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Basis for a Potential Alternative to Revision 2 of Regulatory Guide 1.99
Technical Letter Report

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List of Abbreviations

Abbreviation	Definition
¼-T	location at one-quarter of the total thickness within the reactor pressure vessel as measured from the inner diameter
½-T	location at half of the total thickness within the reactor pressure vessel as measured from the inner diameter
¾-T	location at three-quarters of the total thickness within the reactor pressure vessel as measured from the inner diameter
ACRS	Advisory Committee on Reactor Safeguards
ADAMS	Agencywide Documents Access and Management System
ART	adjusted reference temperature
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BWR	boiling-water reactor
BWRVIP	Boiling Water Reactor Vessel and Internals Program (EPRI)
C	Celsius
CF	chemistry factor
$CF_{defined}$	chemistry factor defined as "mean reality" in simulation
CF_{FIT}	chemistry factor refit to surveillance data
CF_{SIM}	chemistry factor simulated from sampling mean and standard deviation
CFR	*Code of Federal Regulations*
CMM	correlation monitor material (also called a standard reference material)
EMA	equivalent margins analysis
EOL	end of life
EPRI	Electric Power Research Institute
Eq.	equation
ESD	embrittlement shift delta
ETC	embrittlement trend correlation
F	Fahrenheit
F	forging
f_{surf}	fluence at inner diameter of reactor pressure vessel
ID	inner diameter
ISP	Integrated Surveillance Program
Ln(L)	Logarithm of Likelihood
LWR	light-water reactor
MD	management directive
MRP	Materials Reliability Program (EPRI)
MTR	materials testing reactor
NDT	nil-ductility temperature
NIIAR	Research Institute of Atomic Reactors (Russia)
NRC	U.S. Nuclear Regulatory Commission
NRR	Office of Nuclear Reactor Regulation
P	plate
PFM	probabilistic failure mechanism
PSF	pool side facility
PSSP	PWR Supplemental Surveillance Program
PWR	pressurized-water reactor
RAMA	Radiation Modeling Application (BWRVIP)

Abbreviation	Definition
REAP	Reactor Embrittlement Archive Project
RG	regulatory guide
RPV	reactor pressure vessel
RMSD	root-mean-square deviation
RT_{NDT}	reference temperature, nil ductility transition
ΔRT_{NDT}	shift in reference temperature for a reactor vessel material measured at the 30-foot-pound energy level
SD	standard deviation
SLR	subsequent license renewal
SMR	small modular reactor
SRM	standard reference material (also called a correlation monitor material)
σ	standard deviation
σ_{Δ}	standard deviation of ΔT_{41J} measurement
T_0	reference temperature characterizing the onset of cleavage cracking at elastic or elastic-plastic instabilities (or both)
ΔT_{41J}	metric term for ΔRT_{NDT}
TTS	transition temperature shift
U.S.	United States of America
USE	upper-shelf energy
$USE_{(I)}$	upper-shelf energy irradiated
$USE_{(U)}$	upper-shelf energy unirradiated
ΔUSE	shift in upper-shelf energy
VVER	Water-Water Energetic Reactor (Soviet PWR design)
W	weld

Executive Summary

This report serves as a knowledge management tool to document work performed in support of a potential alternative to Regulatory Guide (RG) 1.99, Revision 2, “Radiation Embrittlement of Reactor Vessel Materials,” issued May 1988. RG 1.99 provides guidance to licensees of light water reactors in the United States to predict the change in the material reference temperature and the upper-shelf energy (USE) due to neutron irradiation. At this time, the staff is not pursuing revision of RG 1.99.

In 2019, the NRC staff completed an assessment of the continued adequacy of RG 1.99 in “Assessment of the Continued Adequacy of Revision 2 of Regulatory Guide 1.99—Technical Letter Report.” The assessment identified several issues for further consideration. This report presents the technical basis for a potential alternative to RG 1.99, developed in response to the findings of the 2019 assessment. This report includes the elements for the potential alternative, their development, and the basis for the choices made by the staff in producing the potential alternative.

In RG 1.99, the reference temperature, adjusted to account for the effects of irradiation, and with margin added for uncertainty, is known as the adjusted reference temperature (ART). The potential alternative addresses the prediction of the ART but does not concern the prediction of USE. This is consistent with the findings related to USE from the RG 1.99 assessment, which indicated no change was warranted. The potential alternative is built around the standard American Society for Testing and Materials (ASTM) E900 15, “Standard Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials.”

The potential alternative includes an embrittlement trend curve from ASTM E900 15, recommendations for use of plant-specific surveillance data, margins to account for uncertainty (both on initial properties and the shift in reference temperature due to irradiation), default values of input variables, and limitations on the ranges of input variables. This report also documents the method and findings of a study of the impact, in terms of the changes to the ARTs of the beltline materials, of implementing the alternative framework for the materials from a “smart sample” of 21 reactors.

This report serves a knowledge management purpose. As previously mentioned, the staff is not pursuing a revision to RG 1.99 to implement the proposed alternative. The decision to not pursue a revision is primarily based on the results of a risk study, documented in TLR RES DE CIB 2020 09— “RG 1.99R2 Update FAVOR Scoping Study,” dated October 26, 2020. The findings of this risk study are not discussed in this report.

1. Introduction

The U.S. Nuclear Regulatory Commission (NRC) issued Regulatory Guide (RG) 1.99, Revision 2, “Radiation Embrittlement of Reactor Vessel Materials” (Ref. 1), in 1988. RG 1.99 provides guidance to licensees of light-water reactors (LWRs) in the United States to predict the change in materials properties due to irradiation. RG 1.99 provides a methodology to determine the reference temperature, nil ductility transition (RT_{NDT}) of irradiated materials and the upper shelf energy (USE) of irradiated materials. In RG 1.99, the RT_{NDT} adjusted for the effects of neutron irradiation is called the adjusted reference temperature (ART). RG 1.99 also provides guidance on the use of surveillance program data on plant-specific materials to adjust the prediction of RT_{NDT} and USE.

In 2019, the NRC staff completed an assessment of the adequacy of RG 1.99, which it documented in “Assessment of the Continued Adequacy of Revision 2 of Regulatory Guide 1.99—Technical Letter Report” (Ref. 2). The assessment identified a few issues for further consideration. The most significant of these is the performance of the embrittlement trend correlation at higher neutron fluences (greater than $6x10^{19}$ neutrons per square centimeter (n/cm^2), (energy (E) > 1 mega electron-volt (MeV)).

The staff presented the assessment to the Metallurgy and Reactor Fuels Subcommittee of the Advisory Committee on Reactor Safeguards (ACRS) on August 22, 2019 (Ref. 3), and the ACRS full committee during its 668th meeting on November 6–8, 2019 (Ref. 4). The ACRS replied in its letter dated November 27, 2019 (Ref. 5). The staff responded to the ACRS by letter dated December 23, 2019 (Ref. 6).

The NRC held a public meeting on May 19, 2020, at which it discussed the technical basis supporting a potential alternative to RG 1.99, including the framework elements of the alternative RG, results of a fleet impact study of a smart sample of plants, and the results of a probabilistic fracture mechanics (PFM) analysis assessing the impacts of nonconservatisms associated with the RG 1.99 embrittlement trend correlation (ETC) (Ref. 7).

This report presents the technical basis for a potential alternative to RG 1.99, developed by the NRC staff working group and oversight group in response to the findings of the assessment report, the ACRS review, and its endorsement of the staff’s effort to revise RG 1.99.

The NRC staff working group determined that, based on the assessment report in Reference 2, it was not necessary to update the USE model in RG 1.99 for the potential alternative RG, due to the relatively low safety significance and lack of regulatory need.

Section 2 of this report discusses the motivation for developing a potential alternative to RG 1.99. Section 3 describes the framework elements of a potential alternative RG, including the ETC, margins, use of surveillance data, default values for ETC inputs, and limitations. Section 4 discusses the results of a fleet impact study related to the potential alternative RG, which determined the predicted changes in RT_{NDT} associated with changing to an updated ETC for a smart sample of plants. Section 5 contains conclusions, and Section 6 lists the references.

2. Motivation for the Evaluation Effort

Numerous alternative ETCs published since the original issuance of RG 1.99 use larger databases and more complicated mathematical forms. As a modeling exercise, creating statistical regressions from large databases has proven somewhat challenging, as many improved ETCs contain perceived weaknesses for particular subpopulations within the underlying database. The NRC has closely followed the evolution of American Society for Testing and Materials (ASTM) E900 and, with the advent of ASTM E900-15, "Standard Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials," gained access to the underlying BASELINE dataset. Access to this database supported the conduct of a high-quality preliminary assessment of RG 1.99. The results indicated statistically significant deviations between RG 1.99 predictions and measured data. Consequently, the NRC conducted a thorough assessment of RG 1.99 during its normal RG evaluation period.

In July 2019, the NRC staff completed an evaluation of RG 1.99, documented in "Assessment of the Continued Adequacy of Revision 2 of Regulatory Guide 1.99—Technical Letter Report" (Ref. 2). The assessment identified a few issues for further consideration, of which the most significant is the performance of the ETC at higher neutron fluences (cited as greater than 3 to $6x10^{19}$ n/cm^2, (E > 1 MeV)).

Other findings of the assessment included the following:

- The ETC is inaccurate for low-copper (Cu) materials.
- The standard deviation (SD) of the shift in the reference temperature due to irradiation (ΔRT_{NDT})[a] is too small.
- The ETC has a conservative bias in the low-to-medium fluence range, which creates a potential burden on licensees, because predictions that are too high may narrow the operating window of pressure-temperature limits or increase the required hydrostatic testing temperature.
- The ETC lacks a specific input for irradiation temperature, which creates inaccuracy for conditions near the bounds of the data.
- The credibility criteria are fundamentally flawed due to a higher probability of rejecting new data as credible as more data become available. This is often caused by one outlier that does not meet the scatter requirements. In such cases, RG 1.99 defaults to the prediction based on the generic ETC rather than that based on the surveillance data, even if the surveillance data would result in a more accurate prediction of the material behavior.
- The USE model is nonconservative for 19 percent of materials; however, the safety impact of this nonconservatism is minimal.

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[a] The term ΔT_{41J} is used synonymously with ΔRT_{NDT} in this report. ΔRT_{NDT} is defined as the change in the 30-foot-pound temperature. ΔT_{41J} is the metric equivalent. ASTM E900-15 uses the term transition temperature shift (TTS) synonymously with ΔT_{41J}.

- 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, and degree-for-degree adjustment.

The NRC staff presented the assessment to the ACRS Metallurgy and Reactor Fuels Subcommittee on August 22, 2019 (Ref. 3), and the full committee during its 668th meeting on November 6–8, 2019 (Ref. 4). The ACRS issued a letter to the staff on November 27, 2019 (Ref. 5) related to this topic. The staff responded to the ACRS by letter dated December 23, 2019 (Ref. 6).

