RG 1.99 Revision Evaluation Effort

Public Meeting
May 19, 2020

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Key Messages

- Conducted risk analysis based on 80-year operating period (RG 1.99, Rev. 2 and ASTM E900-15).
- Results: Fleetwide implementation of a revised RG may not be necessary.
- Questions for certain transients (PWR cooldowns on licensed P-T limits and BWR leak tests with higher cooldown rates) – industry input could help.
- Framework of a potential alternative RG 1.99 has been developed.
- Potential burden reduction for some plants – could benefit from industry and licensee input.

Purpose of this Meeting

- The NRC staff is holding this meeting to solicit stakeholder feedback on the following topics:
  - Elements of the potential alternative RG 1.99.
  - Whether potential for burden reduction from a potential alternative regulatory guide would be beneficial to licensees.
  - Whether industry can provide certain information to enable the staff to verify risk analysis conclusions.

Contents of this Presentation

- Motivation for evaluation effort
- Elements and technical basis for a potential alternative RG
- Fleet Impact/Safety Impact Analysis
- Implementation

Motivation for Revision Evaluation Effort

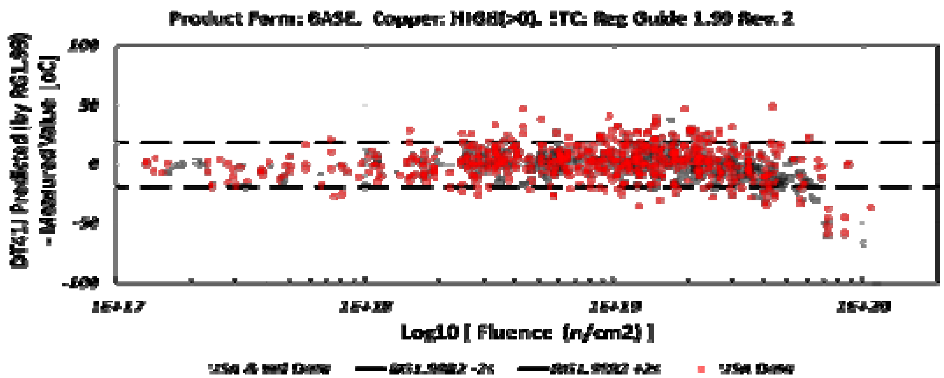
Events to Date

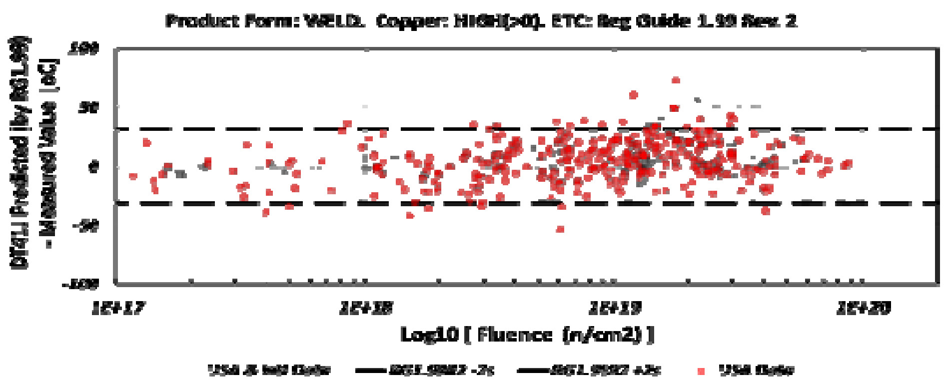
- Technical letter report[1] (TLR) identified several deficiencies in RG 1.99, Rev. 2.
  - Most significant is non-conservatism of ΔRT_{NDT} at high fluence ≥ $6x10^{19}$ n/cm^2 (some PWRs reach during SLR)
- TLR reviewed by ACRS Subcommittee on August 22, 2019 (ML19260E007) and Full Committee November 6, 2019.
- ACRS issued letter to staff on November 27, 2019, supporting revision of RG.
- The NRC staff is currently evaluating the need to develop an alternative to RG 1.99, Rev. 2.
- The NRC staff has not initiated a formal revision process for RG 1.99, Rev. 2.

1 - Assessment of the Continued Adequacy of Revision 2 of Regulatory Guide 1.99 - Technical Letter Report, July 31, 2019, ADAMS Accession Number ML 19203A089

RT_{NDT} Results

- Assessment based on BASELINE dataset generated by ASTM E10.02.
- Dataset includes domestic and international power reactor data (~55% domestic).
- 1901 data points
- In-depth statistical analysis performed.





Limited weld data at high fluence precludes assessment of whether weld trends with base metals at high fluences.

RT_{NDT} Results

- Primary conclusions:
  - Nonconservative high fluence results (base metals)*, becomes prominent at fluences ≥ $6x10^{19}$ n/cm^2.
  - Inaccurate low Cu results
- Secondary conclusions:
  - Standard deviation of ΔRT_{NDT} (σ_Δ) in RG is too low
  - Conservative bias in low-to-mid fluences
  - Lack of temperature adjustment (inaccuracy)

* Limited weld data available at fluences near or above $1x10^{20}$ n/cm^2 (E > 1MeV)

Credibility Criteria

- RG 1.99, Rev. 2 has five credibility criteria.
- Criteria compare measured data to refit (chemistry factor) RG 1.99 prediction results with a requirement of shape-function of RG 1.99
- If surveillance data is deemed credible, RG 1.99 allows reduction in margin term.
- No action is suggested if data is deemed non-credible; however it is common practice to use surveillance data when it supports a more conservative prediction.
- The criterion typically failed is excessive scatter.*

* - One or more surveillance data point outside 2σ where σ is the standard deviation of the ETC (17 °F for base materials and 28 °F for welds)

Credibility Criteria - Issues

- The more surveillance data points, the more likely it is for data to be non-credible due to scatter.
- No documented basis for reduction in margin for credible data.
- High fluence and low Cu data not expected to conform to fluence shape function of RG1.99 and are consequently more likely to be deemed non-credible.

Significant TLR Recommendations

- Correcting the nonconservatism in the embrittlement trend curve at higher fluences is the most significant recommendation of the TLR.
- The credibility criteria should also be revised to be more effective (in combination with an improved ETC).
- Several common practices not addressed in the RG should be addressed in a revision, such as use of sister plant data, implementation of credibility criteria, degree-per-degree, etc.

Framework Elements and Technical Basis

Framework Elements

- Embrittlement Trend Curve
- Use of Surveillance Data
- Margins
- Limitations
- Default Values

Embrittlement Trend Correlation

ETCs Evaluated

- Two trend curves were considered as potential replacements for the RG 1.99, Rev. 2 ETC:
  - 10 CFR 50.61a (EONY) –
    - NRC-approved since incorporated into alternate PTS rule.
    - Fit to 855 ΔT_{41J} values from US light water reactor (BWR and PWR) surveillance data through the year 2004
  - ASTM E900-15
    - Consensus standard.
    - Calibrated to 1878 ΔT_{41J} data points, BWR and PWR only.
    - US and international surveillance data, 1033 US data, through ~2012

Statistical Tests

- Root Mean Square Deviation (RMSD) – a measure of scatter
- Bias- a measure of whether there is a mean overprediction or underprediction of the data by the ETC.
- Ln(L) – Logarithm of Likelihood – a measure of goodness of fit
- Student's t-test – used to examine residual trends versus specific variables.

Summary of Statistical Test Results

- When comparing USA results, both ETCs perform similarly;
- ASTM E900-15 performs significantly better than 10 CFR 50.61a with respect to international data.
- Overall E900-15 performs the best with the lowest bias, better "high fluence" bias, and superior performance with international data (which includes, among other things, a higher percentage of low Cu materials).
- In T-test, E900-15 performs the best overall when compared to all data and subsets.
- Both ETCs retain some modelling residuals, but 50.61a has considerably more and in a broad array of categories, indicating that E900-15 performs better over a broader range of inputs than 50.61a.

Rationale for ETC Selection (1)

- For high fluence materials, E900-15 was selected because:
  - It produces more accurate predictions of surveillance data at high fluence (> $3x10^{19}$ n/cm^2). Based on the statistical comparison, E900 has a small, positive bias for the USA High Fluence subset, while 50.61a underpredicts the same subset.
  - It performs better relative to the international data with high fluence.
- For new reactor applications, E900-15 was selected because:
  - It performs better relative to the international data for the Low Cu category for the statistical measures (RMSD/bias/Ln(L)).
  - It performs better performance with regard to T-test results for the Low Cu subset, as well as the input variables Ni, P, and T. This is particularly pertinent to new reactors which will have low Cu, and consequently will be (relatively) more sensitive to other input variables (Ni, P, T, etc.)

Rationale for ETC Selection (2)

- The E900-15 ETC is based on a larger database, including additional USA surveillance data for 2004-2012 time frame not included in the 50.61a database.
- The staff opinion is that statistical performance versus international data should be considered because the international data contains data in certain areas that are important to US plants, but sparse in US data, such as low Cu and high fluence.
- The staff did not consider mechanistic elements used in the development of 50.61a to be a significant deciding factor. Insufficient evidence that "mechanistic insights" improved performance of 50.61a versus E900 was found.
- The E900 ETC is expected to provide more accurate predictions of embrittlement in a broader band of temperatures than 50.61a.

