined by a fluence limit. In the U.S., the limit is 1 x 10^{17} N-cm^2 (E>1MeV) based on U.S. NRC Regulatory Issue Summary (RIS) 2014-11

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

Consideration of Extended Beltline in RPV Evaluations

- For evaluating RPV integrity in LTO, 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
  - Need to consider RPV nozzles is a notable issue
    - PWROG developed and obtained NRC approval for report PWROG-15109 which demonstrated that nozzles will not control PWR P-T limit curves.
    - Need to address other aspects of RPV integrity for nozzles remains
  - Pedigree of records or certification testing may be lacking for some components that were not expected to be in the beltline at the time of design
    - May require conservative treatment of these components which may make evaluation of RPV integrity requirements challenging

Update to ASME Section XI Non-Mandatory Appendix E

Update to ASME Section XI Appendix E

- Materials Issue Being Addressed:
  - ASME Section XI, Nonmandatory Appendix E, "Evaluation of Unanticipated Operating Events" provides acceptance criteria and guidance for performing an evaluation of the effects of an out-of-limit condition on the structural integrity of the reactor vessel beltline region
    - i.e., violation of plant Pressure-Temperature (P-T) curves
  - Criteria in Appendix E for isothermal pressure transients are based on T_C - RT_{NDT} and are limited to -200˚F (-111˚C), which may not be adequate for some plants pursuing LTO
  - The technical basis for Appendix E addressed the PWR shell only and did not consider RPV nozzles, which now have potential to be limiting for normal operating conditions or out of limit conditions
- Objectives of the Project:
  - Extend applicability of Appendix E to higher RT_{NDT} values
  - Update Appendix E so that it covers nozzles as well as the beltline shell
- Current Status:
  - Technical basis for updates developed and documented in EPRI report MRP-489
  - Changes currently being considered by ASME Section XI committees
  - MRP-489 Rev. 1 under development to address comments received from SCXI committees

Technical Basis for Appendix E Changes – MRP-489 R1 (1/2)

- Isothermal Pressure Transients
  - Deterministic fracture mechanics analyses performed to determine allowable pressure as a function of T_C-RT_{NDT}
  - Analyses performed consistent with basis for original pressure limits, with the following updates:
    - Separate consideration of circumferential welds
    - Use of master curve fracture toughness
    - Use of latest stress intensity factor correlations in ASME Section XI Appendix A
  - FAVOR Probabilistic fracture mechanics analyses performed to assess conservatism of limits with respect to a risk goal of CPF < 1 E-6/yr

Existing Limits

Table E-1
Maximum Allowable Pressure as a Function of $T_c - RT_{NDT}$ for Isothermal Pressure Transients [$\Delta T_c/\Delta t$ < 10°F/hr (5.5°C/h)] for Design Pressures Greater Than 2,400 psig (16.5 MPa)

$T_c - RT_{NDT}$ °F (°C)	Maximum Allowable Pressure, psig (MPa)
+ 25 (14) and greater	1.1 × Design
+ 15 (8)	2400 (16.5)
+ 10 (5.5)	2250 (15.5)
0 (0)	2000 (13.8)
−10 (−5.5)	1750 (12.1)
−25 (−14)	1500 (10.3)
−50 (−28)	1200 (8.3)
−75 (−42)	1000 (6.9)
−105 (−58)	850 (5.9)
−130 (−72)	800 (5.5)
−200 (−111)	750 (5.2)

GENERAL NOTE: Linear interpolation is permitted.

Table E-2
Maximum Allowable Pressure as a Function of $T_c - RT_{NDT}$ for Isothermal Pressure Transients [$\Delta T_c/\Delta t \leq$ 10°F/hr ($\leq$5.5°C/hr)] for Design Pressures Greater Than 2,400 psig (16.5 MPa)

T_c - RT_{NDT} °F (°C)	Maximum Allowable Pressure psig (MPa)	
	Axial Welds, Plates, Forging	Circumferential Welds
+25 (14) and greater	2350 (16.2)	1.1 x Design
+15 (8)	2000 (13.8)	1.1 x Design
+10 (5.5)	1900 (13.1)	1.1 x Design
0 (0)	1650 (11.4)	1.1 x Design
-10 (-5.5)	1450 (10.0)	1.1 x Design
-25 (-14)	1200 (8.3)	2250 (15.5)
-50 (-28)	950 (6.6)	1750 (12.1)
-75 (-42)	800 (5.5)	1500 (10.3)
-100 (-56)	700 (4.8)	1300 (9.0)
-125 (-69)	650 (4.5)	1200 (8.3)
-150 (-83)	600 (4.1)	1150 (7.9)
-175 (-97)	550 (3.8)	1000 (6.9)
-195 (-108)	500 (3.4)	900 (6.2)
-210 (-117)	450 (3.1)	800 (5.5)
-240 (-133)	400 (2.8)	700 (4.8)
-270 (-150)	350 (2.4)	650 (4.5)
-300 (-167)	300 (2.1)	600 (4.1)
Less than -300 (-167)	250 (1.7)	450 (3.1)