3. Regulatory Guide Framework Elements

3.1 Selection of the Embrittlement Trend Correlation

3.1.1 Background

Since the publication of RG 1.99, various research and regulatory organizations have developed numerous ETCs. Many of these were based on considerably more data than the 177 pieces of data on which RG 1.99 was based. ASTM Subcommittee E10.02 has published standards containing an ETC several times since 1989. In 2014, the ASTM E10.02 subcommittee began an effort to update its E900 standard to a more modern ETC. The subcommittee evaluated nine different ETCs. It documented the results of these evaluations in the "Adjunct for ASTM E900-15 Technical Basis for the Equation Used to Predict Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials," dated September 18, 2015 (Ref. 8). The result was the publication of ASTM E900-15 (Ref. 9).

3.1.2 Available Embrittlement Trend Correlations

The staff selected two ETCs for evaluation as potential replacements for the ETC of RG 1.99, considering the results of the ASTM ETC evaluation. The staff selected these because they are either already approved in an NRC regulation (Title 10 of the *Code of Federal Regulations* (10 CFR) 50.61a, "Alternate fracture toughness requirements for protection against thermal shock events") (Ref. 10) or are approved in a consensus standard (ASTM E900-15).

10 CFR 50.61a (EONY)

The NRC sponsored the development of the 10 CFR 50.61a ETC (50.61a ETC) as part of an effort to update 10 CFR 50.61, "Fracture toughness requirements for protection against pressurized thermal shock events" (the Pressurized Thermal Shock Rule). This ETC was eventually incorporated into 10 CFR 50.61a, the Alternate Pressurized Thermal Shock Rule, published in 2010 (Ref. 10). The 10 CFR 50.61a ETC was fit to 855 ΔRT_{NDT} values encompassing U.S. LWR (boiling-water reactor (BWR) and pressurized-water reactor (PWR)) surveillance data through 2004.

The 10 CFR 50.61a ETC has 31 empirically fit parameters and is based on the following:

- three exposure variables: fluence, temperature, and flux
- four composition variables: Cu, nickel (Ni), manganese (Mn), and phosphorous (P)
- three categorical variables: product form, vessel manufacturer, and weld flux type

ASTM E900-15

The ASTM E900-15 ETC (E900-15 ETC) was originally known as WRC(5)-R1. This was one of four ETCs that the ASTM chose for recalibration in 2014. The recalibrated version of WRC(5)-R1 is based on 1,878 ΔRT_{NDT} data points (the "BASELINE" database). BASELINE contains only commercial power reactor material data (BWR and PWR), not material test reactor data. The data include both U.S. and international surveillance data, with 1,033 data points being U.S. surveillance data.

The E900-15 ETC has 32 empirically fit parameters and is based on the following:

- two exposure variables: fluence and temperature

- four composition variables: Cu, Ni, Mn, and P
- one categorical variable: product form

RG 1.99, Revision 2

For comparison, the RG 1.99 ETC was based on 177 ΔRT_{NDT} data points, as follows:

- one exposure variable: fluence
- two compositional variables: Cu, Ni
- one categorical variable: product form

3.1.3 E900-15 vs. 10 CFR 50.61a Statistical Comparison

Statistical comparisons were made of the E900-15 and 10 CFR 50.61a ETCs, and also of both ETCs to the RG 1.99 ETC. The comparisons were made both for all data and for several data subsets or bins, including for PWRs and BWRs; product form (welds, base); low and high Cu; and low and high fluence. Low and high Cu bins were defined based on Cu ≤ 0.08 weight percent (%) (low) and > 0.08 weight % (high). Low and high fluence bins were defined based on neutron fluence values $\leq 3\text{x}10^{19}$ n/cm^2 and $> 3\text{x}10^{19}$ n/cm^2 (E > 1MeV). This fluence value was selected because (1a) it is roughly the point at which the mean base metal predictions in RG 1.99 diverge from the mean of measured data, and (2) it ensured enough data in the high fluence bin to report useful statistical results.

The following statistical measures were evaluated:

- 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

These methods are described below. Before developing the results in this report, researchers expected that the performance of both ATSM E900-15 and 10 CFR 50.61a would be acceptable for U.S. data as both were fit to largely the same data with additional results included in ASTM E900-15. As ASTM E900-15 was also fit to a broader set of data from international sources, it was expected to have superior performance with regard to these data. The results confirmed these expectations.

Caution should be used in interpreting the results here, as both trend curves are being compared to data that were used to fit the curves initially (entirely overlapping in the case of ASTM E900-15), and consequently these results provide no insight on any potential overfitting issues. Additionally, these results do not distinguish where issues arise from a paucity of data related to particular input variables as opposed to the inherent characteristics of the mathematical formulation used in the ETCs. Finally, these results do not (especially for ASTM E900-15) provide clear indications of the stability of the fits when extrapolated beyond the highest fluence data used to calibrate the ETC. Despite these cautions, the mathematical form-functions used for both E900-15 and 10 CFR 50.61a are expected to have superior extrapolation characteristics (i.e., predictions outside their basis data) relative to RG 1.99.

All data used to generate the results below are based on the BASELINE dataset as described in the RG 1.99 assessment.

3.1.4 Methodology of Statistical Tests

Bias

The values reported for bias in this evaluation are the R_{mean} values as defined in Table 3-1.

RMSD

RMSD is defined as an estimate of the average deviation between predicted and observed ΔRT_{NDT} values in a particular data subset. Ideally, these values should be as small as possible. Table 3-2 provides the equations that were used to determine RMSD.

Table 3-1 Statistical Metrics Used To Determine Bias

	Mean Residual (R_{MEAN})	$R_{MEAN} = \frac{S_y}{n}$
	T test on R_{MEAN} (T_{MEAN})	$T_{MEAN} = \frac{\lvert R_{MEAN}\rvert}{s_R/\sqrt{n}}$ *where* $s_R = \sqrt{\frac{\sum_{i=1}^{n}(y_i - R_{MEAN})^2}{n-1}}$
Metric Interpretation	R_{MEAN}	*R_{MEAN} is the mean value of all prediction errors in a particular data subset. A value of zero indicates an unbiased prediction.*
	T_{MEAN}	*T_{MEAN} is a value of Student's t-statistic that can be used to assess the statistical significance of the mean residual. If n exceeds 30, then values of T_{MEAN} above 1.96 are generally considered significant.*
Definitions *$y = \Delta RT_{NDT(PREDICTED)} - \Delta RT_{NDT(MEASURED)}$ or $USE_{(I)MEASURED} - USE_{(I)PREDICTED}$, as appropriate* *n = number of data records* $S_y = \sum_{i=1}^{n} y_i$		

Table 3-2 Determination and Interpretation of RMSD

Metric Definition	RMSD	$\boldsymbol{RMSD = \sqrt{\frac{S_{yy}}{n}}}$
Metric Interpretation	RMSD	An estimate of the average deviation between predicted and observed ΔRT_{NDT} values in a particular data subset. Ideally, this value should be as small as possible.
<u>Definitions</u> y = $\Delta RT_{NDT(PREDICTED)} - \Delta RT_{NDT(MEASURED)}$ or $USE_{(I)MEASURED}$ - $USE_{(I)PREDICTED}$, as appropriate n = number of data records $\boldsymbol{S_{yy} = \sum_{i=1}^{n} y_i^2}$		

Logarithm of Likelihood, Ln(L)

Another statistical metric used in this report is called likelihood, which provides a quantitative answer to the following question:

> Given a particular trend curve equation, and assuming that it is correct, what is the likelihood that a particular data set could have occurred?

Trend curve equations having higher likelihood values provide better representations of the data (i.e., have better goodness-of-fit) than those having lower likelihood values. The logarithm of likelihood, Ln(L), is typically reported and is defined in Equation (Eq.) (3-1) (Ref. 11):

$$\mathrm{Ln}(\mathrm{L}) = -\frac{\mathrm{n}}{2}\mathrm{Ln}(2\pi) - \sum_{i=1}^{n}\left[\ln(\sigma_i) + \frac{1}{2}\left(\frac{\Delta RT_{NDT(measured)i} - \Delta RT_{NDT(predicted)i}}{\sigma_i}\right)^2\right] \tag{3-1}$$

Where:

L	Is the likelihood of a particular trend curve equation being correct, given the set of measurements being considered
n	Is the number of measured values of ΔRT_{NDT}
$\Delta RT_{NDT(measured)i}$	Is a measured value of ΔRT_{NDT}
$\Delta RT_{NDT(predicted)i}$	Is a value of ΔRT_{NDT} predicted by a particular trend curve corresponding to a particular measured value
σ_i	Is the published standard deviation of the $\Delta RT_{NDT(pred)i}$ value. In some trend curve equations σ is the same for all conditions, while in others it may depend on variables such as the product form, Cu, or fluence.

Mathematically, the "likelihood" of a set of data is the product of probability densities of all data in the set; thus, it quantifies the probability of observing the set of data subject to the assumption that the trend curve equation used to calculate the predicted values is correct. Trend curve equations having higher likelihood are therefore more plausible models of reality than lower likelihood models, where "reality" is quantified by the set of data selected for evaluation. Examination of Eq. (3-1) makes clear that Ln(L) quantifies how well both the central tendency and scatter are represented by a particular ETC equation, as described below:

- **<u>Mean</u>:** The $\frac{\Delta \mathrm{R}T_{NDT(meas)i} - \Delta \mathrm{R}T_{NDT(pred)i}}{\sigma_i}$ term in Eq. (3-1) measures the difference between a predicted value and a measured value, normalized by the published standard deviation of the trend curve equation. Predictions that are inaccurate (i.e., far from the measured value) produce larger values of the highlighted term which, since this term is subtracted, decreases the value of Ln(L).

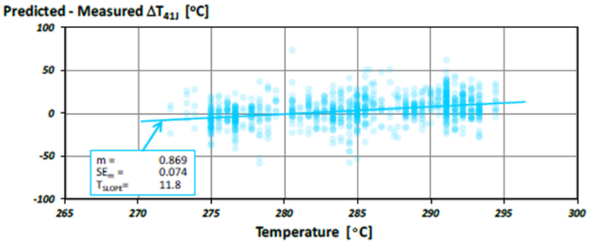
- **<u>Scatter</u>:** The $ln(\sigma_i)$ term in Eq. (3-1) is the published standard deviation for an ETC equation corresponding to the ith measured ΔRT_{NDT} value. Predictions that are uncertain (i.e., have large σ values) decrease the value of Ln(L), since this term is subtracted.

Thus, predictions that are either inaccurate or highly scattered penalize (decrease) the Ln(L) metric. The units of Ln(L) may not seem as "intuitive" as the other statistical metrics. For example, both R_{MEAN} and the RMSD have the same units as the quantity that is measured or predicted. However, as explained by Reference 11, "least-squares fitting is a maximum likelihood estimation of the fitted parameters if the measurement errors are independent and normally distributed with constant standard deviation." Least-squares fitting is a tool familiar to many engineers.

Student's T-Test (T-test on Slope)

Table 3-3 presents the methodology used to perform the t-test.