Summary – ETC Selection

- The ASTM E900-15 and 10 CFR 50.61a ETCs were evaluated as replacements for the RG 1.99, Rev. 2 ETC.
- The staff selected the ETC from ASTM E900-15 for the potential alternative to RG 1.99, Rev. 2.
- The decision was based on both quantitative and qualitative factors.
- Primary reasons for choosing E900-15 are:
  - Better accuracy for high fluence materials
  - Better accuracy for low copper materials

Use of Surveillance Data

Consistency Checks

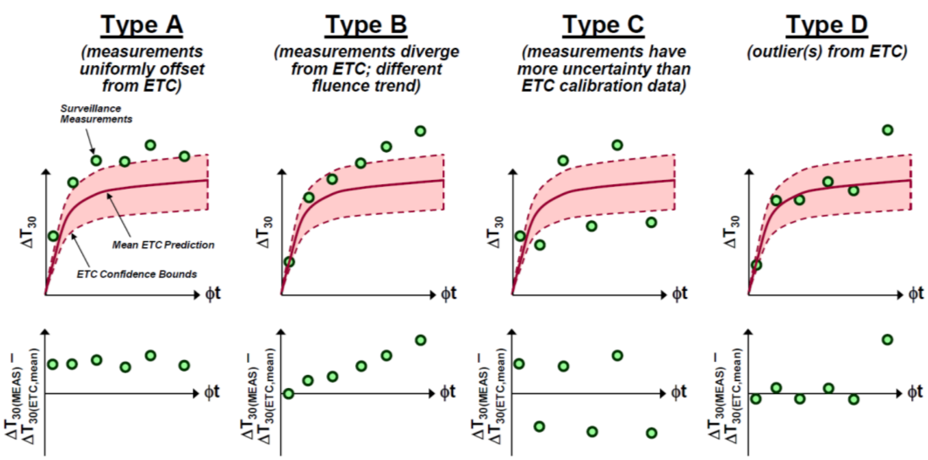
Introduction

- Type testing was used to evaluate surveillance data and construct a refit procedure for use with E900.
- Type testing based on construction of 50.61a tests as described in 50.61a and NUREG-2163, but with σ of E900 (to be replaced with appropriate values from margins effort).
  - Type A – Calculate mean residual, compare to $2.33\sigma/\sqrt{n}$ criteria (α = 1%)
  - Type C – Variance less than 2.33σ (α = 1%)
  - Type D – Compare largest and second largest normalized residual and compare to α = 1% one-sided test

* - Type B test for slope was also conducted but we are proposing not including it. It is described in NUREG-2163

Introduction

Problem: How to assess “consistency” of plant specific data, and leverage it for anomalous situations.



Question: Which test failures are likely to be found “in the field” and in what frequency?

Tested 147 materials using data from BASELINE *.

No Failures	Type A	Type B	Type C	Type D	Any Failures	Multiple Failures
100	29	3	44	35	47	41

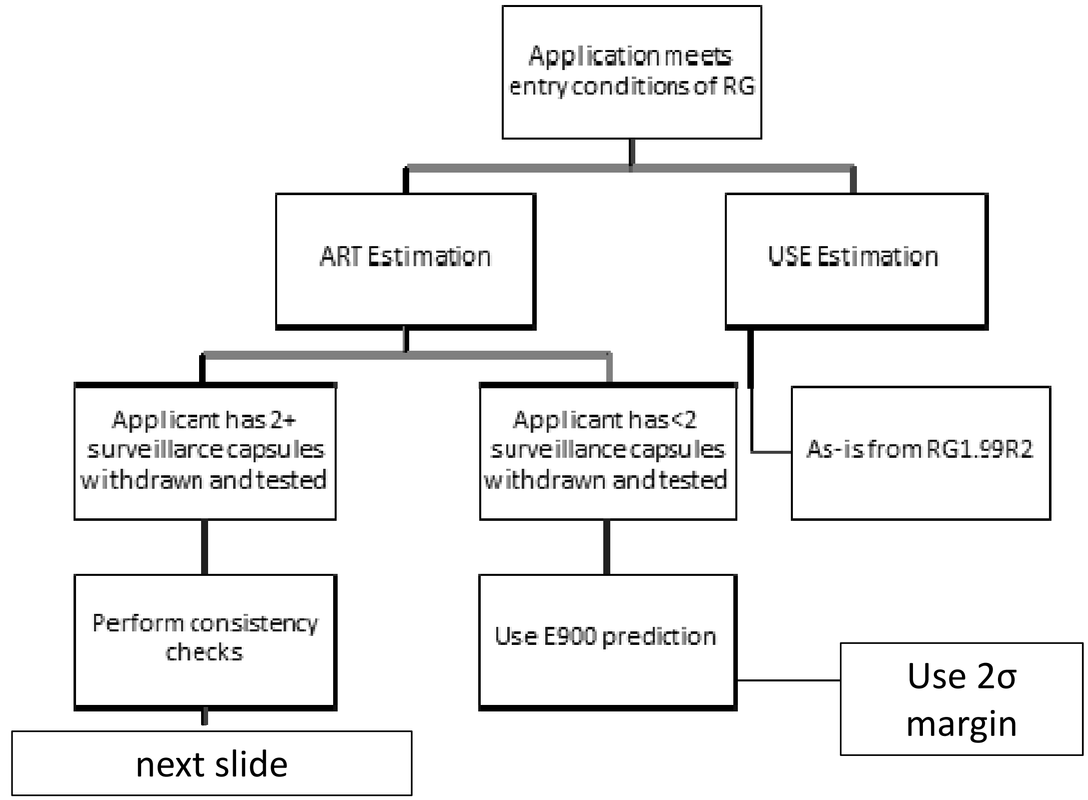
* These were materials with at least 3 surveillance data.

Proposed Refit (1)

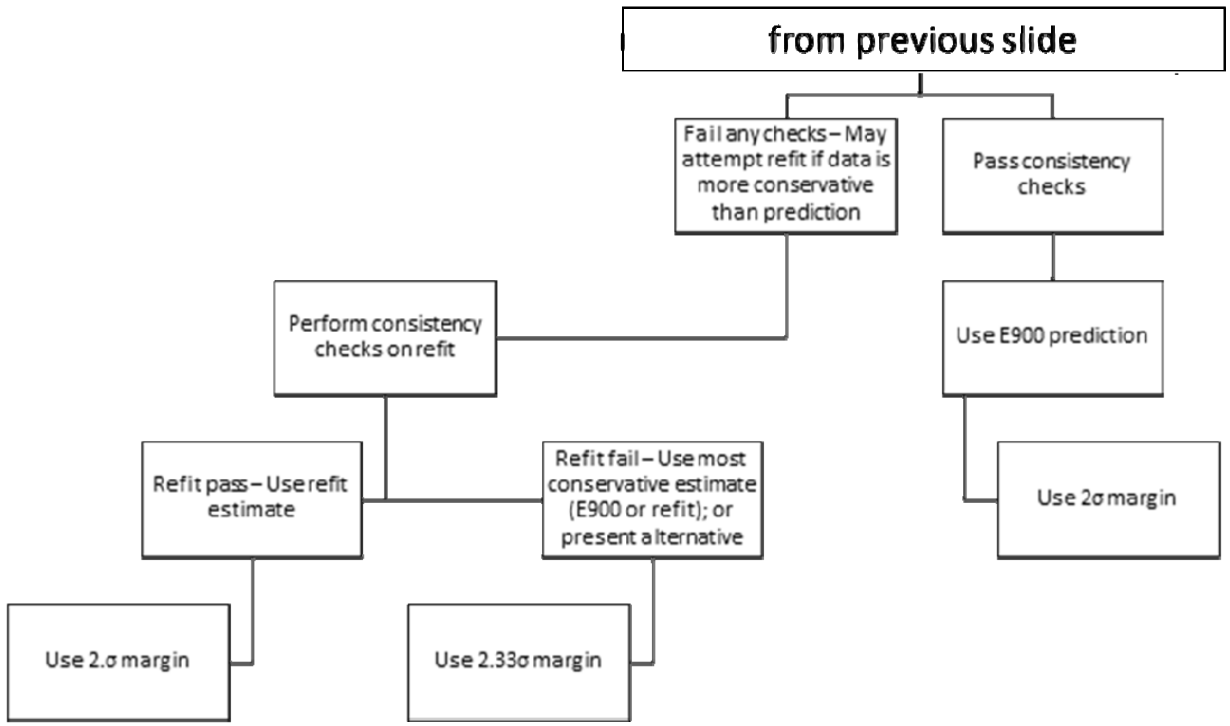
Challenge: Improve result more than threaten statistical basis for curve shape

Proposed solution - mean adjustment

Tools:
Statistical "consistency check"
Bias based "refit"



Proposed Refit (2)



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Proposed Refit (3)

Why a mean adjustment (bias correction) for refit?

A) Simple procedure
B) Clear basis (unirradiated property measurement error, temperature input, etc.)
C) Minimal impact on critical benefit of E900 over RG1.99R2: shape function

Refit Results

Check: Does proposed refit "work"?

Pre-refit:

No Failures	Type A	Type B	Type C	Type D	Any Failures	Multiple Failures
100	29	3	44	35	47	41

Retested 147 materials from E900.

Post-Refit:

No Failures	Type A	Type B	Type C	Type D	Any Failures	Multiple Failures
133	0	3	10	7	14	6

Conclusions

- Most data will "pass."
- Mean adjustment will improve "pass" rate without degrading statistical confidence in results

Margins

Structure of Margin Term

- Structure margin term same as RG 1.99, Rev. 2.
- M is the margin term.

$$M = 2\sqrt{\sigma_\Delta^2 + \sigma_i^2}$$

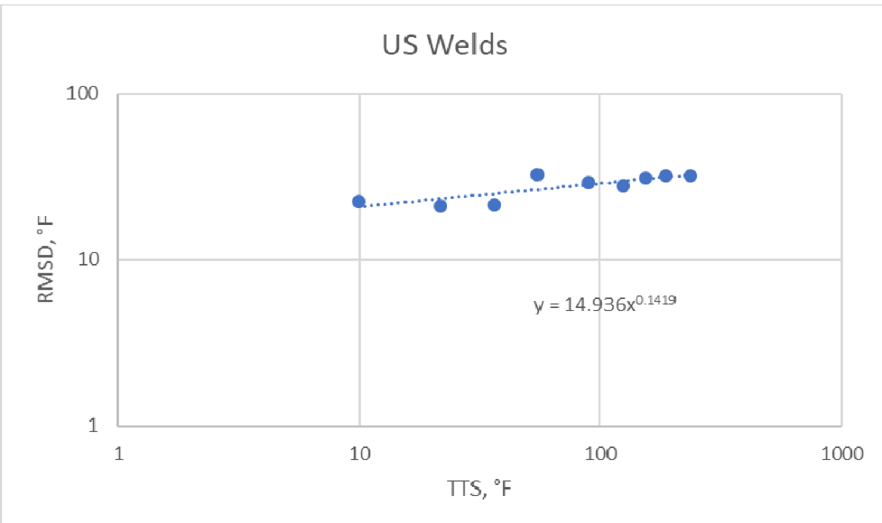
- σ_Δ = standard deviation of transition temperature shift
- σ_i = standard deviation of initial RT_{NDT}. Typically allowed to be zero by staff if a heat-specific measured initial RT_{NDT} exists.
- If initial RT_{NDT} was from a database, σ_i is the standard deviation of the database.

