MRP/BWRVIP Evaluation of BTP 5-3

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Background (1/2)

- Until 1973, the ASME Boiler & Pressure Vessel Code, Section III (the Code) required that materials used in the pressure-retaining components of reactor pressure vessels (RPVs) be qualified by Charpy V-Notch (CVN) impact tests on specimens oriented in the strong direction
- In Summer 1972 Addenda, the Code revised approach to RPV integrity
  - Linear Elastic Fracture Mechanics with toughness characterized by RT_{NDT}
    - Pellini T_{NDT} and T_{cv} (lower-bound Charpy $T_{50\ ft\text{-}lb}$ / $T_{35\ mils\ lat.\ exp.}$) for CVN specimens oriented in weak direction
    - RT_{NDT} = MAX [T_{NDT}, T_{cv} - 60°F]
- 10 CFR 50, Appendix G, introduced in August 1973, required all operating power reactors to assess vessel integrity based on weak direction (T-L) properties
  - RT_{NDT}; Upper Shelf Energy limits for beltline (weak direction)

Background (2/2)

- For the vessels fabricated when only strong direction data was required, the U.S. Nuclear Regulatory Commission (NRC) published methods for estimating weak direction properties from strong direction (L-T) data: Branch Technical Position 5-3 (BTP 5-3)
- In early 2014, a vendor reported that BTP 5-3 method B1.1 (4) for determining Initial RT_{NDT} was potentially non-conservative
- Industry and NRC investigated
- A 1983 NRC-sponsored study EGG-MS-6310 had also identified some methods in BTP 5-3 (then called MTEB 5-2) as potentially non-conservative
  - No change to methods
- Materials Action Plan Committee (MAPC) requested MRP and BWRVIP to assess

Objectives of the MRP/BWRVIP Project

- Conduct survey regarding use of BTP 5-3 in PWR and BWR fleets
- Gather enhanced materials database and evaluate adequacy of the BTP 5-3 procedures which had previously been identified as potentially non-conservative
  - B1.1(3)(a) and (b), B1.1(4), and B1.2
- Determine safety significance of those BTP 5-3 methods found to be potentially non-conservative
  - Does application of BTP 5-3 B1.1(3) (a) and (b) for defining RPV pressure-temperature (P-T) limits provide adequate margins against RPV failure through 60 year license period?
  - Does application of B1.1 (3) or B1.1 (4) for vessel/closure head flange provide adequate protection for areas highly stressed by bolt preload?
  - Does application of B1.2 provide adequate protection from consequences of low Upper Shelf Energy (USE)?

MRP/BWRVIP Survey (1/2)

- Survey was successful in establishing trends regarding use of BTP 5-3
- Many source documents: Generic Letter 92-01 responses; Reactor Vessel Integrity Database (RVID2) verification requests; FSARs; surveillance program documents
- Plants built to a Code edition earlier than Summer 1972 Addenda to ASME III 1971 were required to qualify materials using L-T Charpy specimens and all vessel components will have L-T data
- Supplemental T-L CVN testing was often conducted to permit determination of Initial RT_{NDT} per ASME III NB-2331
  - More common for vessels fabricated in years just prior to 1973
  - Supplemental testing was generally limited to the beltline materials
  - Alternative method for all vessel materials having only L-T data

MRP/BWRVIP Survey (2/2)

- Discrepancies noted between survey responses and RVID2
- Several plants identified T-L Charpy data in NSSS vendor archives not documented in RVID2
- Where BTP 5-3 was used to determine Initial RT_{NDT} for beltline shell plates and forgings, B1.1(3) (a) or (b) was used
- With a few exceptions, when T-L Charpy data is not available, BWRs have used the GE procedure (NEDC-32399P) for determination of Initial RT_{NDT} and BTP 5-3 for determination of Initial USE
  - Evaluation of the NRC-approved GE procedure was not in the scope of the MRP/ BWRVIP project
  - GE procedure received NRC safety evaluation in 1994
    - Recently-initiated MRP/BWRVIP work regarding the GE procedure is discussed later in this presentation