Table 3-3 Equations Used for the T-Test

Metric Definition	Slope (m)	$m = \dfrac{nS_{xy} - S_x S_y}{nS_{xx} - S_x^2}$ For example, on the plot below, m = 0.869 
	T-test on slope (T_{SLOPE})	$T_{SLOPE} = \dfrac{\lvert m \rvert}{SE_m}$ where $SE_m = \sqrt{\dfrac{ns^2}{nS_{xx} - S_x^2}}$ $s^2 = \dfrac{1}{n(n-2)}\left[nS_{yy} - S_y^2 - m^2(nS_{xx} - S_x^2)\right]$ Example: on the plot above, T_{SLOPE} = 11.8
Metric Interpretation	M	Any slope on a plot of prediction error vs. a composition or exposure variable indicates that the TTS equation assessed does not fully describe the embrittlement trends associated with that variable in a particular data subset. Ideally, the value of slope should be zero.
	T_{SLOPE}	T_{SLOPE} is a value of a Student's t statistic that can be used to assess the statistical significance of the slope value (i.e., is the slope statistically different from zero?).

<u>Definitions</u>

x = variable being assessed for trends (e.g., Cu, Ni, fluence, temperature)

y = $\Delta RT_{NDT(PREDICTED)} - \Delta RT_{NDT(MEASURED)}$ or $USE_{(I)MEASURED}$ - $USE_{(I)PREDICTED}$, as appropriate

n = number of data records

$$S_x = \sum_{i=1}^{n} x_i \qquad S_y = \sum_{i=1}^{n} y_i \qquad S_{xy} = \sum_{i=1}^{n} x_i y_i$$

$$S_{xx} = \sum_{i=1}^{n} x_i^2 \qquad S_{yy} = \sum_{i=1}^{n} y_i^2$$

3.1.5 Statistical Test Results

Bias, RMSD, and Ln(L) Results

Table 3-4, Table 3-5, and Table 3-6 present the results for bias, RMSD, and Ln(L) for all data, U.S. data only, and international data only, for the ASTM E900-15 and 10 CFR 50.61a ETCs. Table 3-7, Table 3-8, and Table 3-9 show the RMSD, bias, and Ln(L) for the same data subsets and also add the values for the RG 1.99 ETC and the RG 1.99 ETC with the degree-for-degree modification. Values are color coded as follows:

- Bias—Results that indicate mean underprediction are shown in red, with intensity increasing with the magnitude of mean underprediction. Results that indicate mean overprediction are shown in yellow, with intensity increasing with the magnitude of mean overprediction. The shading intensity is greatest at the maximum underprediction and overprediction values.

- RMSD—Results greater than or equal to 30 are shaded red, with increasing intensity up to the maximum reported value.

- Ln(L) [Log(Likelihood)]—Results were first normalized by prediction of ASTM E900-15. Therefore, the E900 results are 1, by definition, for all data subsets. Shading indicates greater deviation from the ASTM E900-15 result, with increasing intensity up to a maximum intensity at a ratio of 1.5. Normalized Ln(L) values > 1 for 50.61a indicate that the 10 CFR 50.61a ETC predicts the data less accurately than the E900-15 ETC, with accuracy decreasing as the values increase. Conversely, normalized Ln(L) values < 1 for 10 CFR 50.61a indicate that the 10 CFR 50.61a ETC predicts the data more accurately than the E900-15 ETC, with accuracy increasing as the values decrease.

The results in Table 3-7, Table 3-8, and Table 3-9 point out that both the E900-15 and 10 CFR 50.61a ETCs perform significantly better than RG 1.99, with or without the degree-for-degree modification. In particular, it can be seen that RG 1.99 significantly underpredicts the data for the high fluence data subset, based on the bias results, and RG 1.99 also has a large RMSD for the high fluence bin, indicating increased scatter.

When comparing U.S. results, the E900-15 and 10 CFR 50.61a ETCs perform similarly; when comparing international results, the E900-15 ETC predicts the surveillance data results more accurately than 10 CFR 50.61a. Overall, the E900-15 ETC performs the best with the lowest bias, better “high fluence” bias, and superior performance with international data (which include, among other things, a higher percentage of low Cu materials similar to more recently constructed nuclear power plants).

Table 3-4 RMSD, Bias, and Ln(L) Results for Residuals—All Baseline Data [b]

		[°F] Bias		[°F] RMSD		Ln(L) normalized	
		E900-15	10 CFR 50.61a	E900-15	10 CFR 50.61a	E900	10 CFR 50.61a
All	1878	-0.143	-1.566	23.981	30.918	1	1.113
Base	1212	-0.037	-1.505	22.445	24.883	1	1.050
Welds	666	-0.337	-1.678	26.548	39.608	1	1.224
BWR	342	-2.682	-0.107	22.076	22.792	1	1.017
PWR	1536	0.422	-1.891	24.384	32.452	1	1.134
Low Cu (≤0.08)	852	1.044	-6.254	20.749	33.117	1	1.198
High Cu (>0.08)	1026	-1.130	2.327	26.365	28.966	1	1.046
Low F (≤3E19)	1512	-0.253	-0.924	22.843	23.518	1	0.994
High F (>3E19)	366	-1.251	-10.925	28.195	49.707	1	1.019

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[b] Low/High Cu is cut at 0.08 weight %; Low/High Fluence is cut at 3×10^{19} n/cm^2 (E > 1 MeV).

Table 3-5 RMSD, Bias and Ln(L) Results for Residuals—U.S. Data Only[c]

		[°F] Bias			[°F] RMSD		Ln(L) normalized	
		E900-15	10 CFR 50.61a		E900-15	10 CFR 50.61a	E900	10 CFR 50.61a
All	1040	1.169	0.944		23.645	22.822	1	0.993
Base	692	0.960	0.448		21.197	20.207	1	0.992
Welds	348	1.584	1.932		27.882	27.287	1	0.994
BWR	170	-2.015	-0.483		20.954	22.761	1	1.012
PWR	870	1.791	1.223		24.136	22.834	1	0.989
Low Cu (≤0.08)	331	5.155	0.575		20.220	19.609	1	0.995
High Cu (>0.08)	709	-0.692	1.117		25.085	24.176	1	0.992
Low F (≤3E19)	921	0.763	0.103		23.126	22.111	1	0.992
High F (>3E19)	119	0.592	-5.510		27.441	27.670	1	0.983

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[c] Low/High Cu is cut at 0.08 weight %; Low/High Fluence is cut at $3x10^{19}$ n/cm^2 (E > 1 MeV).

Table 3-6 RMSD, Bias and Ln(L) Results for Residuals—International Data Only [d]

		[°F]	Bias	[°F]	RMSD	Ln(L) normalized	
		E900-15	10 CFR 50.61a	E900-15	10 CFR 50.61a	E900	10 CFR 50.61a
All	838	-1.772	-4.682	24.390	38.677	1	1.262
Base	520	-1.365	-4.104	24.005	29.997	1	1.125
Welds	318	-2.439	-5.627	25.007	49.707	1	1.487
BWR	172	-3.343	0.264	23.133	22.823	1	1.022
PWR	666	-1.367	-5.959	24.705	41.806	1	1.323
Low Cu (≤0.08)	521	-1.567	-10.593	21.079	39.361	1	1.327
High Cu (>0.08)	317	-2.110	5.033	29.023	37.528	1	1.165
Low F (≤3E19)	591	-1.836	-2.526	22.395	25.556	1	0.998
High F (>3E19)	247	-2.138	-13.534	28.550	57.378	1	1.036

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[d] Low/High Cu is cut at 0.08 weight %; Low/High Fluence is cut at 3x10^{19} n/cm^2 (E > 1 MeV).

Table 3-7 Bias, RMSD, and Ln(L) Results for Residuals for BASELINE (U.S. plus International Data)

		Bias, °F				RMSD, °F				Ln(L) normalized to E900 (higher => worse)			
Subset	No.	RG 1.99R2	E900-15	10 CFR 50.61a	RG 1.99R2 (D/D)	RG 1.99R2	E900-15	10 CFR 50.61a	RG 1.99R2 (D/D)	RG 1.99R2	E900	10 CFR 50.61a	RG 1.99R2 (D/D)
All	1878	0.012	-0.143	-1.566	6.095	39.328	23.981	30.918	37.404	1.614	1	1.113	11.174
Base	1212	-4.476	-0.037	-1.505	1.906	35.622	22.445	24.883	32.147	1.654	1	1.050	16.758
Welds	666	8.180	-0.337	-1.678	13.717	45.300	26.548	39.608	45.436	1.543	1	1.224	1.403
BWR	342	-3.250	-2.682	-0.107	15.392	25.873	22.076	22.792	29.699	2.608	1	1.017	1.259
PWR	1536	0.738	0.422	-1.891	4.024	41.737	24.384	32.452	38.913	1.398	1	1.134	13.327
Low Cu (≤0.08)	852	-1.545	1.044	-6.254	0.848	34.117	20.749	33.117	34.516	1.539	1	1.198	23.722
High Cu (>0.08)	1026	1.305	-1.130	2.327	10.452	43.179	26.365	28.966	39.643	1.672	1	1.046	1.349
Low F (≤3E19)	1512	6.812	-0.253	-0.924		28.727	22.843	23.518		0.967	1	0.994	
High F (>3E19)	366	-27.715	-1.251	-10.925		67.357	28.195	49.707		1.956	1	1.019	

Table 3-8 Bias, RMSD, and Ln(L) Results for Residuals for U.S. Data Only

		Bias, °F				RMSD, °F				Ln(L) normalized to E900 (higher => worse)			
Subset	No.	RG 1.99R2	E900-15	10 CFR 50.61a	RG 1.99R2 (D/D)	RG 1.99R2	E900-15	10 CFR 50.61a	RG 1.99R2 (D/D)	RG 1.99R2	E900	10 CFR 50.61a	RG 1.99R2 (D/D)
All	1040	5.546	1.169	0.944	10.483	28.391	23.645	22.822	28.378	1.406	1	0.993	1.753
Base	692	3.906	0.960	0.448	8.991	25.702	21.197	20.207	26.138	1.344	1	0.992	2.082
Welds	348	8.808	1.584	1.932	13.449	33.096	27.882	27.287	32.376	1.520	1	0.994	1.142
BWR	170	-5.112	-2.015	-0.483	10.895	26.685	20.954	22.761	27.473	2.889	1	1.012	1.312
PWR	870	7.629	1.791	1.223	10.403	28.713	24.136	22.834	28.552	1.123	1	0.989	1.837
Low Cu (≤0.08)	331	6.135	5.155	0.575	6.144	23.974	20.220	19.609	23.975	1.358	1	0.995	3.092
High Cu (>0.08)	709	5.271	-0.692	1.117	12.509	30.234	25.085	24.176	30.215	1.427	1	0.992	1.158
Low F (≤3E19)	921	7.388	0.763	0.103		27.538	23.126	22.111	0.000	0.955	1	0.992	
High F (>3E19)	119	-9.221	0.592	-5.510		34.646	27.441	27.670	0.000	1.111	1	0.983	

Table 3-9 Bias, RMSD, and Ln(L) Results for Residuals for International Data Only