GENERAL NOTE: Linear Interpolation is permitted

Proposed Limits (Now Table E-2)

Technical Basis for Appendix E Changes – MRP-489 R1 (2/2)

- Applicability of Appendix E to RPV Nozzles
  - FAVOR PFM analyses performed for RPV shell and RPV nozzles
    - Used to determine allowable pressure as a function of temperature and cooldown rate where a risk goal of CPF=1E-6/yr was met
    - Nozzle analyses considered elevated stresses determined from FEA
  - Resulting P-T limits of shell and nozzle compared to assess when nozzles may be limiting – Shell region bounding in most cases
    - If RT_{MAX}* > 60°F (15.6˚C), nozzles are not limiting
    - If RT_{MAX}* < 60°F (15.6˚C), nozzles may be limiting, unless specific P-T limits of Table E-1 for the nozzle corner can be met
    - Plant specific analysis including nozzles needed if P-T limits of new Table E-1 cannot be met

    *RT_{MAX} = RT_{NDT} – margin

Table E-1
Allowable Minimum Temperature as a Function of Pressure for the Outlet Nozzle Corner

Pressure, ksi (MPa)	Allowable Minimum Temperatures[1], °F [°C]
2.50 (17.2)	116 (47)
2.00 (13.8)	110 (43)
1.50 (10.3)	100 (38)
1.00 (6.9)	88 (31)
0.50 (3.4)	70 (21)
0.25 (1.7)	59 (15)
0.0 (0.0)	50 (10)

[1] Allowable Minimum Temperature is based on bulk coolant temperature

GENERAL NOTE: Linear Interpolation is permitted

Upper Shelf Energy
Update to ASME Section XI Non-Mandatory Appendix K

Update to ASME Section XI Appendix K

- Materials Issue Being Addressed:
  - ASME Section XI, Nonmandatory Appendix K, provides acceptance criteria and analytical evaluation procedures for determining acceptability for continued operation of a reactor vessel with low upper shelf energy – In the U.S., less than 50 ft-lb (68J)
    - Often referred to as an “equivalent margins analysis”
  - Appendix had not been updated in 30+ years and lacks information needed to perform evaluations
  - As plants pursue LTO, increased use of Appendix K is possible
- Objectives of the Project:
  - Update Appendix K to include detailed information on selection of a J-integral resistance (J-R) curve
  - Include additional information to improve useability, including limiting transient selection
- Current Status:
  - Approved by ASME. Published in the 2025 Edition of Section XI

Revised Appendix K

- Paragraph K-3300 now identifies four options with specific requirements including crack orientation, temperature, and irradiated neutron fluence conditions:
  1. **A *J-R* curve generated following ASTM E1820.** A best-estimate J-R curve shall be developed based on the mean of the measured data including all multiple tests. A minimum of three measurements shall be performed to adequately characterize the scatter in upper shelf toughness. A conservative fracture toughness curve shall be developed representing the lowest measured test data.
  2. **A specific database analysis** methodology for estimating *J-R* curves for RPV welds, and low sulfur (S) plate materials developed in the form of a correlation based on USE with limitations on applicable materials and fluence.
  3. **A measurement of the Master Curve transition temperature T_0 using ASTM E1921** and using the methodology from ASME Code Case N-830-1, which provides a method to develop a J-R curve from the associated value of T_0.
  4. An alternative method is permitted provided it is justified and accepted by the regulatory authority having jurisdiction at the plant site (can be based on other indirect or combined methods)
- Paragraphs K-4000 and K-5000 now provide better clarity on the definition of transients, definition of metal temperature to be evaluated for each transient.

Summary and Conclusions

Summary and Conclusions

- Maintaining reactor vessel integrity has the potential to be a limiting requirement in the pursuit of long-term operation.
- Early planning along with novel approaches may be necessary to ensure that adequate surveillance data will be available to meet regulatory requirements and provide adequate data to inform ETC development.
- Refinement and updating of analytical methods, such as those to ASME Section XI Appendices E and K, help enable plants pursuing LTO to continue to meet RPV integrity requirements despite increased fluence exposure and an expanding beltline region.

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