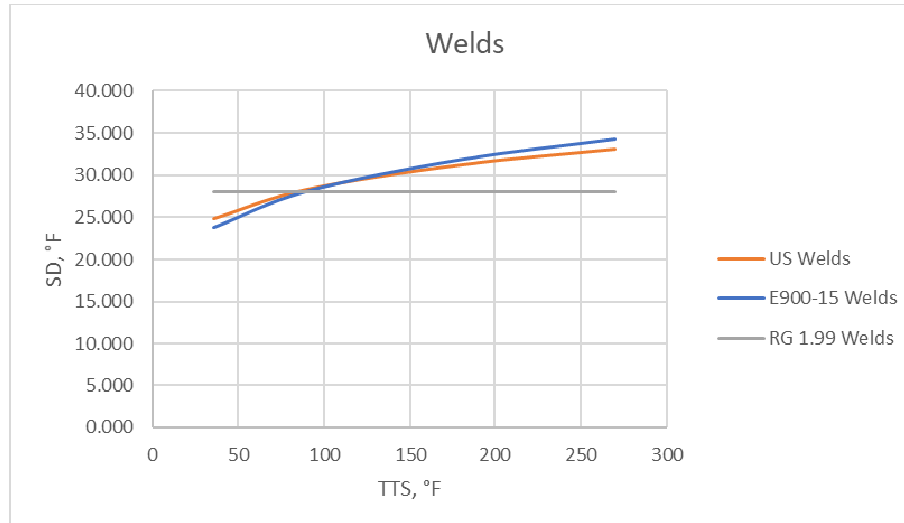
Determination of σ_Δ

- For plates and welds,
  - $\sigma_\Delta = C^* (\Delta RT_{NDT})^D$, where
    - ΔRT_{NDT} = TTS (°F) as determined by Equation 1 of E900-15 (converted to °F).
  - C and D values are based on fit to root mean square deviation versus TTS for US data from the BASELINE database.
  - More appropriate to base C and D on scatter of US data only, vs. E900-15 which used both US and international data.
- For forgings, equation had a flat trend, so simpler just to use a constant SD (σ_Δ) based on RMSD of the whole data set, (21.49°F).

Product Form	C	D
Plate	5.112	0.345
Weld	14.936	0.142

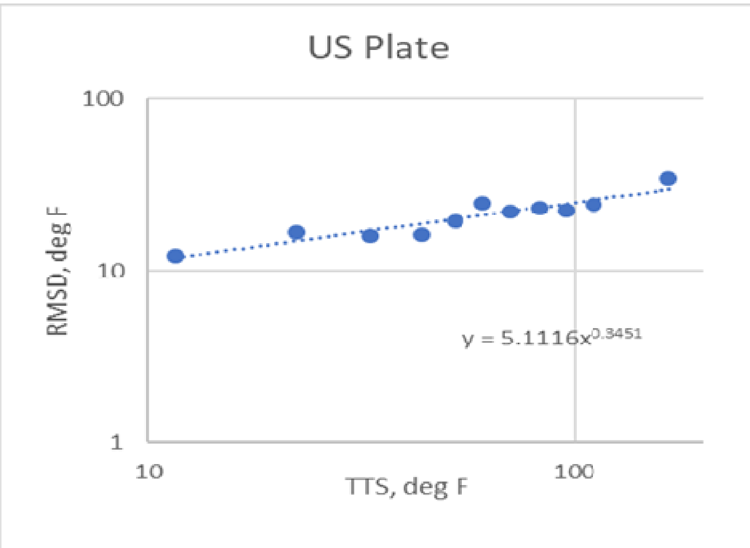
Fit for Welds



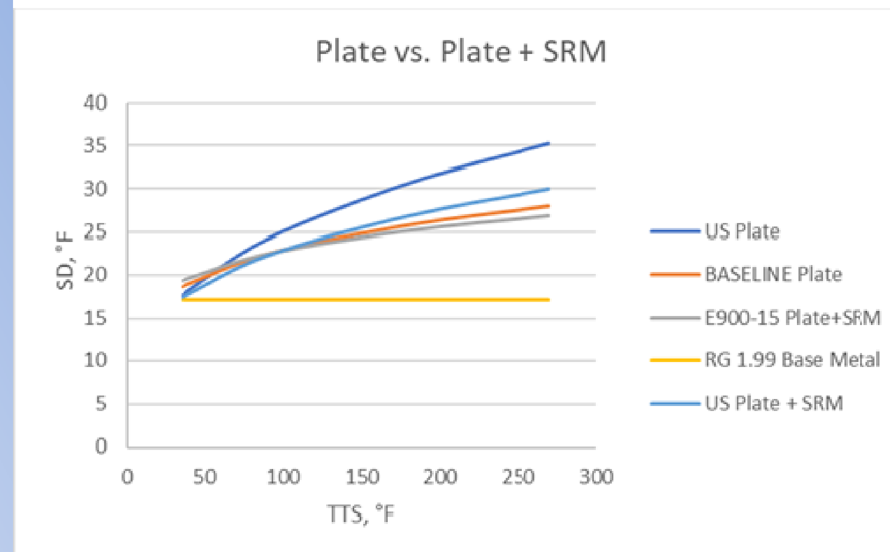


Welds: US – data only fit is similar to E900-15 fit, slightly lower SD at high TTS and opposite at low TTS.

Fits for Plate



- Plate: E900-15 combined plate plus SRM for SD.
- Inclusion of SRM with plate results in lower SD for both US and US + international data.
- SRMs have no regulatory purpose and not required to be tested, therefore does not seem appropriate to mix with plate data for purpose of determining SD.
- Therefore, C and D were determined based on US plate only.



Default Values

Default Values

- Default values can be used in the ΔRT_{NDT} calculation when certain data is not available.
- Cu, Ni, Mn, P, temperature.
- Selected to be conservative-
  - Chemistry values are high
  - Temperature is low
- Expect that missing chemistry values will be rare for beltline materials, particularly Cu and Ni.
- Need to use default value for irradiation temperature expected to be rare.

Approach

- Determine distribution of values for each variable in BASELINE
- Plotted histograms
- Determined quartiles of data

Recommendation - Chemistry

- Use maximum value from database for Cu, Ni, Mn, P.
  - Basis – Considered using an upper 95% value or 75% value. Since values do not appear to be normally distributed, WG decided to use maximum values from distribution.
  - These values are conservative, and missing chemistry values are expected to be a rare case.
  - WG considered using specification maximum, however specifications do not contain ranges for all elements
    - Example, SA-533 does not specify a range for Cu.

Recommended Default Chemistry Values (PWR and BWR)

Product Form	Cu	Ni	Mn	P
Forgings	0.16	0.86	1.41	0.020
Plate	0.25	0.68	1.65	0.021
Welds	0.41	1.20	1.96	0.024

Recommendation – Temperature (PWRS)

- RG will include guidance to use the reactor inlet or cold leg temperature for irradiation temperature for PWRs
- Use a time-weighted average if temperature changed for different cycles, such as due to power uprates, etc.
- Default value for PWRs: 523 °F (272.8 °C) based on US fleet minimum from BASELINE

Recommendation – Temperature (BWRs)

- RG will include guidance to use recirculation loop temperature for irradiation temperature of BWRs
- Use a time-weighted average if temperature changed for different cycles, such as due to power uprates, etc.
- Default value for BWRs: 530 °F (276.7 °C) based on minimum value from BASELINE

Limitations

Approach

- E900-15 specifies limitations on chemistry, fluence and temperature based on the maxima and minima of the database used to develop the trend curve.
- A commenter during the ASTM voting process for E900-15[1] recommended more restrictive limitations based on +/- 3σ, and "warning levels" based on +/- 2σ.
- The staff evaluated need for similar limits.
- Divide database into two populations based on percentile of all data.
- Perform surveillance data consistency checks (Type A, B, C, D) on both populations.
- Is there a difference in the proportion of passing and failing the consistency checks?