		Bias, °F				RMSD, °F				Ln(L) normalized to E900 (higher => worse)			
Subset	No.	RG 1.99R2	E900-15	10 CFR 50.61a	RG 1.99R2 (D/D)	RG 1.99R2	E900-15	10 CFR 50.61a	RG 1.99R2 (D/D)	RG 1.99R2	E900	10 CFR 50.61a	RG 1.99R2 (D/D)
All	838	-6.856	-1.772	-4.682	0.648	49.656	24.390	38.677	46.216	1.872	1	1.262	22.840
Base	520	-15.631	-1.365	-4.104	-7.522	45.591	24.005	29.997	38.725	2.056	1	1.125	35.788
Welds	318	7.493	-2.439	-5.627	14.009	55.669	25.007	49.707	56.361	1.570	1	1.487	1.701
BWR	172	-1.409	-3.343	0.264	19.837	25.044	23.133	22.823	31.747	2.330	1	1.022	1.207
PWR	666	-8.263	-1.367	-5.959	-4.307	54.227	24.705	41.806	49.268	1.757	1	1.323	28.275
Low Cu (≤0.08)	521	-6.424	-1.567	-10.593	-2.517	39.221	21.079	39.361	39.787	1.654	1	1.327	36.752
High Cu (>0.08)	317	-7.566	-2.110	5.033	5.850	63.167	29.023	37.528	55.179	2.201	1	1.165	1.760
Low F (≤3E19)	591	5.915	-1.836	-2.526		30.489	22.395	25.556		0.986	1	0.998	
High F (>3E19)	247	-36.625	-2.138	-13.534		78.387	28.550	57.378		2.361	1	1.036	

T-Test on Slope Results

Table 3-10, Table 3-11, and Table 3-12 present the t-test results for the E900-15 ETC and the 10 CFR 50.61a ETC for the BASELINE data set, U.S. data only, and international data only. Table 3-13 provides a key defining the data subsets and variables in the t-test results tables. The t-test on slope results are presented here organized by data subset (listed in the second-to-left column) and variables (listed in the top row). The values reported in the tables are the T_{slope} values for each data subset and variable. The variables evaluated are the chemistry values (weight %) of Cu, Ni, P, Mn, temperature, neutron fluence, and neutron flux. Results for RG 1.99 are not presented because they are poor in most data subsets and provide little additional insight. The results have been overlaid with conditional formatting as follows:

- Results < 2, representing statistically “acceptable” residuals in slope, have been marked in blue with increasing intensity for lower values.
- Results > 2, representing statistically significant (95 percent) residuals in slope, have been marked in red with increasing intensity for higher values.

The following examples illustrate how to interpret results in these tables. For example, in Table 3-11, for 10 CFR 50.61a, in the High F (fluence) data subset, the value of 3.610 in the Temp (temperature) column indicates that the 10 CFR 50.61a ETC does not model temperature very accurately for materials in the high fluence (> $3x10^{19}$ n/cm^2) category. Also, in Table 3-11, for E900 in the low Cu data subset, the value of 3.675 in the Log(f) (log flux) column indicates that the E900-15 ETC does not model the effect of flux very accurately for materials in the low Cu (< 0.08 weight %) data subset. All results in red indicate likely inaccuracies in modeling. These results do not indicate whether the necessary data to improve these inaccuracies exist. It should be noted that extremely low t-test results do not, by themselves indicate model sufficiency, as such results may also indicate overfitting.

When comparing U.S. results, 10 CFR 50.61a performs better than E900-15; when comparing international results, 10 CFR 50.61a fares poorly in comparison to E900-15. Overall, E900-15 performs the best when compared to all data and subsets. It is particularly significant that 10 CFR 50.61a has a t-test slope > 2 for U.S.-only base materials and high fluence subsets, as this was of particular concern as a motivation for this work.

Although both E900-15 and 10 CFR 50.61a appear to contain statistically significant modeling residuals, 10 CFR 50.61a has considerably more and in a broader range of data subsets. This indicates that E900-15 performs better over a broader range of data subsets than 10 CFR 50.61a.

Table 3-10 T-Test on Residuals Results for E900-15 and 10 CFR 50.61a—BASELINE

E900

Major Set	Subset	n	Cu	Log(F)	Ni	Temp	P	Mn	Log(f)
BASELINE	All	1878	0.287	0.653	0.783	1.100	0.605	1.347	2.535
BASELINE	Base	1212	1.290	0.482	1.284	0.679	1.521	0.657	2.521
BASELINE	Welds	666	1.164	1.443	1.539	0.958	0.781	3.487	0.977
BASELINE	BWR	342	0.566	0.405	0.828	1.445	1.223	0.097	1.346
BASELINE	PWR	1536	0.187	1.164	0.450	0.296	0.045	1.133	0.682
BASELINE	Low Cu	852	1.808	4.148	1.813	0.796	0.867	1.648	3.699
BASELINE	High Cu	1026	2.192	2.074	0.034	0.209	0.147	0.421	0.558
BASELINE	Low F	1512	1.400	1.950	0.290	1.290	0.930	2.310	3.220
BASELINE	High F	366	2.620	3.400	1.380	0.010	0.290	1.430	0.120

10 CFR 50.61a

Major Set	Subset	n	Cu	Log(F)	Ni	Temp	P	Mn	Log(f)
BASELINE	All	1878	2.864	2.959	4.003	7.249	6.085	0.496	0.248
BASELINE	Base	1212	2.461	2.468	5.064	8.937	4.761	1.618	1.328
BASELINE	Welds	666	1.665	1.781	5.815	1.867	4.093	2.590	1.380
BASELINE	BWR	342	2.200	2.410	0.603	1.986	1.773	0.109	1.589
BASELINE	PWR	1536	3.796	2.511	4.327	7.241	7.131	0.607	2.322
BASELINE	Low Cu	852	4.601	4.377	10.704	3.067	1.045	1.209	2.406
BASELINE	High Cu	1026	1.560	0.566	6.532	5.219	4.115	0.475	2.220
BASELINE	Low F	1512	1.610	0.080	1.700	4.910	1.780	1.730	0.240
BASELINE	High F	366	2.010	1.300	6.550	5.200	6.420	0.960	3.520

Table 3-11 T-Test on Residuals Results for E900-15 and 10 CFR 50.61a—U.S. Data

E900

Major Set	Subset	n	Cu	Log(F)	Ni	Temp	P	Mn	Log(f)
US	All	1040	0.592	1.046	2.306	2.700	2.338	0.744	2.808
US	Base	692	0.755	0.273	0.689	1.936	2.920	1.345	2.523
US	Welds	348	0.355	1.761	1.961	1.865	0.870	0.726	1.457
US	BWR	170	0.376	0.130	0.907	1.023	1.544	0.544	1.385
US	PWR	870	0.597	0.319	2.735	1.817	1.796	1.041	1.911
US	Low Cu	331	1.394	4.336	0.644	1.931	0.320	0.087	3.675
US	High Cu	709	2.687	1.164	2.845	0.848	1.063	1.765	1.204
US	Low F	921	0.120	1.370	2.460	2.980	1.560	0.930	2.800
US	High F	119	2.060	1.100	0.180	0.110	2.400	0.400	0.620

10 CFR 50.61a

Major Set	Subset	n	Cu	Log(F)	Ni	Temp	P	Mn	Log(f)
US	All	1040	0.068	0.797	0.414	2.349	0.403	0.895	0.249
US	Base	692	1.908	2.868	1.233	2.954	1.668	2.243	0.626
US	Welds	348	1.336	1.731	0.033	0.352	0.380	1.961	1.001
US	BWR	170	1.333	1.621	2.173	1.867	1.046	0.210	0.802
US	PWR	870	0.558	0.868	0.447	2.517	0.059	1.200	0.408
US	Low Cu	331	0.929	0.237	0.639	1.730	1.476	0.068	0.237
US	High Cu	709	0.319	0.714	0.944	1.725	0.113	1.018	0.202
US	Low F	921	0.310	0.510	0.350	1.070	0.060	0.920	0.760
US	High F	119	0.040	0.850	0.140	3.610	1.360	0.250	0.620

Table 3-12 T-Test on Residuals Results for E900-15 and 10 CFR 50.61a—International Data

E900

Major Set	Subset	n	Cu	Log(F)	Ni	Temp	P	Mn	Log(f)
INTERNATIONAL	All	838	0.343	0.189	2.098	1.166	0.773	2.685	1.119
INTERNATIONAL	Base	520	2.009	0.155	3.349	0.814	0.025	0.562	1.388
INTERNATIONAL	Welds	318	1.574	0.375	0.504	0.847	1.626	4.350	0.032
INTERNATIONAL	BWR	172	0.164	1.003	2.026	1.188	0.589	0.458	0.354
INTERNATIONAL	PWR	666	0.447	0.460	2.894	1.994	1.208	2.614	0.498
INTERNATIONAL	Low Cu	521	1.227	2.330	0.590	1.313	0.278	0.975	2.271
INTERNATIONAL	High Cu	317	0.603	1.653	3.313	0.656	1.206	2.635	0.333
INTERNATIONAL	Low F	591	1.070	1.100	3.910	1.560	0.490	4.940	1.570
INTERNATIONAL	High F	247	2.190	3.110	1.220	0.070	1.600	2.090	0.170

10 CFR 50.61a

Major Set	Subset	n	Cu	Log(F)	Ni	Temp	P	Mn	Log(f)
INTERNATIONAL	All	838	2.607	2.519	3.757	7.052	6.630	1.017	0.164
INTERNATIONAL	Base	520	0.531	0.614	7.175	8.732	5.854	0.156	2.190
INTERNATIONAL	Welds	318	2.657	2.737	6.083	2.146	4.324	1.485	1.963
INTERNATIONAL	BWR	172	1.881	1.869	1.674	0.725	1.398	0.118	1.576
INTERNATIONAL	PWR	666	3.624	1.172	3.375	6.491	7.653	1.125	3.540
INTERNATIONAL	Low Cu	521	4.590	4.374	10.856	3.579	0.786	0.175	2.447
INTERNATIONAL	High Cu	317	1.517	1.032	7.309	4.222	5.607	0.078	2.304
INTERNATIONAL	Low F	591	1.600	0.970	3.180	6.040	1.670	3.390	0.580
INTERNATIONAL	High F	247	2.310	0.880	6.770	4.330	7.000	1.210	3.930

Table 3-13 Key for T-Test Tables

Low Cu	≤ 0.08 weight % Cu
High Cu	> 0.08 weight % Cu
Low F	Fluence ≤ $3x10^{19}$ n/cm^2 (E > 1 MeV)
High F	Fluence > $3x10^{19}$ n/cm^2 (E > 1 MeV)
n	number of data in bin
Cu	copper content, weight %
Ni	nickel content, weight %
F	neutron fluence
f	neutron flux
P	phosphorus content, weight %
Mn	manganese content, weight %
Temp	Temperature, °C

3.1.6 Statistical Comparison Conclusions

Several ETCs were compared using standard statistical methods consistent with the 2019 RG 1.99 assessment. The E900-15 and 10 CFR 50.61a ETCs perform roughly equivalently when compared using the U.S. data major set. The E900-15 ETC has significantly better performance when compared to the international data major set. Overall, E900-15 performs the best with the lowest bias, better “high fluence” bias, and better performance with international data (which include, among other things, a higher percentage of low Cu materials). In the t-test, E900-15 performs the best overall when compared to all data and subsets. Both ETCs retain some modeling residuals, but 10 CFR 50.61a has considerably more, and in a broad array of data subsets, indicating that E900-15 performs better over a broader range of inputs than 10 CFR 50.61a. Both E900-15 and 10 CFR 50.61a perform significantly better than RG 1.99 and RG 1.99 D/D over all tests and all data major sets (i.e., BASELINE, U.S., and international), particularly with regard to the bias and RMSD in the high fluence data subset.