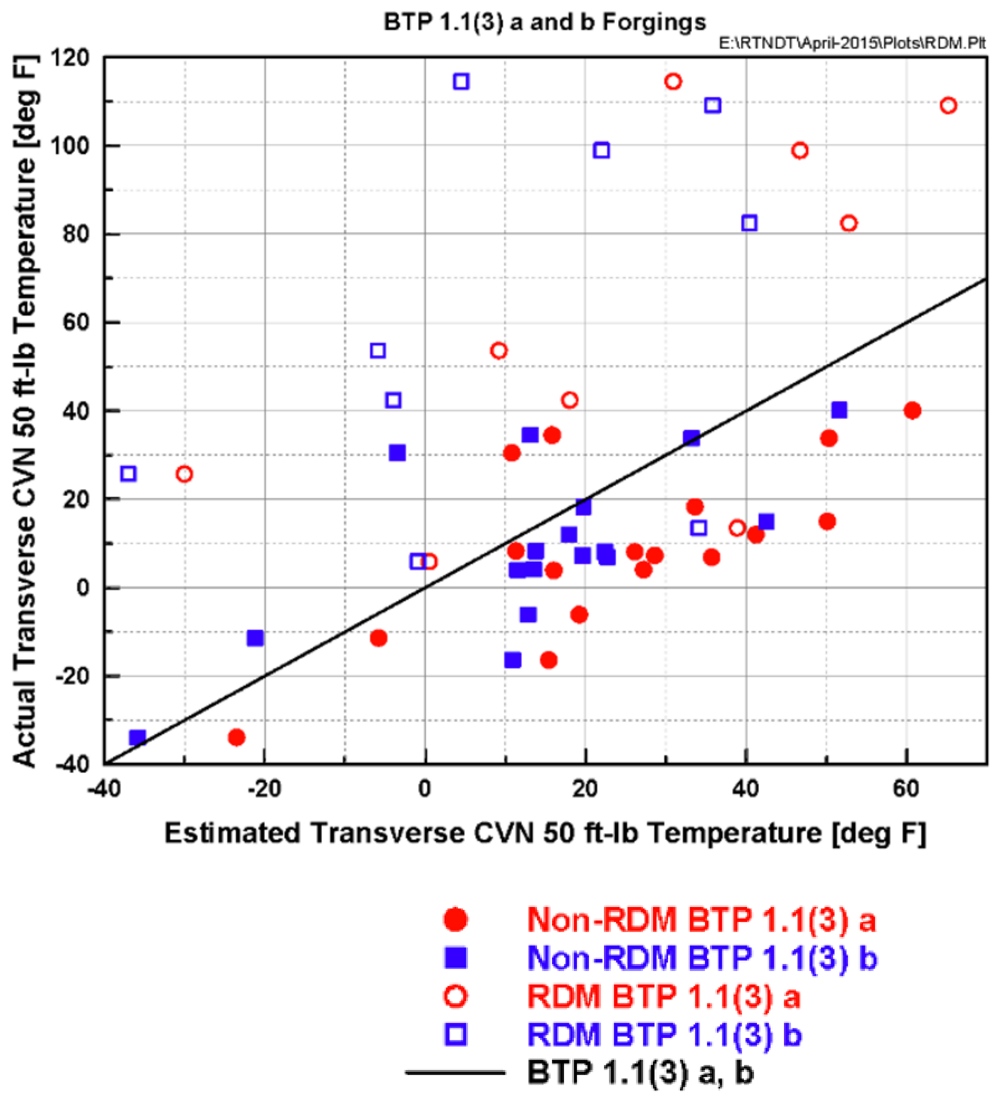
Evaluation of BTP 5-3 Procedures

Evaluation of Conservatism of BTP 5-3

- Project team assembled enhanced database: plate and forging materials with measured CVN properties in both weak (T-L) and strong (L-T) directions
  - For each plate and forging material, weak direction properties were estimated from the strong data using BTP 5-3 prediction methods
  - Predicted weak properties were then compared to the measured weak properties to determine the conservatism or non-conservatism of the BTP 5-3 methods
  - This comparison indicated that in some cases the BTP 5-3 methods were less conservative than expected
  - The standard errors associated B1.1(3) methods were quantified
  - Regression analyses of the data were also performed, for use in probabilistic fracture mechanics (PFM) analyses using FAVOR

Analysis of BTP 5-3 B1.1(3) – Forgings

- Two different populations of data
- Preliminary evaluation suggested populations may be differentiated by L-T USE
- Further evaluation showed that all but one low USE forging are Rotterdam Drydock (RDM) forgings, and the one non-RDM low USE forging is well-predicted by BTP 1.1(3)
- Consequently, forgings are categorized as either RDM or non-RDM forgings



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Evaluation Summary: Conservatism of BTP 5-3

BTP Paragraph	Toughness Parameter Estimated	Product Form	Is the BTP Potentially Non-conservative?
B1.1(3)(a) or (b)	T-L T_{50} / T_{cv}	Plate	Yes
		RDM Forging	Yes
		Non-RDM Forging	No
B1.1(4)	RT_{NDT}	Plate	Yes
		Forging	Yes
		Weld	No
B1.2	USE	Plate & Forging	No