1- Attachment 2 to Appendix E of E900 Adjunct, p. 132-134

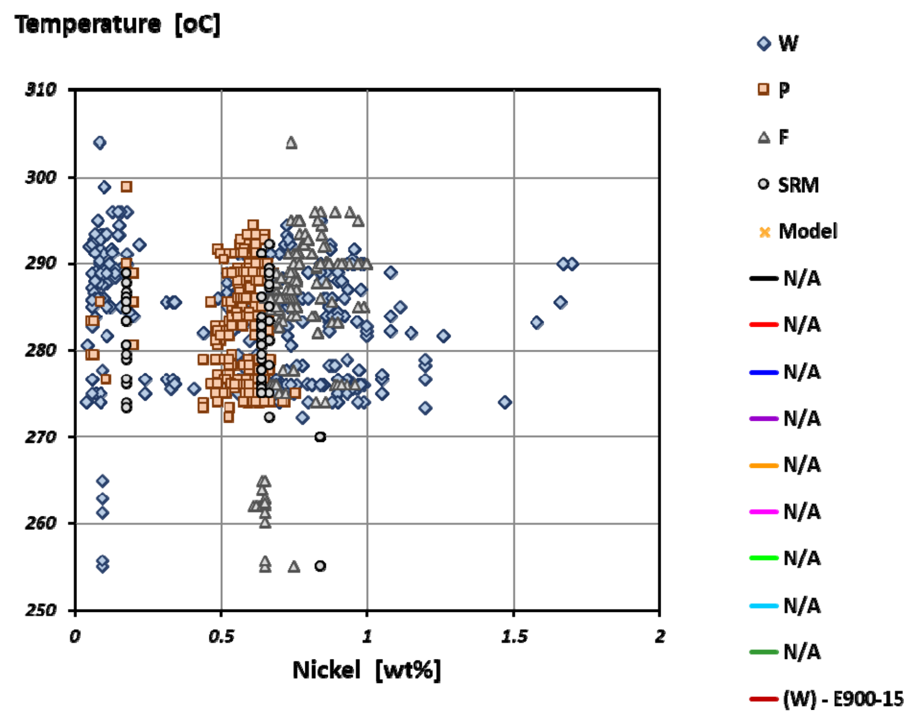
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Results

- Ran Type A,B,C and D tests for the entire population, 95^{th}, 96^{th}, 97^{th} , 98^{th} and 99^{th} percentiles.
- No statistically significant differences between entire population and any of the other percentiles.
- Therefore, it is not necessary to impose limitations more restrictive than those specified in E900-15, except for temperature.

Temperature Limitation

- A minimum temperature limitation of 523 °F (272.8 °C) is recommended.
- This corresponds to the minimum of the US operating fleet, as the data becomes sparse below this temperature.

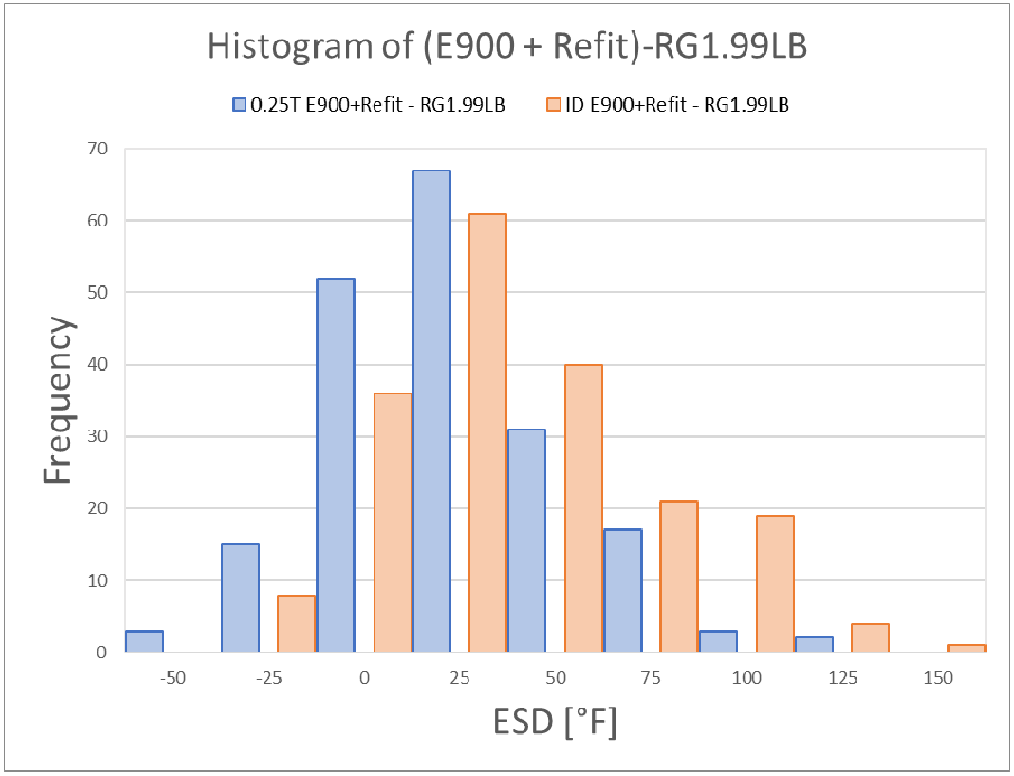


Fleet Impact Analysis

Fleet Impact Study Methodology

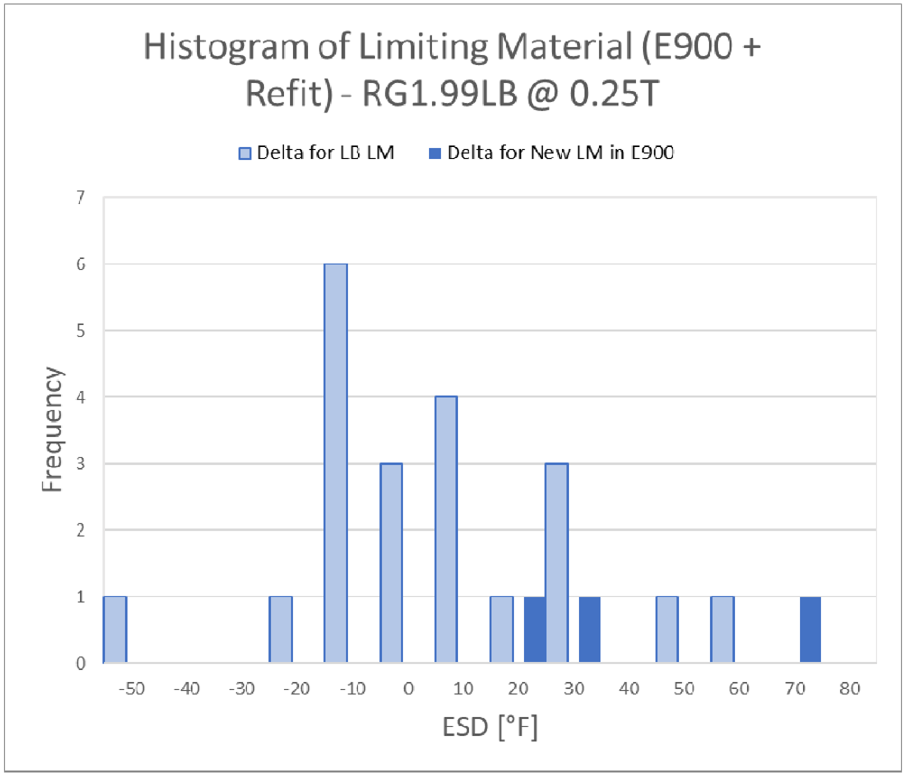
- Looked at a "smart sample" of 21 plants concentrating on high fluence PWRs, with additional plants with low Cu materials and BWRs added to span the fleet chemistry values (Cu, Ni).
- Used licensing basis material inputs (chemistry; fluence; $RT_{NDT(u)}$; licensing basis CF and ART for RG 1.99, Rev. 2).
- Calculated ART resulting from RG 1.99, Rev. 2, and E900-15, including the proposed RG margins and surveillance data tests/refit procedure.
- Determined changes in ART resulting from switching ETCs – "embrittlement shift delta" (ESD)

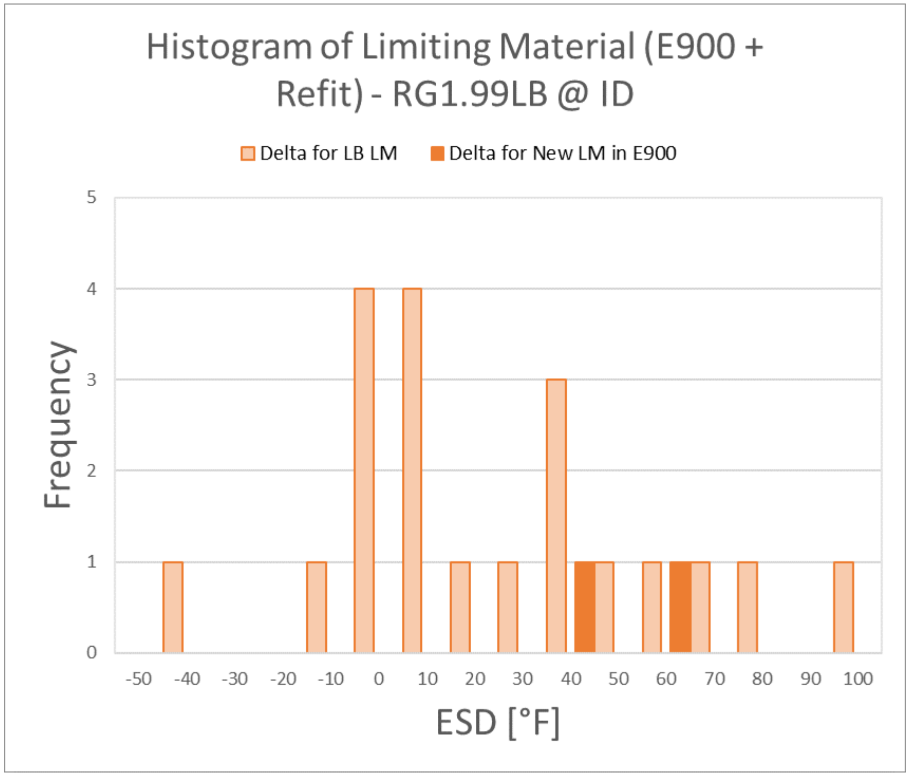
Reference Temperature Results All Materials