3.1.7 Subjective Factors Considered in Embrittlement Trend Correlation Selection

Several important aspects of the E900-15 and 10 CFR 50.61a ETCs are not fully apparent through a direct statistical comparison. This section elucidates several subjective factors considered in arriving at E900-15 as the preferred ETC.

First, while both ETCs represent findings from considerably larger datasets than available for the development of RG 1.99, the E900-15 dataset included a larger quantity of data in the high fluence range. While the predominant source of this high fluence data is international, it represents the preponderance of available data in this regime. Consequently, while there may be some variation in process and measurement for the international data, the staff determined that this would be of less significance than the relative improvement in the ETC due to its inclusion (i.e., that the uncertainty of prediction would increase more by lack of data than by a potential difference in data acquisition between countries).

Second, researchers considered the utility of weighing performance of the 10 CFR 50.61a ETC against that of the E900-15 ETC for the international data. The international data comes from a somewhat more diverse group of designs, which are predominantly U.S. or U.S.-derived technologies. In addition, the international fleet is somewhat newer than the U.S. fleet and consequently contains material characteristics that would be more representative of any potential domestic new reactors (especially low Cu materials). Finally, as mentioned above, the international data constitute the bulk of high fluence data, providing the best estimate basis for curve-fitting in that regime.

Third, both ETCs required additional inputs relative to RG 1.99. This constituted an implementation concern. For the E900-15 ETC, the additional inputs are temperature, Mn, and P, of which only temperature was a strong term. For the 10 CFR 50.61a ETC, the additional inputs include temperature, flux, vessel manufacturer, and weld flux type, of which several have measurable impacts. The larger number of input variables for 10 CFR 50.61a (especially flux, for which no satisfying broad-range expression has yet been demonstrated) was found to increase the likelihood of overfitting while providing minimal improvements in overall ETC performance but would be worse when considering additional international data. Therefore, it would be more difficult for a licensee to implement the 10 CFR 50.61a ETC, as the additional required data may be difficult to ascertain for multiple reactor locations.

3.1.8 Rationale for Selection of the E900-15 Embrittlement Trend Correlation

The NRC staff found that E900-15 was a better alternative ETC for the following primary reasons:

- for high fluence materials (i.e., > 3 x10^{19} n/cm^2), E900-15:
  - produces more accurate predictions of U.S. surveillance data; E900-15 has a small, conservative bias for the U.S. High Fluence subset, while 10 CFR 50.61a underpredicts the same subset
  - produces more accurate predictions of the international data
- for new reactor applications, E900-15:
  - performs better relative to the international data for the Low Cu category for the statistical measures (RMSD, bias, and Ln(L))
  - performs better relative to t-test results for the Low Cu subset, as well as the input variables Ni, P, and temperature; this is particularly pertinent to new reactors, which will have low Cu, and consequently will be (relatively) more sensitive to other input variables (e.g., Ni, P, and temperature)

Additionally, the E900-15 ETC is based on a larger database, including additional U.S. surveillance data for 2004–2012 not included in the 10 CFR 50.61a database. Also, the 10 CFR 50.61a ETC may overfit due to the large number of input variables. Finally, the E900-15 ETC is expected to provide more accurate predictions of embrittlement in a broader band of temperatures than the 10 CFR 50.61a ETC, as indicated by the lower average t-test results for temperature for the E900-15 ETC.

3.2 Use of Surveillance Data

3.2.1 Background

It has long been standard practice that plant-specific surveillance data be used in conjunction with the ETC. The procedure by which this has been historically completed in RG 1.99 was assessed as limited and, in certain cases, counterproductive in the RG assessment (Ref. 2). Specifically, the likelihood that plant-specific surveillance data will be deemed noncredible when the RG 1.99 credibility criteria are applied increases as the number of surveillance data increases. Also, the default assumption of the RG 1.99 credibility criteria is that the RG 1.99 trend curve shape is correct, so the criteria do not effectively identify materials that have trend curve shapes not conforming the RG 1.99 trend curve shape. As a result, the staff investigated the potential for a more flexible and defensible methodology for the use of surveillance data.

3.2.2 Methodology and Results

The staff used the statistical tests from 10 CFR 50.61a to investigate the quality of E900-15 ETC predictions and the plant-specific surveillance data, and then, depending on the outcome of these tests, to construct a “refit” procedure to provide a statistically justifiable adjustment to the E900-15 criteria that attains superior accuracy through use of the plant-specific data while not jeopardizing or overwhelming the statistical confidence gained by using a trend curve.

The statistical tests in 10 CFR 50.61a consist of four generic tests on the residuals between the E900-15 prediction and a series of plant-specific measured values for each material. NUREG-2163, “Technical Basis for Regulatory Guidance on the Alternate Pressurized Thermal Shock Rule, issued September 2018 (Ref. 12), describes the basis and significance of these tests. Figure 3-1 illustrates the function of these tests. The Type A test represents a bias test; Type B, a slope test; Type C, a scatter test; and Type D an outlier test. Note that 10 CFR 50.61a requires only the Type A, B, and D tests.

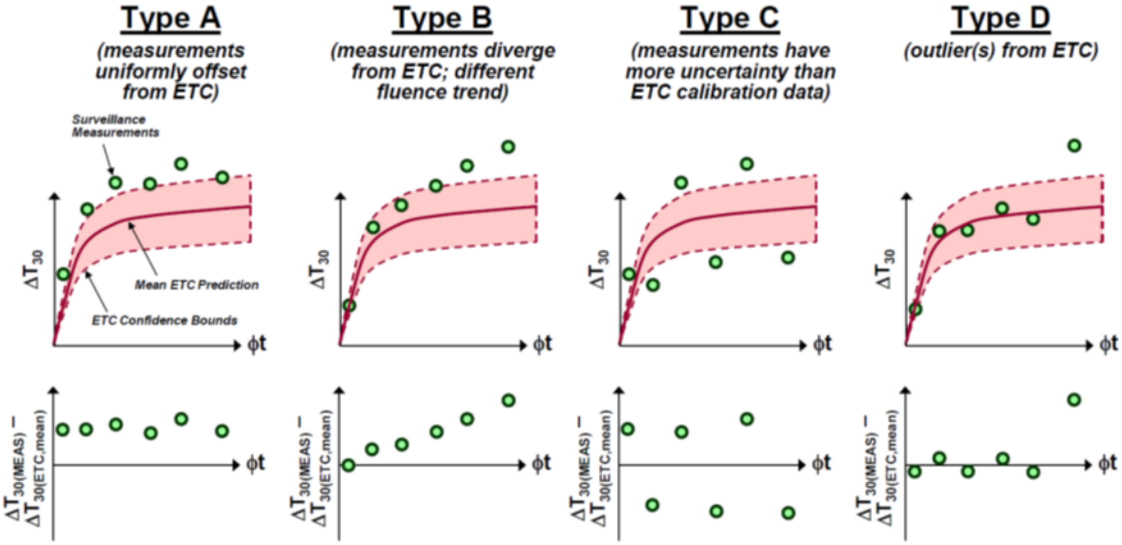

Figure 3-1 Explanatory diagram of Type A through D errors

Section 5.4 of NUREG-2163 (Ref. 12) defines the procedures for the Type A, B, and D tests, except for the Type C test procedure, which is performed as follows:

> Determine the residual r for each datum using the following formula:
>
> $$r = \Delta T_{30(measured)} - \Delta T_{30(predicted)}$$
>
> For each heat of material if:
>
> $$\sqrt{\frac{\sum r^2}{n}} \leq \sigma$$
>
> then there is no Type C error.
>
> Where n is the number of data and σ is the standard deviation for the highest fluence datum as defined in Section 3.3 of this report.

The staff investigated the utility of these tests for the purpose described above. To do so, the staff applied the tests, using the E900-15 standard deviation formula (as U.S. specific standard deviations described in Section 3.3 were not yet available), to all domestic materials in the BASELINE dataset with sufficient data per material to apply the tests (any material with measurements at 3 or more fluence values). Use of the E900-15 SD should have resulted in needing to refit slightly more often compared to basing the SD on the U.S. data only (described in Section 3.3.), because the SD based on U.S. data tends to be larger than the E900-15 SD developed for the entire BASELINE dataset. Therefore, the number of materials requiring refit determined by this evaluation should be conservative. A 1-percent criterion (i.e., 2.33 SDs) was applied on the basis that a high degree of assurance would be desired that a genuine trend existed, contrary to the E900-15 results. A 1-percent criterion was also used for the surveillance checks required by 10 CFR 50.61a described in NUREG-2163. Use of a higher criterion (e.g., 5 percent) would give more weight to the plant-specific surveillance data. This was deemed appropriate, as E900-15 was generated using a large dataset to minimize the effects of errors in measurements of the individual materials. Consequently, the ETC is considered generically to have the greatest likelihood of approximating a “true” property without a strong material-specific contraindication (i.e., a 2.33 SD occurrence). Table 3-14 shows the results.

Table 3-14 Preliminary Type Testing Results with Unmodified BASELINE Data

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

Of the materials investigated, fully two-thirds exhibit acceptable behaviors according to the tests. Of the 47 that failed the Type tests, 41 exhibited multiple failures, suggesting a correlation. Two methods were proposed to “refit” data failing the tests. The first was to adjust the ETC by a bias adjustment (i.e., the Type A test result for that material, a scalar modifier), while the second was to refit a modifying term to the ETC (equivalent to the "CF" (chemistry factor) refit in RG 1.99, a linear multiplying term). The objective was to manipulate the E900-15 ETC to the smallest degree (and thus retain the error-cancelling advantages of a broadly based ETC).

The results of the two refit procedures were virtually identical, and consequently the bias-based refit was selected as the most appropriate. Multiple reasonable scenarios exist for bias errors (e.g., variation in unirradiated property estimation, temperature effects). This provides a satisfying basis to both use a bias adjustment and potentially identify further sources of error with a numerically satisfying basis should such an exercise prove warranted. The slope adjustment lacked a high-confidence basis for overriding the curve-shape of E900-15 without a generic statistically justifiable numerical basis, while at the same time producing virtually identical results. Table 3-15 shows the results of bias-adjusted data.

Table 3-15 Preliminary Type Testing Results with Bias-Refit BASELINE Data

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

The results showed a large improvement in statistical performance with a minimal adjustment; specifically, the pass rate improves from 2/3 to 9/10. Several aspects of the conversion stand out. First, while 41 of the 47 failures in the unmodified sample exhibited multiple failures in testing, only 6 of 14 refit failures are correlated to multiple failure modes. This gives some confidence that the mean adjustment was the likeliest single cause of test failures in the overall population.