Assessment of
Potential Impact on RPV Integrity

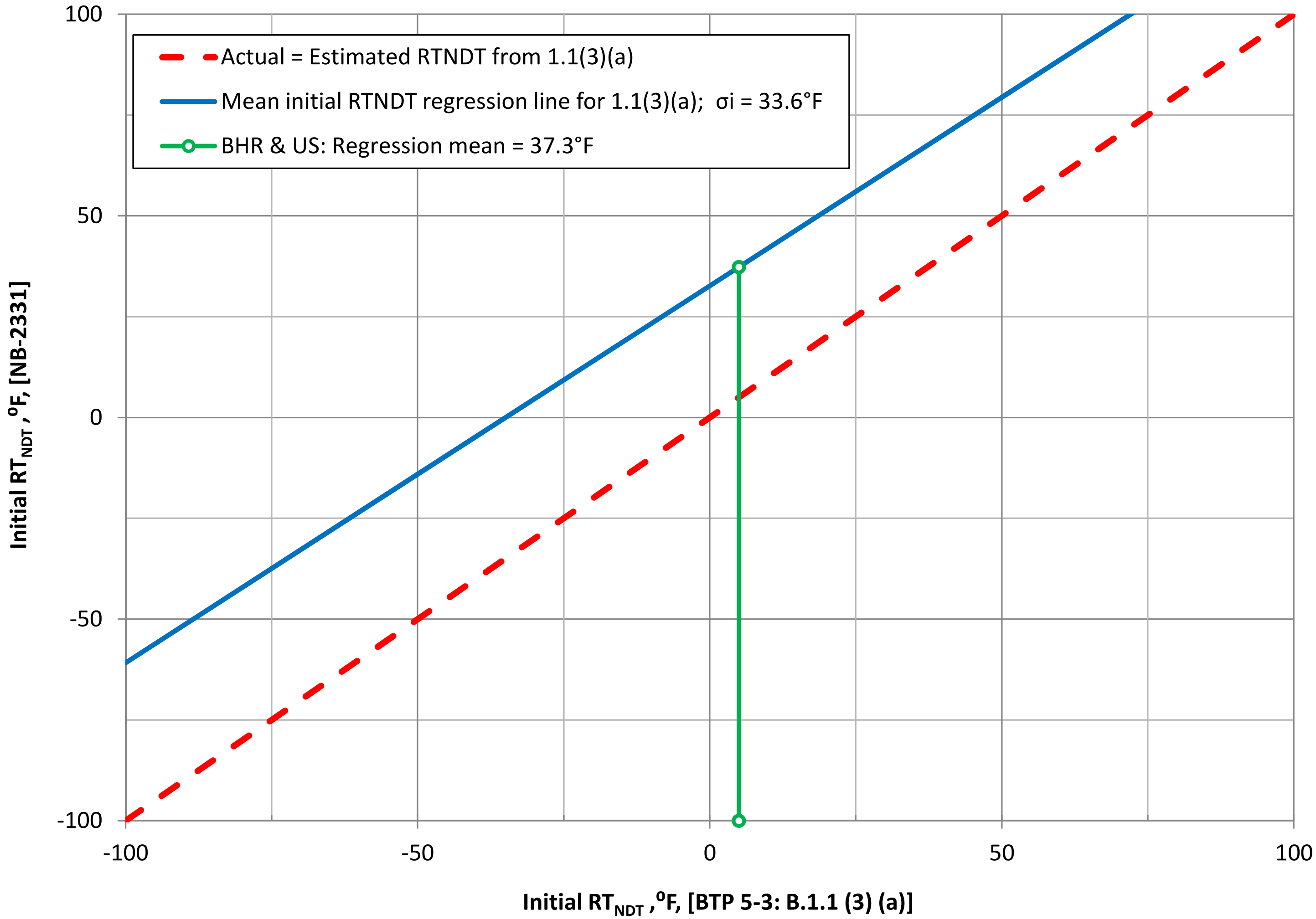
RPV Integrity Assessment

- Assess the effect of uncertainty in Initial RT_{NDT} estimated from BTP 1.1(3) (a) & (b) on Appendix G P/T limit curves, low temperature overpressure (LTOP) enable temperature, and pressurized thermal shock (PTS) reference temperature, RT_{PTS} (10CFR50.61)
- Determine if the effect of the uncertainty in Initial RT_{NDT} suggests a need to revise BTP 5-3 in order to ensure adequate RPV integrity limits
- The need to revise the RPV integrity limits is assessed by the conditional probability of failure (CPF) and the change in CPF (ΔCPF) when Initial RT_{NDT} is determined from:
  – Current NRC BTP method with $\sigma_i = 0^oF$, and
  – Mean Initial RT_{NDT} and standard error for Initial RT_{NDT} determined from regression analysis of experimental data