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

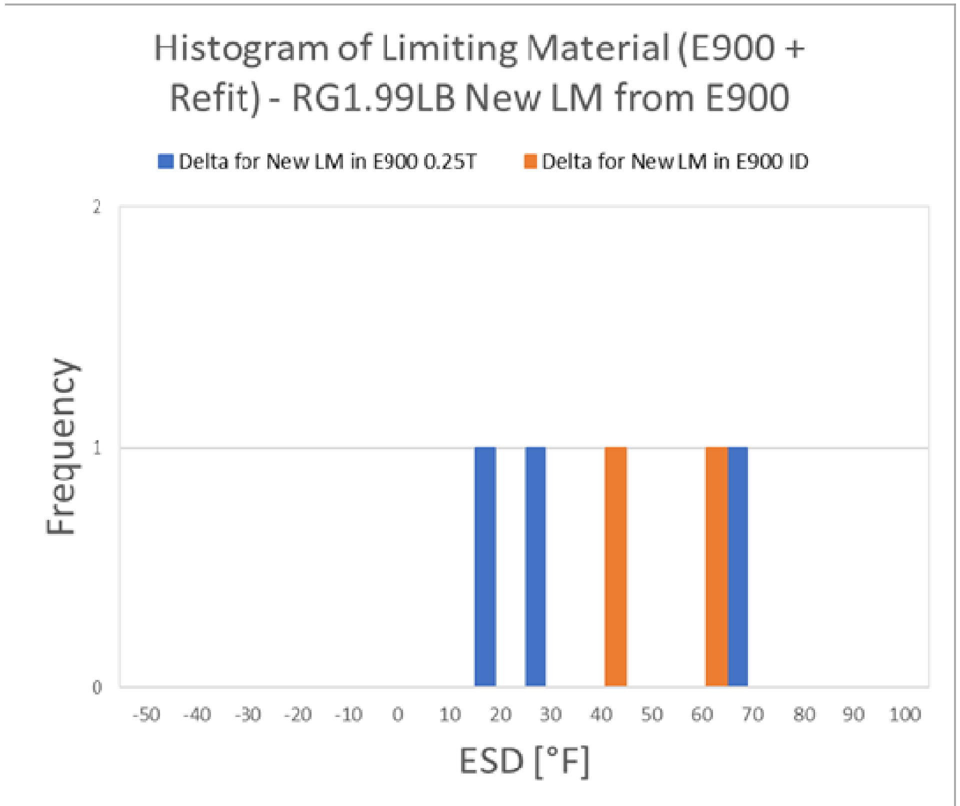
Reference Temperature Results – Limiting Materials





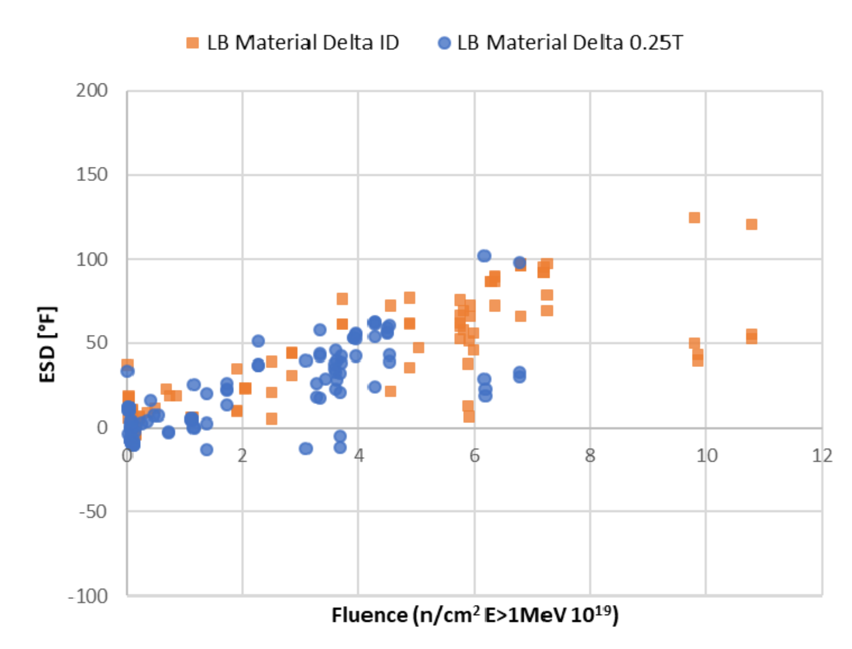
"new limiting material" refers to the situation where application of the E900-15 ETC causes a different material to have a higher ART than with RG 1.99, Rev. 2.

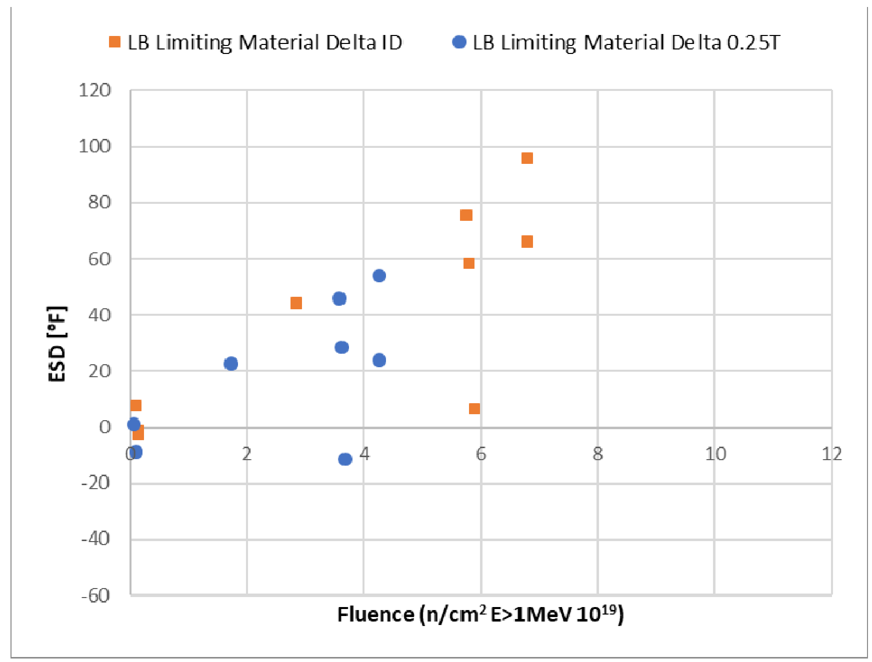
Potential New Limiting Materials



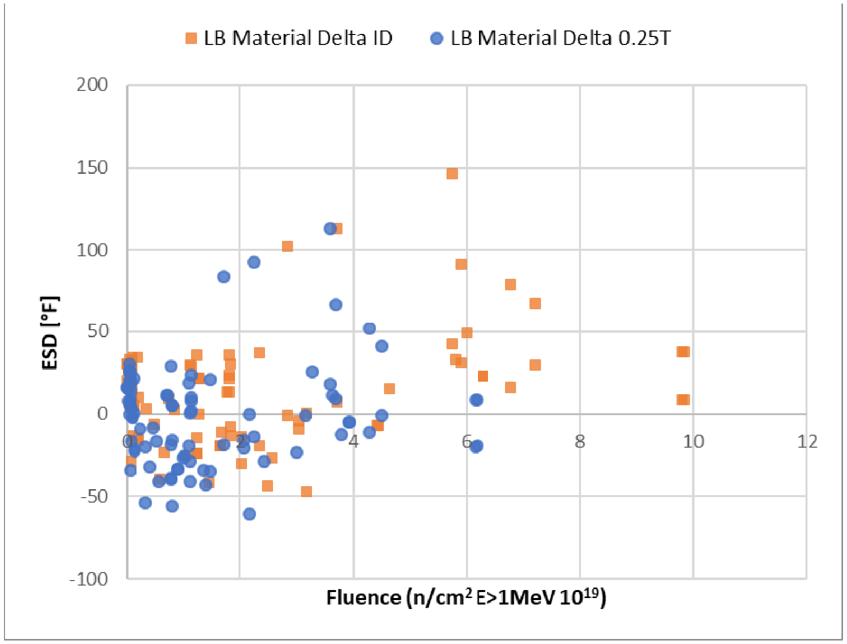
“new limiting material” refers to the situation where application of the E900-15 ETC causes a different material to have a higher ART than with RG 1.99, Rev. 2.

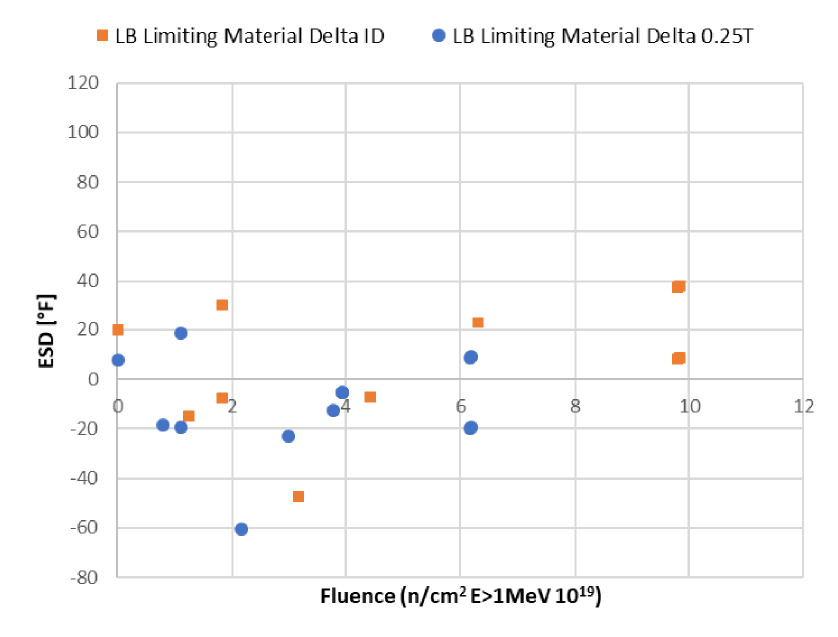
Reference Temperature Results– Base Metal





Reference Temperature Results – Weld Metal





U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Fleet Impact - Summary

- There is a tendency for material reference temperatures to increase when switching from RG 1.99, Rev. 2 to ASTM E900-15.
- ID reference temperatures tend to increase more than the 1/4T reference temperature (ART).
- Base materials are more likely to see increases in reference temperatures.
- Many weld materials see reductions in reference temperatures at fluences < 4×10^{19} n/cm^2 .
- Based on the smart sample, only a handful of plant limiting materials will have ESDs* > 50 °F, and these tend to be at fluences ~6×10^{19} n/cm^2 .