The Type B failures were identical for the unmodified and refit ETC. Each material data set for which a Type B failure occurred was manually examined. No common trend was evident among the three Type B failure materials. Consequently, the rarity of Type B failures and the lack of consistency among the Type B material data suggested that using Type B testing would be unproductive for the proposed refit framework.

As for the remaining postrefit Type C and D failures, a manual examination revealed no consistent trend in failure cause. Generally, these data sets exhibited odd scatter, large outliers, or other effects that would require a more indepth analysis to refit and consequently were not good candidates for constructing a generic methodology.

Figure 3-2 (top plot) shows an example of the E900-15 ETC for a plate material from a BWR plant, with the actual surveillance data also plotted. This material initially failed the Type A, C, and D tests. The bottom plot shows the residuals versus the ETC. Figure 3-3 shows the data for the same plant after the refit procedure. After refit, the material passed all four tests. Figure 3-4 shows an example of the E900-15 ETC and actual surveillance data for a PWR plant forging material. This material passed all four type tests. Figure 3-5 shows the ETC for the same material after the refit procedure. While the refit curve does fit the data better, refit would not be allowed for this material in accordance with the procedure described below and shown in Figure 3-6.

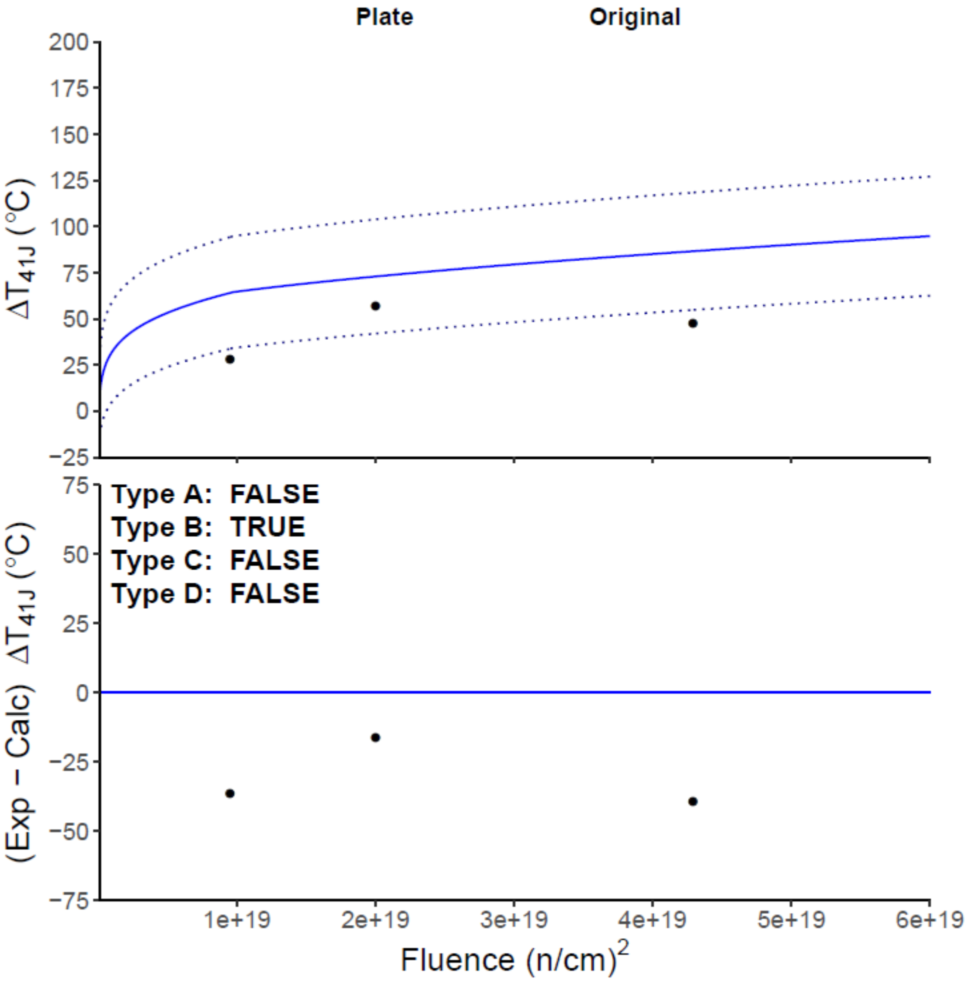

Figure 3-2 Data for BWR Plant A before refit

Top Plot—E900-15 ETC for BWR Plant A with actual surveillance data superimposed
Bottom Plot—Residuals for the data versus the ETC

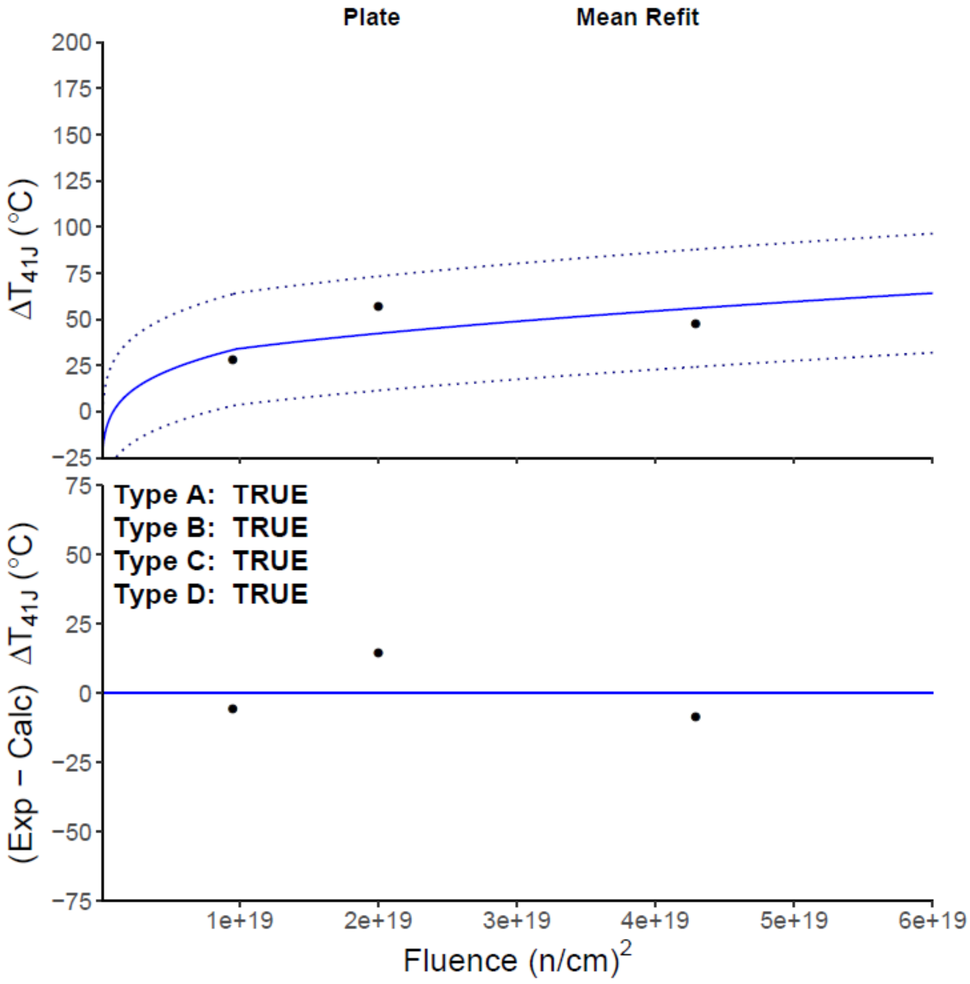

Figure 3-3 Data for BWR Plant A after refit

Top plot—E900-15 ETC with surveillance data superimposed
Bottom Plot—Residuals for the data versus the ETC

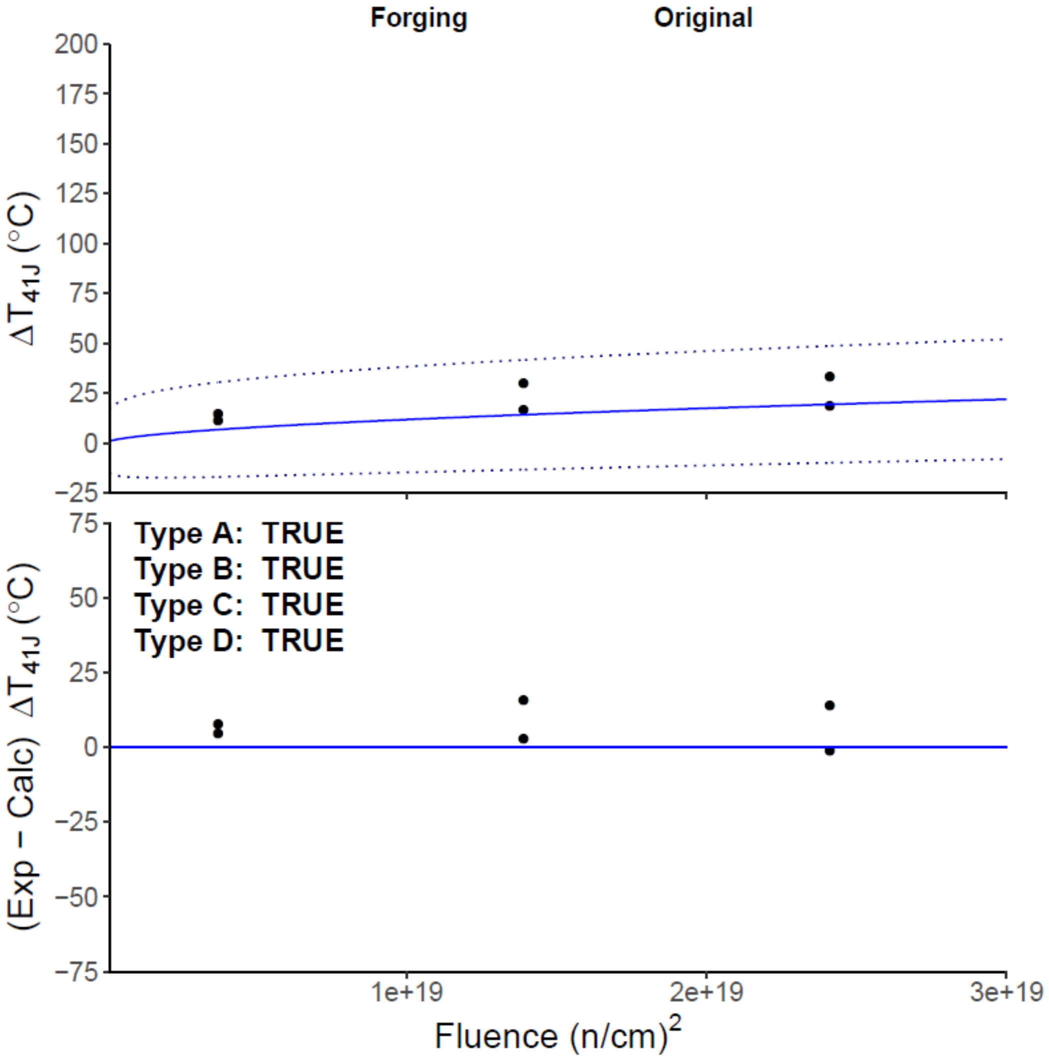

Figure 3-4 Data for PWR Plant B before refit

Top Plot—E900-15 ETC for PWR Plant B forging with actual surveillance data superimposed
Bottom Plot—Residuals for the data versus the ETC