Materials Evaluated in RPV Integrity Assessment

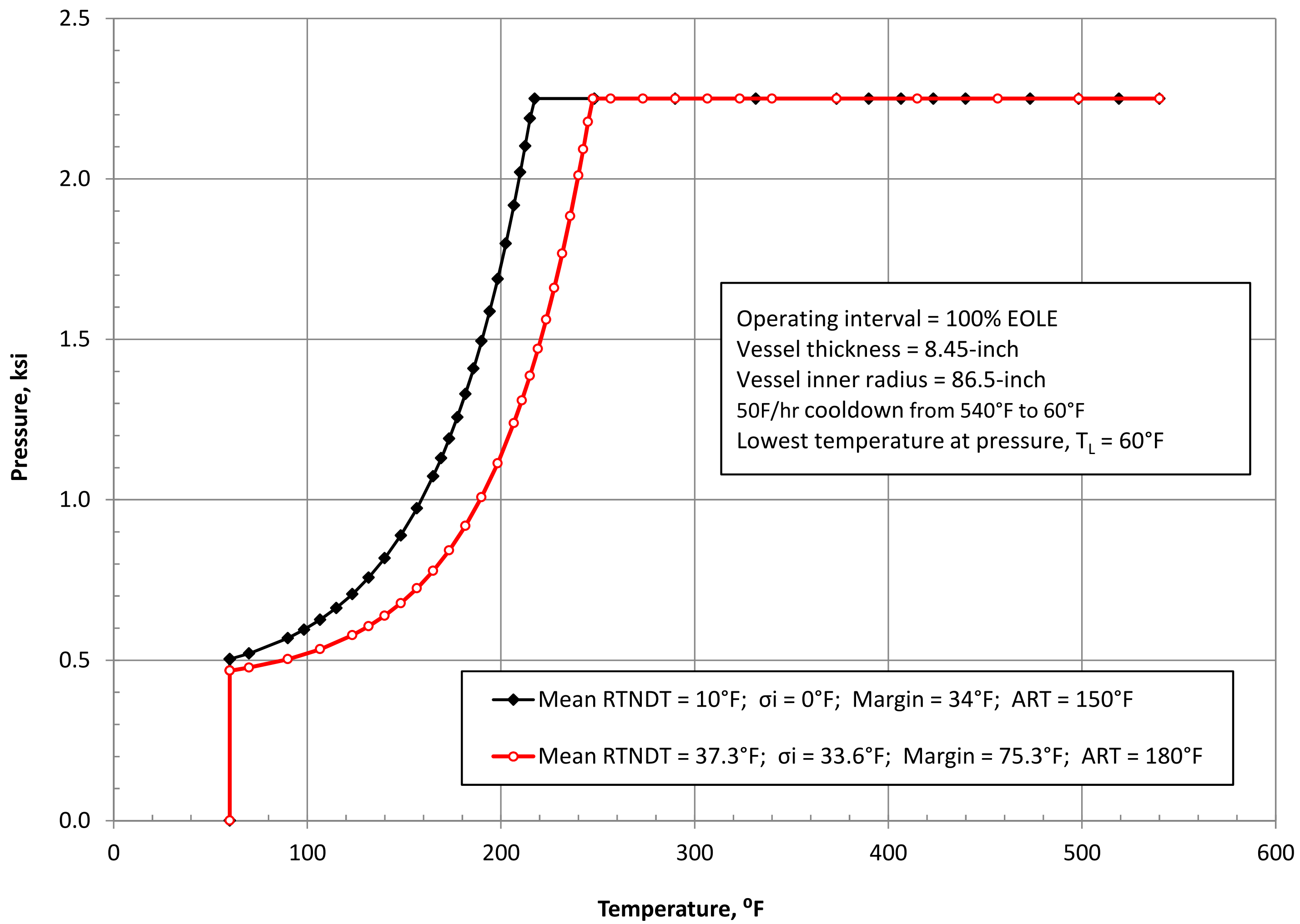
- Plate with the highest 60-year (EOLE) ART in the PWR fleet
  - Limiting material is in the RPV beltline
- Non-RDM forging with the highest EOLE ART in the PWR fleet
  - Limiting material can be in either the RPV beltline (highest fluence region of the RPV shell) or the extended beltline (lowest fluence region of the RPV shell)
- RDM forging with the highest EOLE ART in the PWR fleet
  - Limiting material is in the RPV extended beltline
    - Survey indicated all RDM beltline ring forgings have T_{NDT} and T-L CVN data available