ESD – Embrittlement shift delta

Safety Impact Analysis

Objective

- Determine safety impact of a potentially nonconservative material reference temperature (ART or RT_{PTS}) associated with normal cooldown and leak test transients and PTS transients.
- Evaluated potential ETC non-conservatism by calculating the change in the conditional probability of failure (CPF) as a function of the "embrittlement shift delta" (ESD) (i.e., amount by which the material reference temperature changes using E900-15 vs. RG 1.99, Rev. 2).

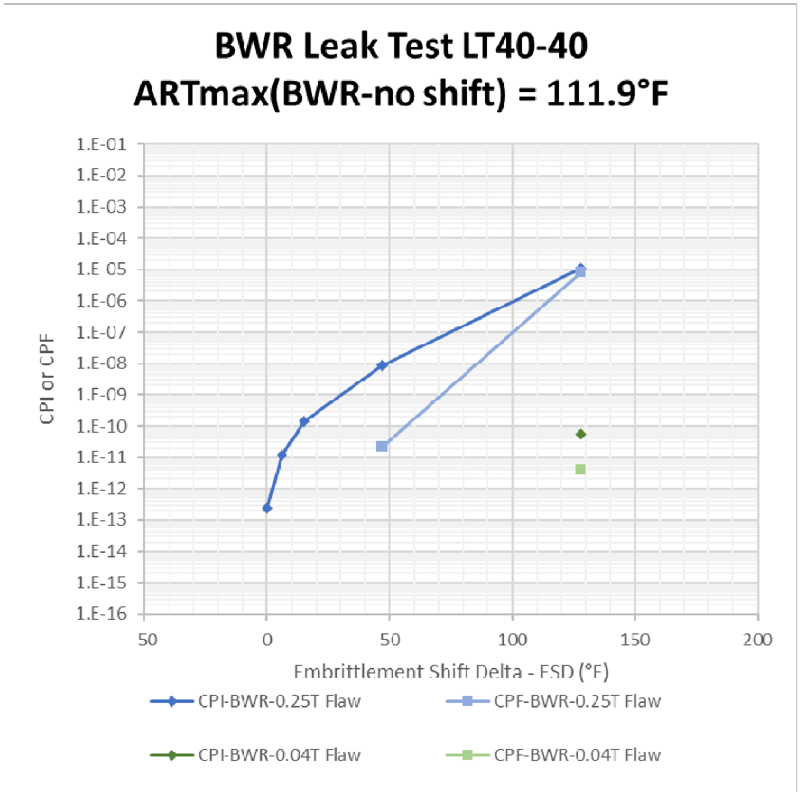
Method

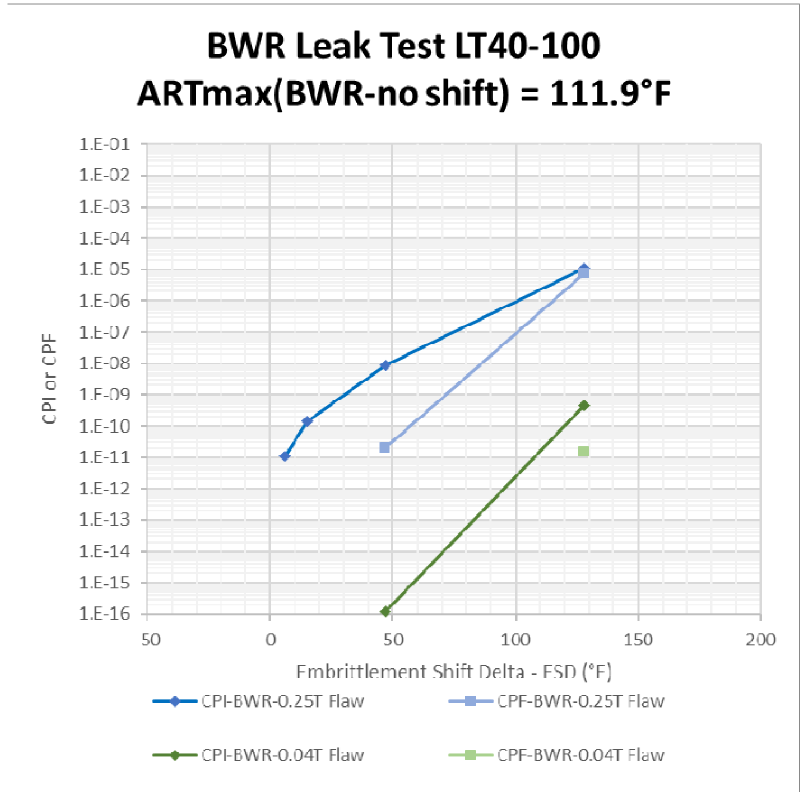
- Analysis uses FAVOR code.
- CPI and CPF calculated for a distribution of different ESDs from -40°F to 193°F.
  - Compared to fleet impact study, few limiting materials have ESDs > 50°F.
- Various transients were modeled.
- 1/4T and shallow surface-breaking flaws modeled.

Method

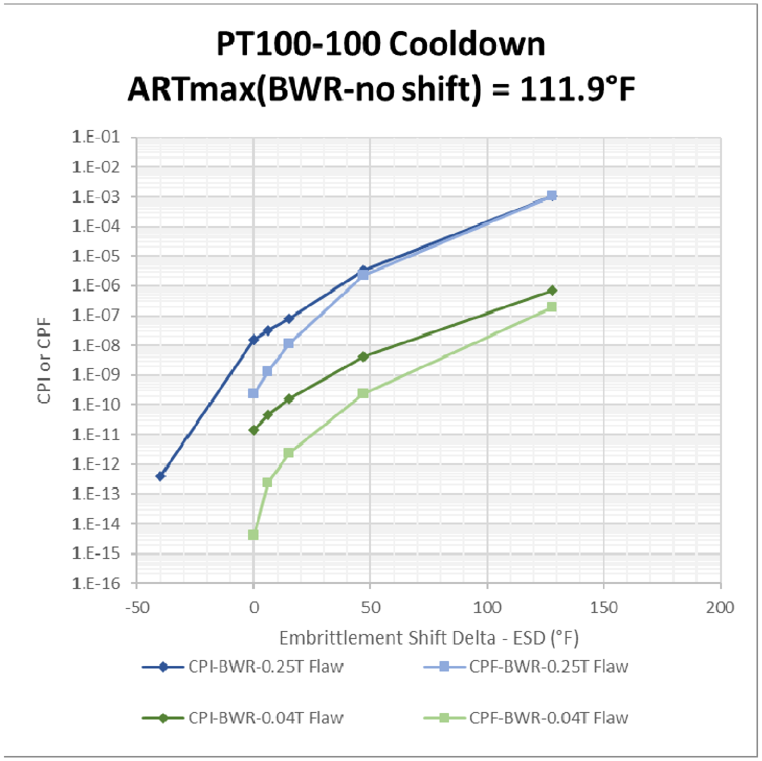
- CPF used as a "screening criterion" for reasonable assurance that no safety issue exists rather than through-wall cracking frequency (TWCF) due to uncertainty about some event frequencies.
- Determined the CPF associated with a nonconservative ETC, for the following scenarios:
  - BWR cooldowns following licensed P-T limits,
  - BWR saturation cooldowns,
  - BWR leak tests,
  - PWR PTS transients,
  - PWR cooldowns following licensed P-T limits,
  - PWR actual plant cooldowns.