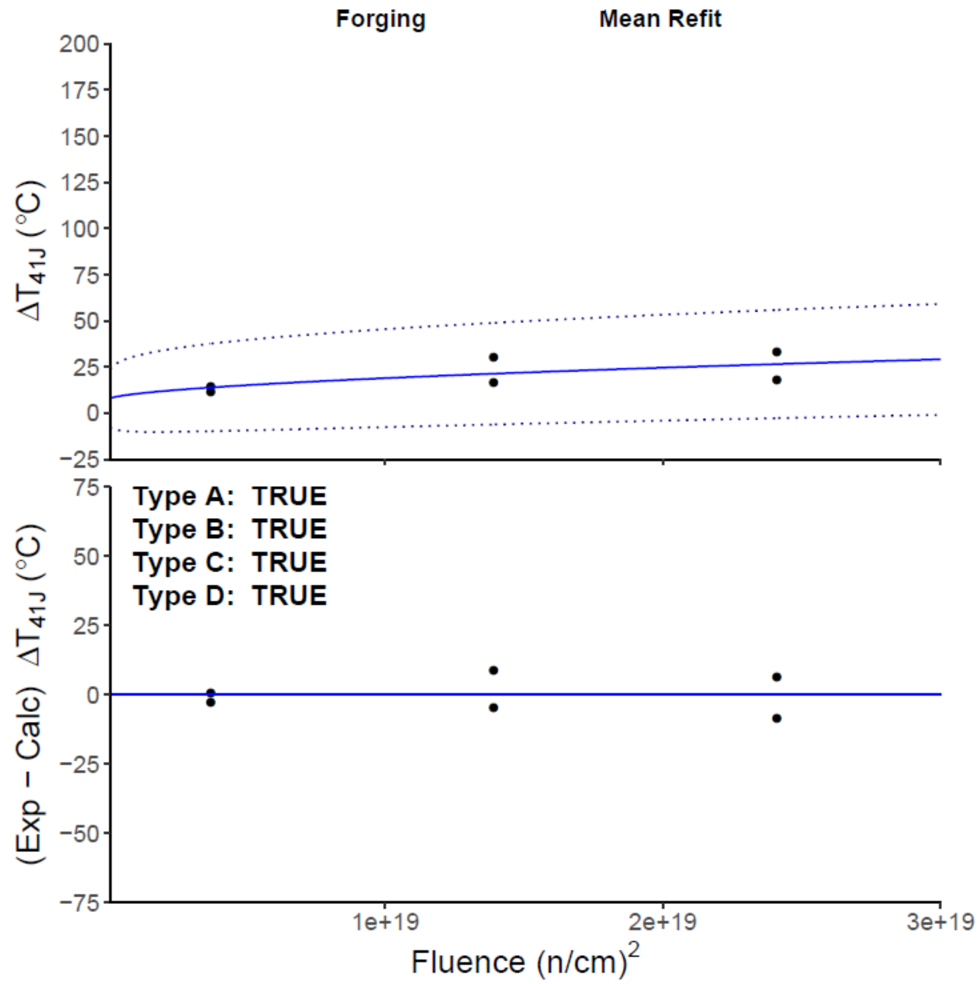

Figure 3-5 Data for PWR Plant B forging after refit

Top plot—E900-15 ETC with surveillance data superimposed
Bottom Plot—Residuals for the data versus the ETC

3.2.3 Recommended Procedure

Based on the above, the staff proposed a methodology to incorporate surveillance data as follows:

A. The material of interest must meet the limitations of this alternative as described in Section 3.5.

B. If three or more surveillance data points are available for the material of interest then the users should apply the Types A, C, and D tests to their data using a 2.33σ criterion (do not add margin for comparison). Use σ as defined in Section 3.3 of this report.

    a. If the data pass, use the ETC with a 2σ margin term.

    b. If the data do not pass one or more of the Type A, C, or D tests, the user may attempt to refit the data by adding the bias adjustment from the Type A result to the ETC and then performing the Type A, C, and D tests again.

        i. If the data now pass, use the refit ETC with a 2σ margin term.

        ii. If the refit data do not pass, use the more conservative of the refit ETC or the initial E900-15 ETC (or present an acceptable alternative ETC) and add a 2.33σ margin.

C. If two or fewer surveillance data points are available for the material of interest, use the E900-15 ETC with a 2σ margin term.

Figure 3-6 depicts the process above in flowchart form.

The staff notes that the philosophy of use of surveillance data in the procedure outlined above differs from RG 1.99 in that RG 1.99 defaults to the use of the plant-specific surveillance data rather than the generic RG 1.99 ETC, provided the surveillance data meet certain criteria, while the proposed alternative defaults to the use of the generic E900-15 ETC, as long as the surveillance data pass certain tests. The refit procedure proposed above for materials that do not pass the tests also maintains the shape function of the E900-15 by a simple bias adjustment that simply moves the curve up or down.

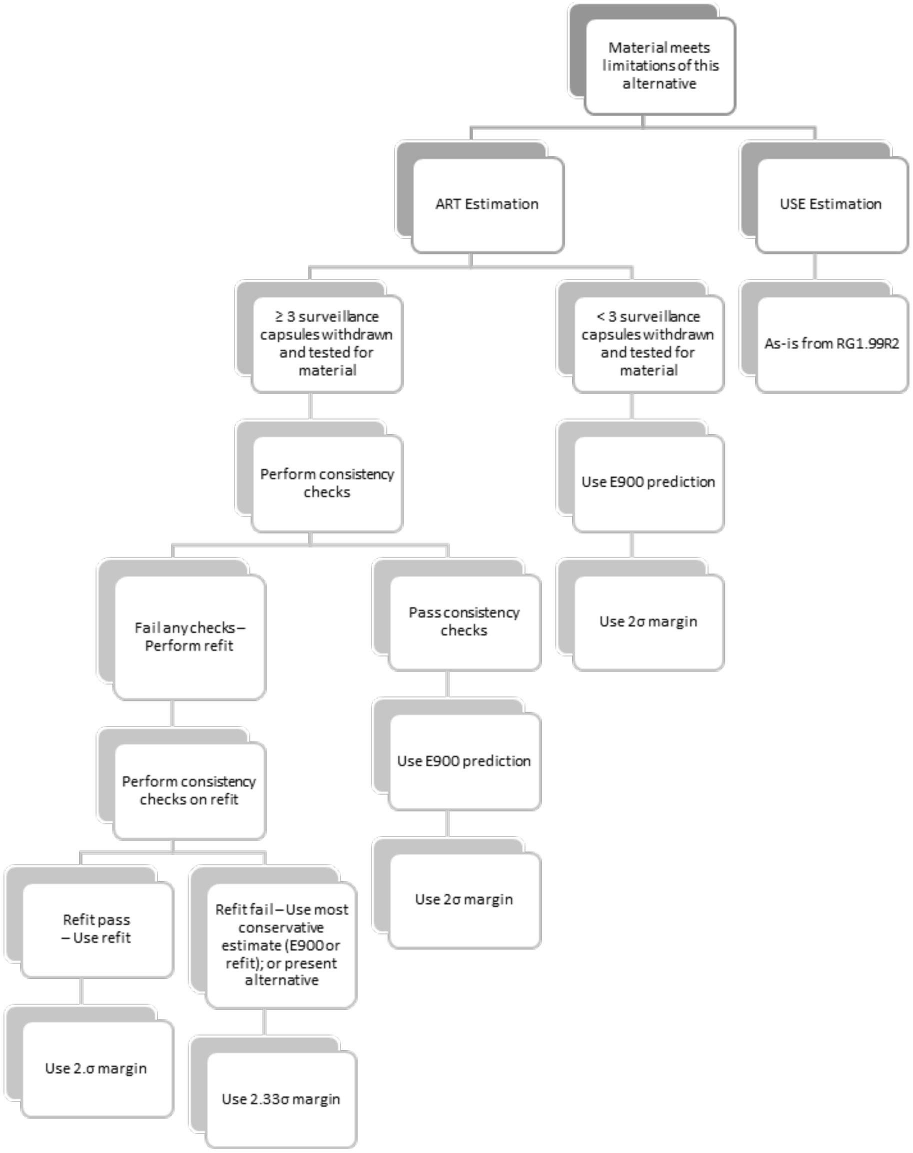

Figure 3-6 Flowchart of surveillance data refit process

3.3 Margins

3.3.1 Structure of Margin Term

The margin term is structured identically to that of RG 1.99.

M is the margin term.

$$M = A\sqrt{\sigma_{\Delta}^2 + \sigma_i^2} \qquad (3\text{-}2)$$

σ_i is the SD for the initial RT_{NDT}. In accordance with RG 1.99, if a measured value of initial RT_{NDT} for the material in question is available, σ_i is to be estimated from the precision of the test method. The NRC staff has typically allowed the value of σ_i to be zero when a heat-specific measured value is available, although this is not explicitly stated in RG 1.99. Under this alternative, σ_i may be set to zero when a heat-specific measured value is available, consistent with the precedent established by the staff in applying RG 1.99.

A is the number of SDs, normally A = 2. However, if the material has surveillance data, which failed one or more of the surveillance data consistency checks, even after refit, A = 2.33.

If generic mean values for that class of material are used, σ_i is the SD obtained from the set of data used to establish the mean.

For plates and welds,

$$\sigma_{\Delta} = C \times (\Delta RT_{NDT})^{D} \qquad (3\text{-}3)$$

where

$$\Delta RT_{NDT} = TTS\ (°\ F)\ as\ determined\ by\ Equation\ 1\ of\ E900 - 15$$

and C and D are constants from Table 3-16.

3.3.2 Basis

In RG 1.99, σ_{Δ} is defined as the standard deviation of ΔRT_{NDT}. The SD term determined using ASTM E900-15 Equation (9) is functionally identical to the σ_{Δ} term of RG 1.99. ASTM E900-15 does not address the uncertainty in initial RT_{NDT} represented by the σ_i term in RG 1.99. Therefore, it is reasonable to use a margin term with the same structure as the RG 1.99 margin term, allowing for the inclusion of a nonzero σ_i value, if appropriate.

RG 1.99 specifies a product form dependent form of the σ_{Δ} value, which is 17 degrees Fahrenheit (F) (9.44 degrees Celsius (C)) for plates and forgings, and 28 degrees F (15.56 degrees C) for welds. The RG 1.99 assessment (Ref. 2) noted that these values were too small when compared to the SD suggested by the BASELINE data set.