Initial RT_{NDT} for the RDM Forging with the Highest EOLE ART in the PWR Fleet (Extended Beltline Region)



US = upper shell
BHR = bottom head ring

Appendix G P/T Limit Curves for the RDM Forging with the Highest EOLE ART in the PWR Fleet (Extended Beltline)



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Comparison of CPF and ΔCPF from BTP Current Practice with Regression Analysis - Limiting PWR RDM Forging

Variable	Initial RT_{NDT} from BTP B1.1 (3) (a)	Initial RT_{NDT} from data regression for BTP B1.1 (3) (a)	Initial RT_{NDT} from BTP B1.1 (3) (a)	Initial RT_{NDT} from data regression for BTP B1.1 (3) (a)
Operating interval	40 Years		60 Years	
Limiting material	IS forging	BHR forging	IS forging	BHR forging
Used BTP 5-3	No, NB-2331	Yes	No, NB-2331	Yes
Initial RT_{NDT}, ^{0}F	10	37.3	10	37.3
σ_i, ^{0}F	0	33.6	0	33.6
ART for P/T limit curve, ^{0}F	138.5	168.3	150.5	180.8
CPF	3.530E-9	1.735E-9	7.286E-9	4.037E-9
ΔCPF	1.8E-9		3.2E-9	

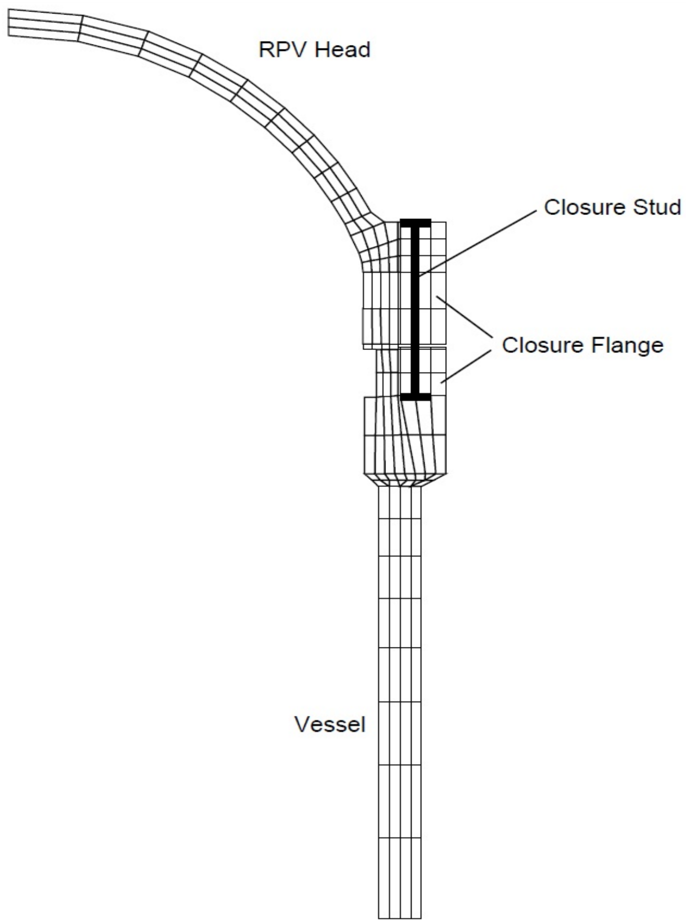
→**The insignificant difference in CPF shows there is negligible safety benefit to changing BTP B1.1(3) or its application to RDM forgings**

IS = intermediate shell
BHR = bottom head ring

RPV Integrity Assessment Conclusions

- The ΔCPF associated with using either the BTP or regression analysis to define Initial RT_{NDT} is very small (less than 1E-7). Consequently, any safety benefit to be gained by changing the BTP 5-3 procedure for estimating Initial RT_{NDT} or its application for defining P-T limit curves and LTOP enable temperature is insignificant.
- Compliance with the PTS screening criterion (10 CFR 50.61) was evaluated using the regression analysis from the materials property database. The analysis for the most limiting material in the PWR fleet (beltline plate) shows that for current EOLE conditions all base metals in the PWR fleet (that used BTP) will remain below the PTS screening limit of 270°F.
- These conclusions have been demonstrated for the three material classifications, including plate, non-RDM forgings and RDM forgings in both the beltline and extended beltline regions.