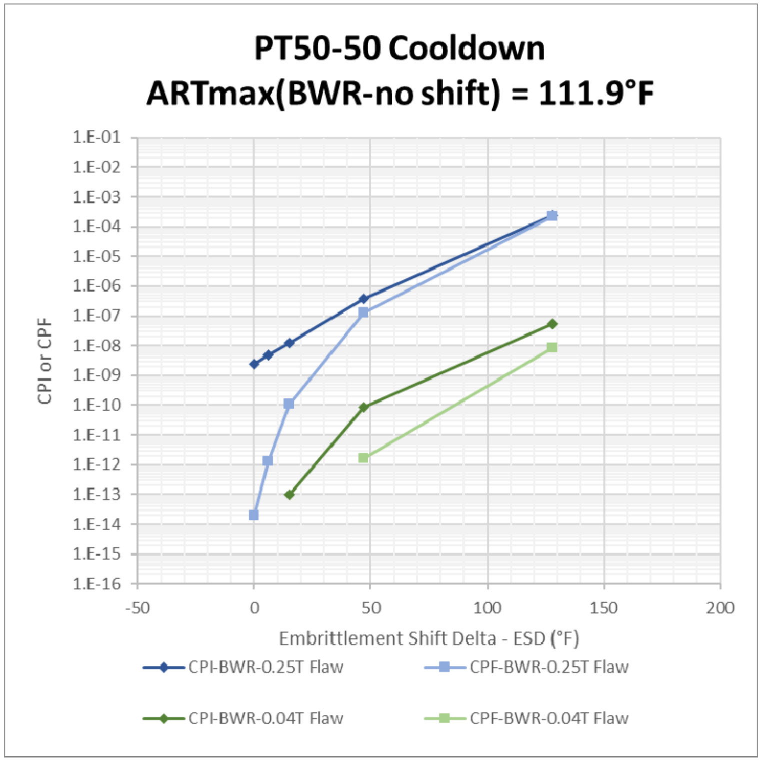
BWR Leak Test





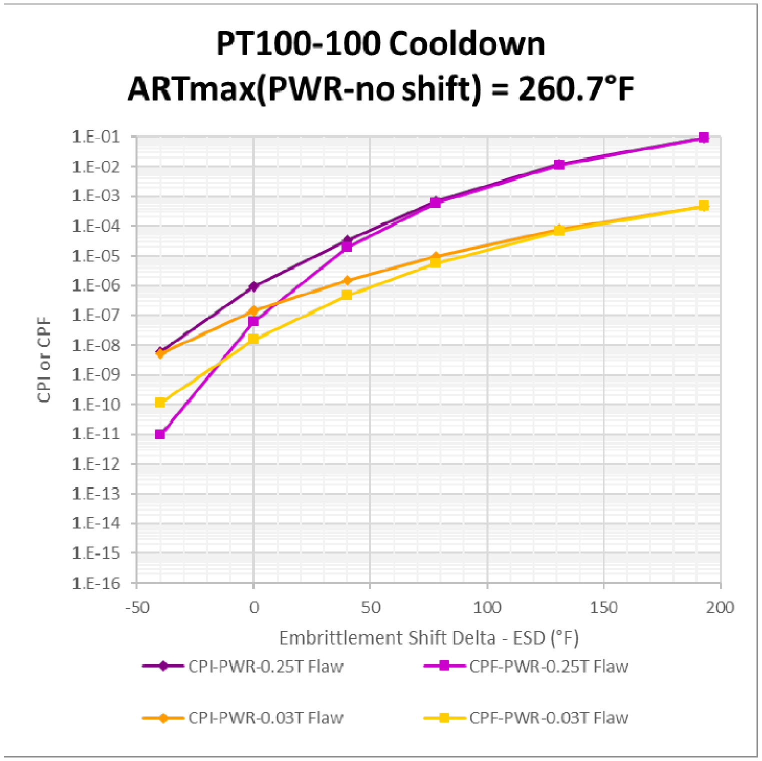
P-T Limits – BWR Cooldown Summary
(Licensed P-T limits)

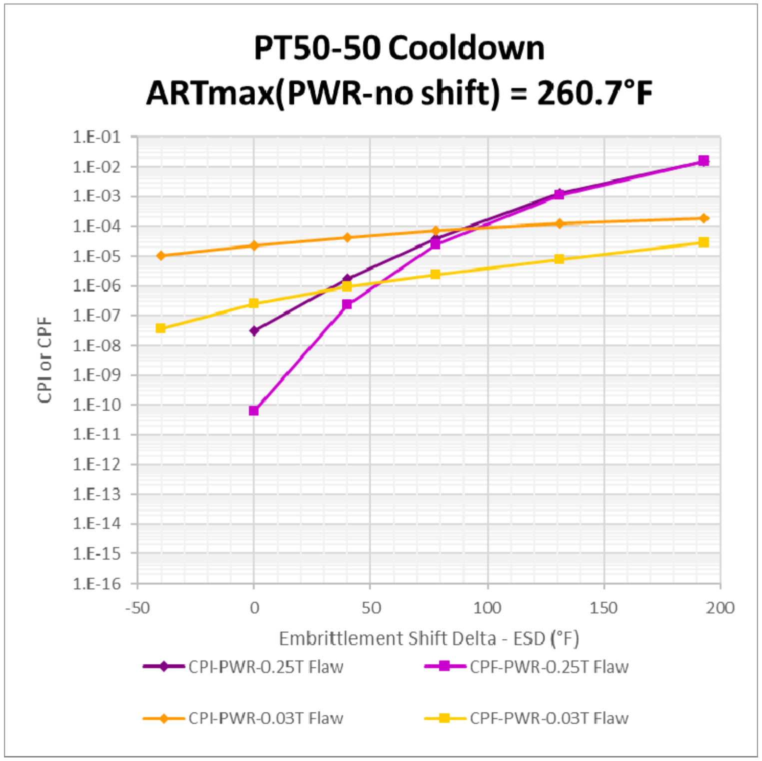




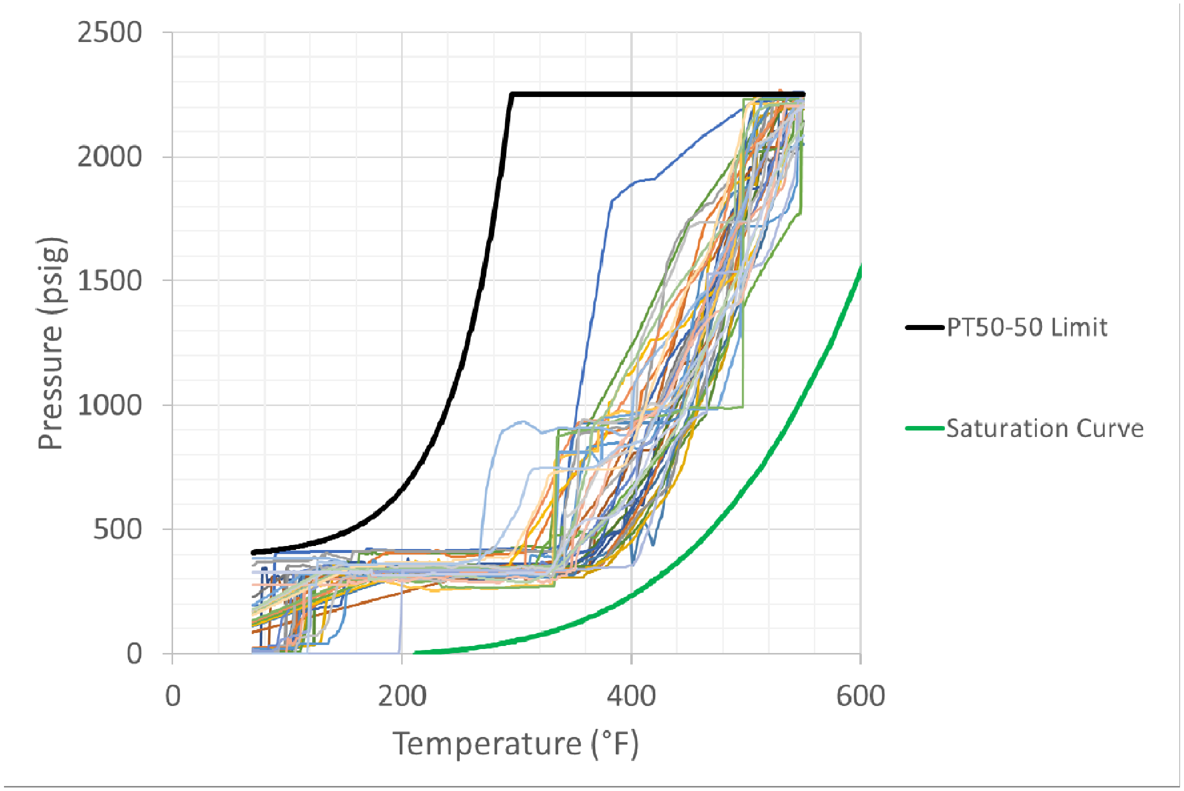
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

P-T Limits – PWR Cooldown Summary
(Licensed P-T limits)