Impact on Vessel/Closure Head Minimum Temperature Requirements

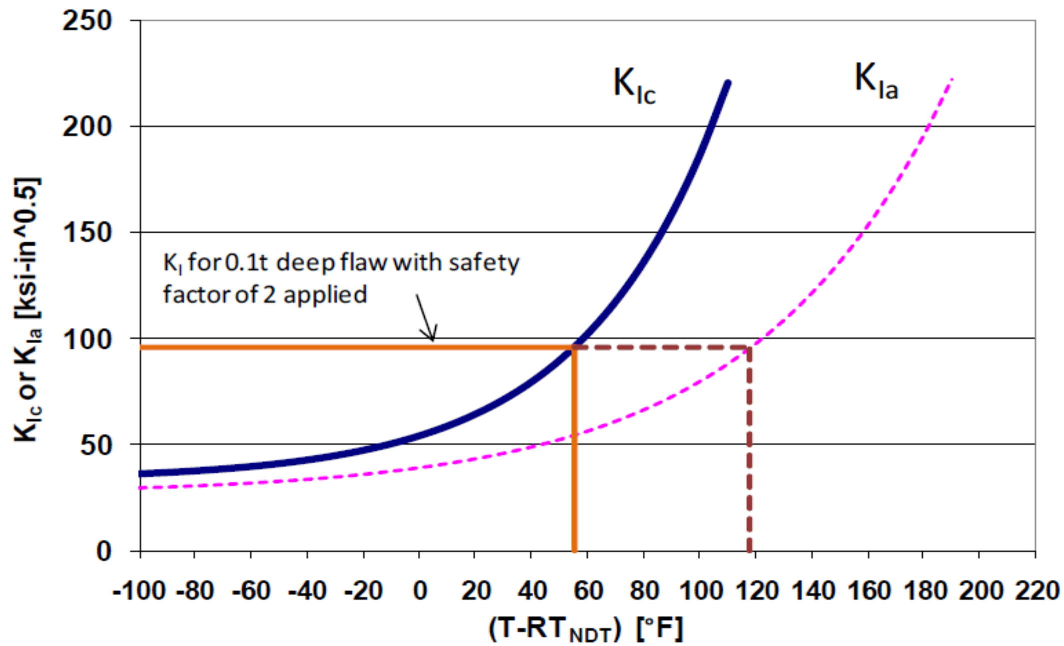


Vessel/Closure Head Minimum Temperature Requirements

- 10 CFR 50 Appendix G, Table 1, establishes minimum temperature requirements for the vessel based on the highest reference temperature, RT_{NDT}, of the material in the closure flange region that is highly stressed by the bolt preload (tensioning of the RPV closure studs)
  - During normal operation when the core is not critical, vessel pressure may not exceed 20% of the pre-service hydrostatic test pressure until the metal temperature of the closure flange region is greater than Initial RT_{NDT} + 120°F
- BTP 5-3 has been used for Initial RT_{NDT} of flanges
  - Only B1.1(3) observed but insufficient data to rule out B1.1(4)
- WCAP-15315, Rev. 1, "Reactor Vessel Closure Head/Vessel Flange Requirements Evaluation for Operating PWR and BWR Plants" (2002) petitioned for removal of requirements
  - NRC is considering this petition in rulemaking related to 10CFR50 Appendix G (ref: NRC-2008-0582)

Available Margin Due to Use of K_{IA} Fracture Toughness

- NRC staff presented analysis in PVP2011-57208
  - Basis of minimum temperature requirements in SECY-83-80; requirements are based on K_{IA} fracture toughness curve
  - When more appropriate K_{IC} fracture toughness is used, a significant margin exists to compensate for potential non-conservatism in BTP 5-3



Minimum (T-RT_{NDT}) based on 2*K_I for a 0.1t deep flaw (L/a=6).

Figure from E. Focht, "Evaluation Of The Minimum Temperature Requirements For The RPV Closure Head Flange Region In 10 CFR 50 Appendix G," PVP2011-57208

Margin Available for Each Vessel Type Compensates for BTP 5-3 Issue

Plant	Column A T-RT_{NDT} (°F) using K_{Ia} (a/t = 0.1)	Column B T-RT_{NDT} (°F) using K_{IC} (a/t = 0.1)	Column C Available Margin to Offset BTP 5-3 (°F)
PWR			
CE	68	13	120 - 13 = **107**
B&W	100	41	120 – 41 = **79**
Westinghouse 4 Loop	1	0	120 – 0 = **120**
Westinghouse 3 Loop	0	0	120 – 0 = **120**
BWR			
GE (CB&I 251-in.)	97	38	120 – 38 = **82**
GE (B&W 251-in.)	118	56	120 – 56 = **64**
GE (CE 218-in.)	43	0	120 – 0 = **120**

BTP 5-3 issue has no safety significance relative to potential fracture in the flange region because of RPV head bolt tensioning