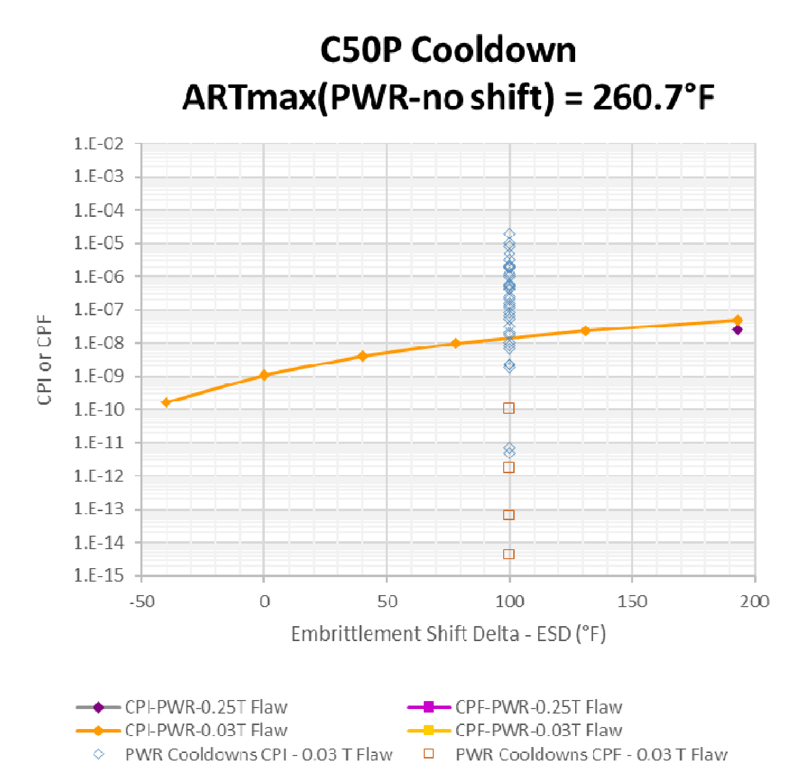


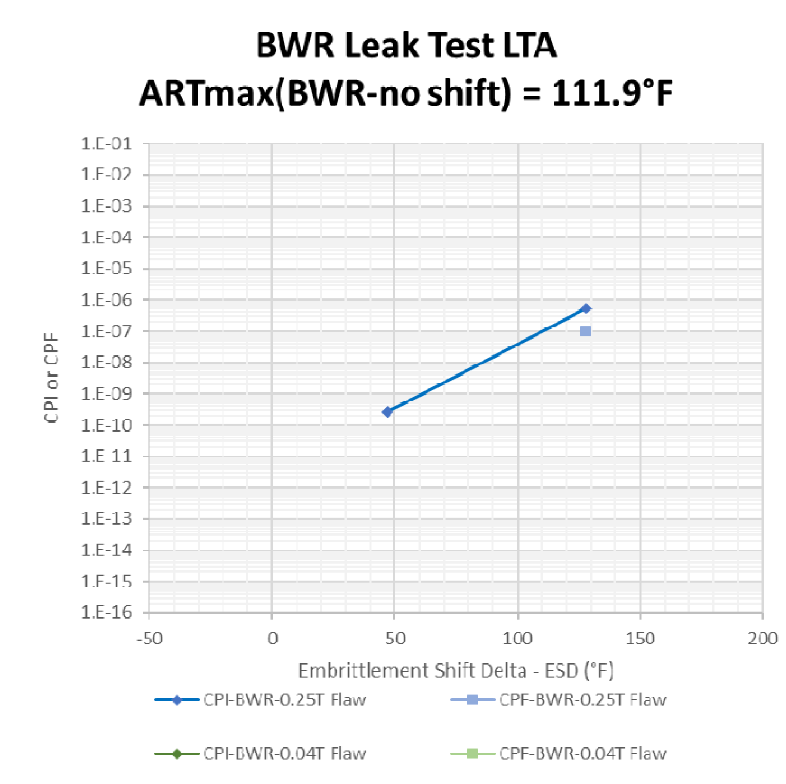


Actual Cooldowns – P-T Curves



Actual Cooldowns





U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Summary of Results

Transient Type	**Shallow Flaw**	**1/4T Flaw**	**Comment**
BWR P-T Limit Cooldown (C/D)	CPF ≤ 10^{-6} for all ESDs	CPF ≤ 10^{-6} for ESD ≤ 50 °F. CPF may be > 10^{-6} for higher ESDs	BWRs must cooldown on saturation curve, so C/D on licensed limits not plausible.
BWR Saturation Cooldown	CPF ≤ 10^{-6} for all ESDs	CPF ≤ 10^{-6} for all ESDs	
BWR Leak Test	CPF ≤ 10^{-6} for all ESDs	CPF ≥ 10^{-6} for ESD > 100 °F	Information from industry desired to confirm high cooldown rates are not possible, or code action to prohibit.
PWR P-T Limit Cooldown	CPF >10^{-6} for ESDs ≥ 50 °F	CPF > 10^{-6} for ESD ≥ 20 °F	Additional information on event frequencies is desired to confirm TWCF< 10^{-6}/year.
PWR Cooldown, Actual Transients	<< 10^{-6} for most transients	n/a	
PTS	**n/a**	**n/a**	All TWCF < 10^{-6}

Note, "all ESDs" means range of evaluated in the FAVOR analyses, -40 °F – 193 °F for PWRs and -40 °F to 128 °F for BWRs – corresponds to the 5^{th} through 99^{th} percentiles

Results – BWR

- BWR P-T limit cooldowns – Low CPF < 10^{-6}.
- BWR saturation cooldowns – Low CPF < 10^{-6}.
- BWR leak test - CPF > 10^{-6} for high ESDs.

Results – PWR P-T Limits

- Cooldowns on licensed P-T limits.
  - 1/4T flaws – no safety issue for ESD < 20 °F.
  - Shallow flaws can have CPF > 10^{-6} without ESD. ESD of 50-75 °F can increase CPF by an order of magnitude.
  - Shallow flaw high CPF is a known issue and is being studied by both NRC and EPRI.
  - Frequency of operating on licensed P-T limits is believed to be << 1/year, which is expected to result in TWCF ≤ 1×10^{-6}/year for most transients. However, staff would like more information on operational procedures and system constraints that prevent violating the licensed P-T limits.
- Actual plant transients
  - No significant failure risk.
  - Staff would like additional information to confirm that its sample of actual plant transients is representative.

PTS Method and Results

- Applied the same method used to develop the technical basis for the alternative PTS rule (NUREG-1874).
- NUREG-1874 defines relationship between maximum RT_{NDT} (RT_{MAX}) and TWCF.
- The TWCF was calculated for three different ETCs (RG 1.99, Rev. 2, E900-15, and 10 CFR 50.61a).
- TWCF < 10^{-6} /year for the 21-plant smart sample at 72 EFPY fluence, regardless of the ETC model applied.

PWR Summary

- Up to 50°F of ESD can conservatively be considered not to significantly increase the failure risk associated with P-T limits in light of additional plant constraints and an evaluation of a small subset of plant transients.
- No safety concern for PTS based on the smart sample evaluation.
- The main areas of uncertainty are:
  - The event frequency for impinging on the licensed P-T limits. What controls and procedures are in place to prevent violating licensed P-T limits?
  - How representative are the actual transients used in the staff's analysis? Can bounding actual transients be identified?

Safety Analysis - Conclusions

- Based on an 80-year analysis of a smart sample of plants, potentially nonconservative reference temperatures do not represent a significant safety issue in most cases for normal cooldowns, leak tests and PTS transients.
- Higher CPF calculated for the following transients:
  - Licensed P-T limits for plants with high ESDs.
  - BWR leak tests with high ESDs.
    - Lower cooling rates are expected to result in lower CPF values.
- Additional information desired to help confirm that the risk is low for the high ESD plants.
- Safety analysis results do not justify generic implementation of a revised RG based on ASTM E900-15.

Implementation

Potential for Burden Reduction

- Implementation of an E900-15-based RG has the potential to reduce burden for certain categories of reactors by reducing the reference temperature for a given neutron fluence, which in turn results in less restrictive P-T limits.
- Categories of plants that may see burden reduction include:
  - BWRs,
  - Low-fluence plants,
  - Plants with low-copper content materials,
  - Plants for which the limiting material is a weld.
- NRC received a petition for rulemaking from NuScale to implement E900-15 as the ETC for PTS and P-T limits, in lieu of RG 1.99 Rev. 2 with a degree-per-degree adjustment. The staff is currently evaluating the petition.

Summary

Feedback Requested on the Following Topics:

- Elements of potential RG framework that have been presented by the staff,
- Desire for an alternative to the current RG,
- Provide additional information to verify risk estimates for plants with ESD > +50 °F (see discussion questions next slide)

Additional Information/Discussion Topics

- PWRs
  - What controls and procedures are in place to prevent violating licensed P-T limits?
    - How standardized are these controls/procedures?
    - Are controls typically indexed to ART or absolute in P-T space?
    - Can controls be identified by plant type and design or are they entirely plant specific?
  - Is there a way to develop "bounding transients" that are more representative than the P-T limit curve based on the answers to the above questions? Can these be identified for specific design types, for example, Westinghouse 3-loop?
  - Is there is a more quantitative way to assess and sample the population of actual plant cooldown transients?
- BWR Leak Tests
  - Is it physically possible to heat up and cool down on the licensed P-T limits? Are there any physical, Code, or administrative limits to heat-up and cool-down rates?
  - Is an ASME Code activity planned to limit leak test heatup and cooldown rates?

Next Steps

- Decision on whether to proceed with developing an alternative regulatory guide.
  - Consider feedback from industry.
  - Further discussions with industry?
  - Complete fleet impact study if appropriate.

Acronyms/Definitions (1)

- **ART** – Adjusted reference temperature used for pressure-temperature limits (initial RT_{NDT} + ΔRT_{NDT} + margin)
- **CPF** – Conditional probability of failure – Probability that the reactor vessel will fracture through-wall given a certain event occurs.
- **ESD** = embrittlement shift delta - amount by which the material reference temperature changes using E900-15 vs. RG 1.99, Rev. 2
- **ETC** – Embrittlement trend curve – a mathematical relationship defining the relationship of ART to key variables such as chemistry and neutron fluence.
- **FAVOR** – Fracture Analysis of Vessels, Oak Ridge – A probabilistic fracture mechanics computer code.
- **P-T Limits** – Limits on pressure versus temperature for normal operations of a reactor
- **PTS** – Pressurized thermal shock, a challenging transient that may occur in PWRs

Acronyms/Definitions (2)

- **RT_{NDT}** – The reference temperature, nil-ductility transition.
- **$RT_{NDT(u)}$** – The initial or unirradiated RT_{NDT}. Per 10 CFR 50, Appendix G, $RT_{NDT(u)}$ is evaluated according to the procedures in the ASME Code, Paragraph NB-2331. NUREG-0800 BTP 5-3 provides an alternative procedure.
- **ΔRT_{NDT}** -The change in RT_{NDT} due to irradiation, defined in RG 1.99, Rev. 2 as the shift in the Charpy curve at the 30 foot-pound level. Also referred to as ΔT_{41J} in this presentation, 41 joules = 30 foot-pounds.
- **RT_{PTS}** – Adjusted reference temperature used for pressurized thermal shock criteria
- **P-T Limits** – Limits on pressure versus temperature for normal operations of a reactor
- **TWCF** – Through-wall cracking frequency – CPF x event frequency per reactor year

Backup Slides

Statistical Error Types

Residuals between BASELINE data and the ASTM E900-15 ETC are calculated using the best estimate chemistries time weighted operating temperatures. $r = \Delta T_{41J(Measured)} - \Delta T_{41J(Predicted)}$

Note: All tests were conducted as described in NUREG-2163 (ML18255A118), Section 5.4, with the exception that σ for all tests was SD determined per Equation [9] of E900-15. The proposed procedure will use the σ determined per Slide 30.

<u>Type A</u>: Mean Test: If r_{mean} of all of the residuals for heat of material fall below the threshold value, $r_{max} = \frac{2.33\sigma}{\sqrt{n}}$, then there is no Type A error. $r_{mean} = \frac{1}{n}\sum_{i=1}^{n} r_i$

<u>Type B</u>: Slope Test: Plot the residual values for each heat of material on a semi log plot of fluence and calculate the T-statistic using the best-fit slope and standard error of the best-fit slope. $T_{stat} = \frac{m}{se(m)}$ if the calculated T-statistic is below the tabulated 1% 1-sided T-statistic value, then there is no Type B error.

<u>Type C</u>: Scatter Test: For each heat of material if $\sqrt{\frac{\sum r^2}{n}} \leq \sigma_{(\text{at the maximum fluence})}$ then there is no Type C error.

<u>Type D</u>: Outlier Test: $r_1^* = \frac{r}{\sigma}$ and $r_2^* = \frac{r}{\sigma}$ are the largest and second-largest values of $\frac{r}{\sigma}$ for each heat of material. Compare these to r_{limit_1} and r_{limit_2} from Table 5-4 (NUREG-2163). If $r_1^* \leq r_{limit_1}$ and $r_2^* \leq r_{limit_2}$ then there is no Type D error