Conclusions, Report Schedule, & Ongoing Work

Summary of Evaluations (1/2)

BTP 5-3 Paragraph	Material	Evaluation of BTP 5-3	Frequency of Use for RPV Beltline	Assessment of BTP Paragraph Use on RPV Integrity
B1.1(3) (a) or (b)	**SA533B-1 Plates**	BTP 5-3 estimate of T-L T_{50} is an approximate mean relationship with standard error 19.0 - 19.5°F.	Frequent. When BTP 5-3 was used for a beltline shell plate, it was almost always B1.1(3)	• **There is no safety benefit to be gained by changing the current BTP requirements and implementation procedures to define P-T limit curves and LTOP system enable temperature for either plates or forgings in the beltline and extended beltline regions of the RPV.** • **Application of the data regression equations demonstrates compliance with the 10 CFR 50.61 screening limit at EOLE for the RPV with the limiting plate in the PWR fleet** • **For all other RPVs fabricated from plate or forgings, application of either BTP 5-3 or data regression equations demonstrates compliance with the 10 CFR 50.61 screening limit at EOLE.**
	Non-RDM SA508-2 and SA508-3 Forgings	BTP 5-3 estimate of T-L T_{50} generally is a bounding relationship and adequately conservative.	Frequent. When BTP 5-3 was used for a beltline shell forging, it was almost always B1.1(3)	
	RDM SA508-2 Forgings	BTP 5-3 estimate of T-L T_{50} is potentially non-conservative.	Low or no use for RDM beltline ring forgings but frequent use for extended beltline rings and flanges	

Summary of Evaluations (2/2)

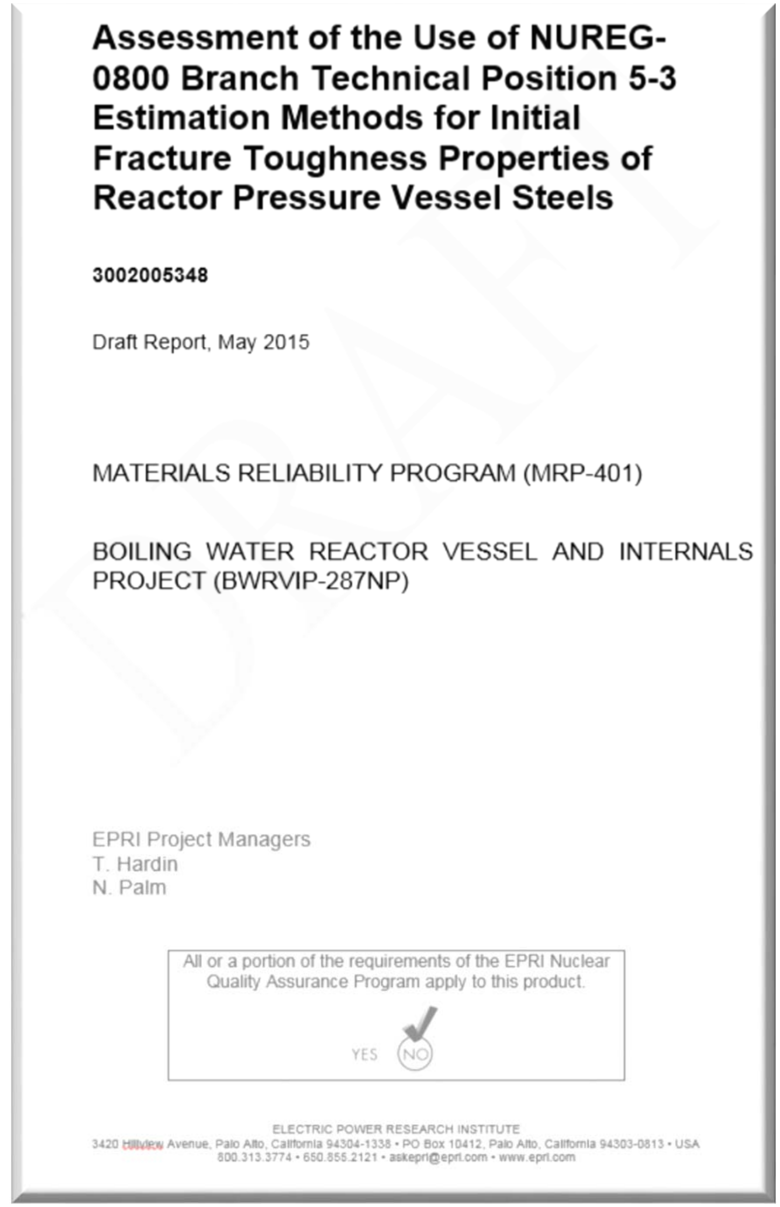
BTP 5-3 Paragraph	Material	Evaluation of BTP 5-3	Frequency of Use for RPV Beltline	Assessment of BTP Paragraph Use on RPV Integrity
B1.1(4)	**SA533B-1 Plates**	BTP method is potentially non-conservative; RT_{NDT} = 40°F provides a 90-95% bounding value	None identified	**No integrity assessment required – no use identified**
	SA508-2 Forgings (Data from B&W-supplied Vessels)	BTP method is potentially non-conservative; RT_{NDT} = 50°F provides a 90-95% bounding value	None identified for beltline shell. One BWR nozzle was identified	**Impact on forged nozzles to be addressed by PWROG PA-MSC-1091R1** **Impact on vessel flanges: adequate safety margins are maintained**
	RPV Welds (MMAW and SAW)	BTP estimate of RT_{NDT} is generally very conservative and adequate	Low. One RPV weld was identified from RVID2	**No integrity assessment required; guidance is adequate**
B1.2	**All Plates and Forgings**	BTP estimate is adequate per this evaluation and a 1990 NRC evaluation. Data are adequately predicted with 86% of the data conservatively estimated	Frequent.	**No integrity assessment required; guidance is adequate and previous EMA calculations have validated USE values much less than 50 ft-lb**

Summary and Conclusion

- Impact of potential non-conservatism of BTP 5-3 on P-T limit curves, PTS screening criteria, USE requirements and vessel/closure head flange minimum temperature requirements has been assessed
- MRP/BWRVIP study concludes that the existing values of Initial RT_{NDT} and Initial Upper Shelf Energy (USE) determined from the methods of Branch Technical Position 5-3 (Revision 2, March 2007) or MTEB 5-2 are acceptable for continued use in demonstrating compliance with the requirements of 10 CFR 50 Appendix G and 10 CFR 50.61 through a sixty-year license period.

Project Status and Schedule

- Draft report MRP-401/BWRVIP-287 was issued to MRP, BWRVIP, PWROG in December 2014
  - Review comments have been addressed
- Final draft report issued for MRP & BWRVIP review / approval in May 2015
  - Target publication: July 2015
- BWRVIP & MRP are sponsoring a study by GEH to evaluate the "GE procedure" for determination of Initial RT_{NDT} for nozzles
  - Project to be completed by end of 2015



Assessment of the Use of NUREG-0800 Branch Technical Position 5-3 Estimation Methods for Initial Fracture Toughness Properties of Reactor Pressure Vessel Steels

3002005348

Draft Report, May 2015

MATERIALS RELIABILITY PROGRAM (MRP-401)

BOILING WATER REACTOR VESSEL AND INTERNALS PROJECT (BWRVIP-287NP)

EPRI Project Managers
T. Hardin
N. Palm

All or a portion of the requirements of the EPRI Nuclear Quality Assurance Program apply to this product.

YES NO

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Background Slides

Text of BTP 5-3 B1.1(3)

- *"If transversely-oriented Charpy V-notch specimens were not tested, the temperature at which 68 J (50 ft-lbs) and 0.89 mm (35 mils) LE* [lateral expansion] *would have been obtained on transverse specimens may be estimated by one of the following criteria:*
  - *(a) Test results from longitudinally-oriented specimens reduced to 65% of their value to provide conservative estimates of values expected from transversely oriented specimens.*
  - *(b) Temperatures at which 68 J (50 ft-lbs) and 0.89 mm (35 mils) LE were obtained on longitudinally-oriented specimens increased 11°C (20°F) to provide a conservative estimate of the temperature that would have been necessary to obtain the same values on transversely-oriented specimens."*

Text of BTP 5-3 B1.1(4)

- "*If limited Charpy V-notch tests were performed at a single temperature to confirm that at least 41 J (30 ft-lbs) was obtained, that temperature may be used as an estimate of the* RT_{NDT} *provided that at least 61 J (45 ft-lbs) was obtained if the specimens were longitudinally oriented. If the minimum value obtained was less than 61 J (45 ft-lbs), the* RT_{NDT} *may be estimated as 11°C (20°F) above the test temperature.*"

Text of BTP 5-3 B1.2

- *"...Reactor vessel beltline materials must have Charpy upper shelf energy, in the transverse direction for base material and along the weld for weld material according to the ASME Code, of no less than 102 J (75 ft-lbs) initially and must maintain Charpy upper shelf energy throughout the life of the vessel of no less than 68 J (50 ft-lbs). If tests were only made on longitudinal specimens, the upper shelf energy values should be reduced to 65% of the longitudinal values to estimate the transverse properties."*

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