The C and D values were determined by the same procedure described in the E900 adjunct, Appendix D, except using the U.S. data only rather than all the baseline data for a given product form. Using the RMSD for the U.S. surveillance data for the SD of the TTS shift (σ_{Δ}) is more appropriate than using the E900-15 SD equation because it is representative of the scatter to be expected in the U.S. fleet materials. In addition, the SDs based on the U.S. data are somewhat higher that the E900-15 SDs, which is conservative. Also, the E900-15 SD for plate material is based in part on the data for standard reference materials (SRMs), which generally had less scatter than the plate, resulting in a lower SD. The staff considered use of an SD equation based partly on data from SRMs to be inappropriate because SRMs are not required to be tested and have no regulatory use in the United States. Further discussion of the effect of SRMs appears below under the heading "Plate vs. Plate + SRM."

The data were sorted with respect to the predicted TTS[e] from E900-15, in ascending order. The data were then grouped in bins of 40 materials. The mean TTS for each bin, and the RMSD for each bin, were calculated. Table 3-16 provides the recommended C and D values.

$$RMSD = \sqrt{\Sigma(TTS_{predicted} \ + TTS_{measured})^2 \Big/ n} \tag{3-4}$$

Where n is the number of data in the bin.

The RMSD values were then plotted against TTS and a fit equation was determined using Excel. Since the fit equation for forgings had an essentially flat trend, it was determined to use a constant value for forgings. This was determined based on the RMSD of all 143 U.S. forging data, which was 21.49 degrees F (11.9 degrees C).

Table 3-16 Recommended C and D Values for σ_Δ Calculation

Product Form	C, ° F(°C)	D
Plate	5.11 (3.48)	0.35
Weld	14.94 (9.02)	0.14
Forging	21.49	0

Plate vs. Plate + SRM

E900-15 uses a common SD term for plate and SRMs, which was determined based on the plate and SRM data combined (i.e., the BASELINE dataset). The staff found that when an SD equation was determined based on plate data only, the SD values as a function of TTS increased. This was true for both the U.S. data only and all the plate data in BASELINE. The effect of the SRM materials was to reduce the mean RMSD. SRMs are included in some but not all U.S. surveillance capsules, and there is no requirement to test SRMs (i.e., there is no regulatory use for them). Therefore, it seems appropriate to determine an SD based on plate data only. Figure 3-7 shows the fit of the equation to the U.S. plate data. Figure 3-8 shows a comparison of the SD values that would be determined from the U.S. plate data only, a fit for U.S. plate data plus SRM materials, a fit equation determined from both U.S. and international plate data only (labeled BASELINE plate), the E900-15 Plate + SRM equation, and finally the RG 1.99 base metal SD of 17 degrees F (9.44 degrees C), which applies to both plate and forgings. Figure 3-9 includes the same curves as Figure 3-8, plus showing the curves for SRMs

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[e] The TTS from E900-15 is equivalent to the ΔT_{41J}. TTS values were converted to degrees F for the purpose of determining the fit equation for degrees F.

only (BASELINE and U.S. only) that demonstrate why the inclusion of SRMs with plate reduces the SDs.

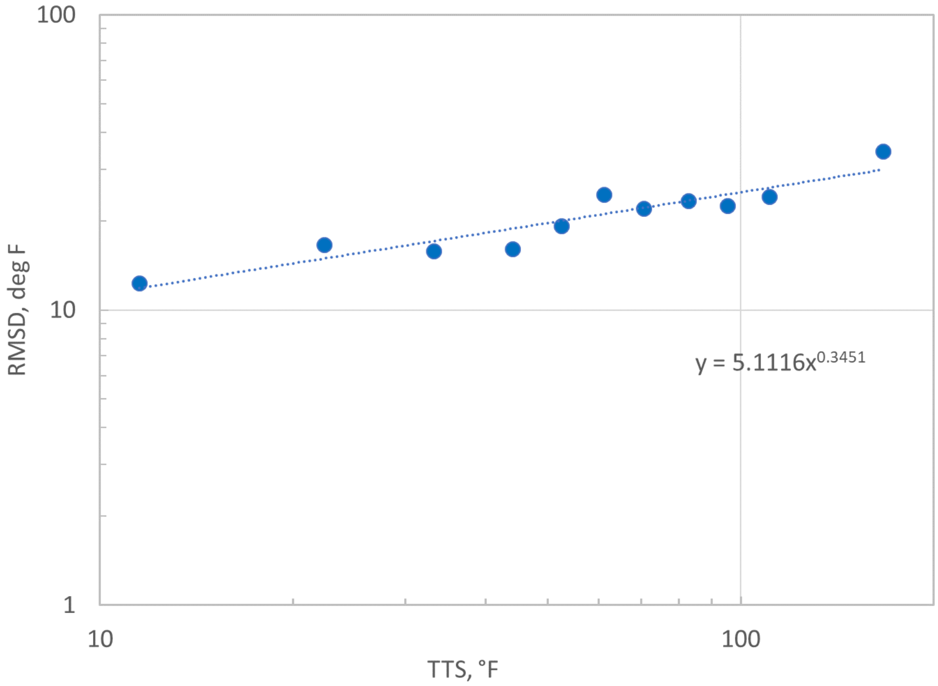

Figure 3-7 RMSD vs. TTS fit for U.S. Plate only

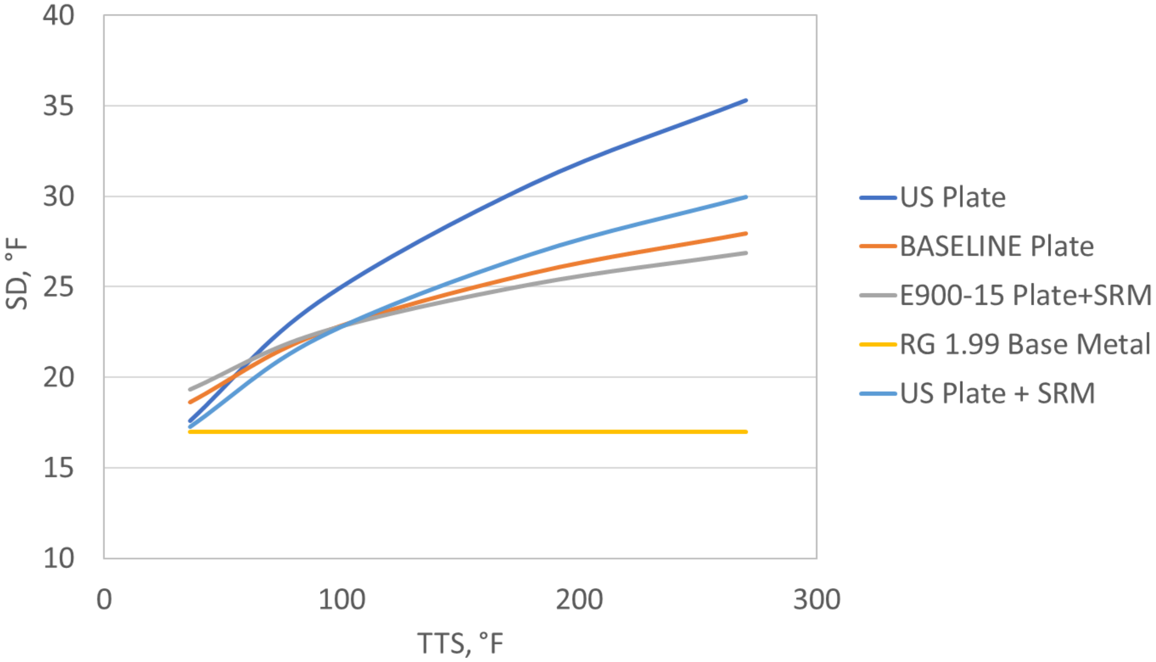

Figure 3-8 Comparison of SD for Plate and Plate + SRM

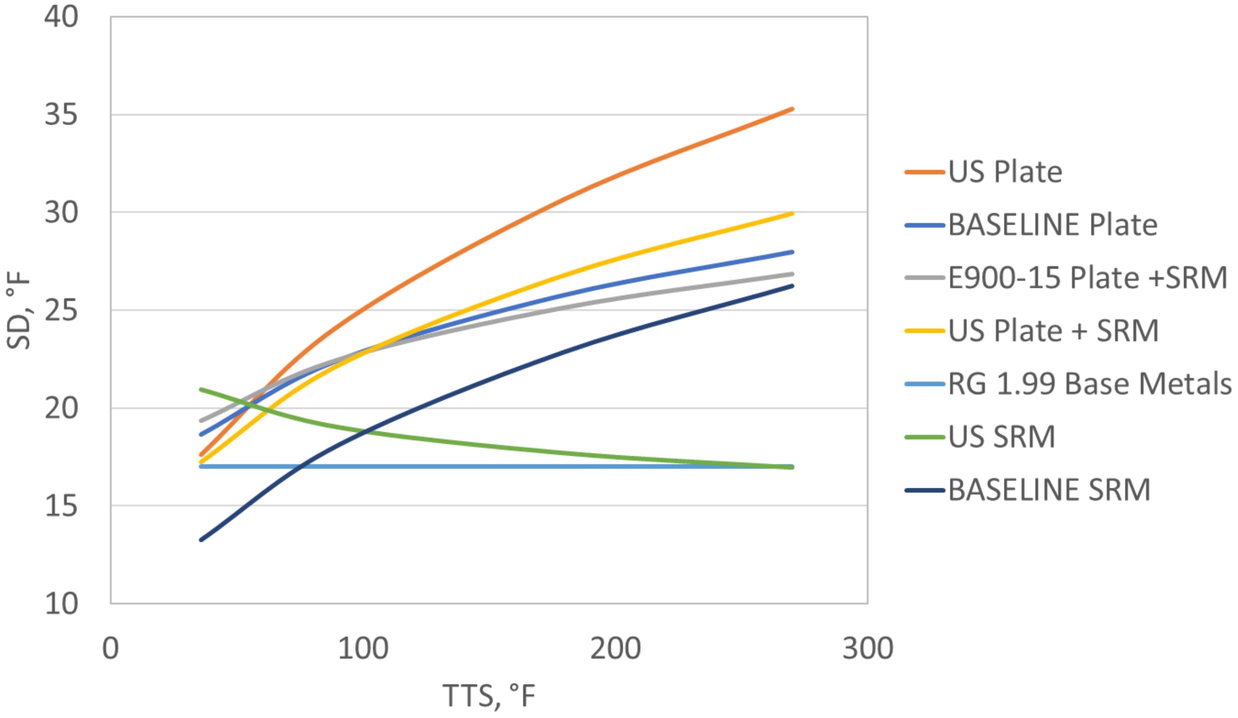

Figure 3-9 Comparison of SD based on various data sets for Plate and Plate + SRM, and SRMs only

Welds

Figure 3-10 shows the fit to the U.S. weld data. Figure 3-11 shows a comparison of the TTS that would be calculated using both the E900-15 SD equation for welds, the U.S. weld-only equation from Figure 3-10, and the RG 1.99 constant SD value of 28 degrees F (15.56 degrees C). The SD values are similar for both, with the U.S. data predicting a slightly lower SD at higher TTS values, and the opposite at lower TTS values.

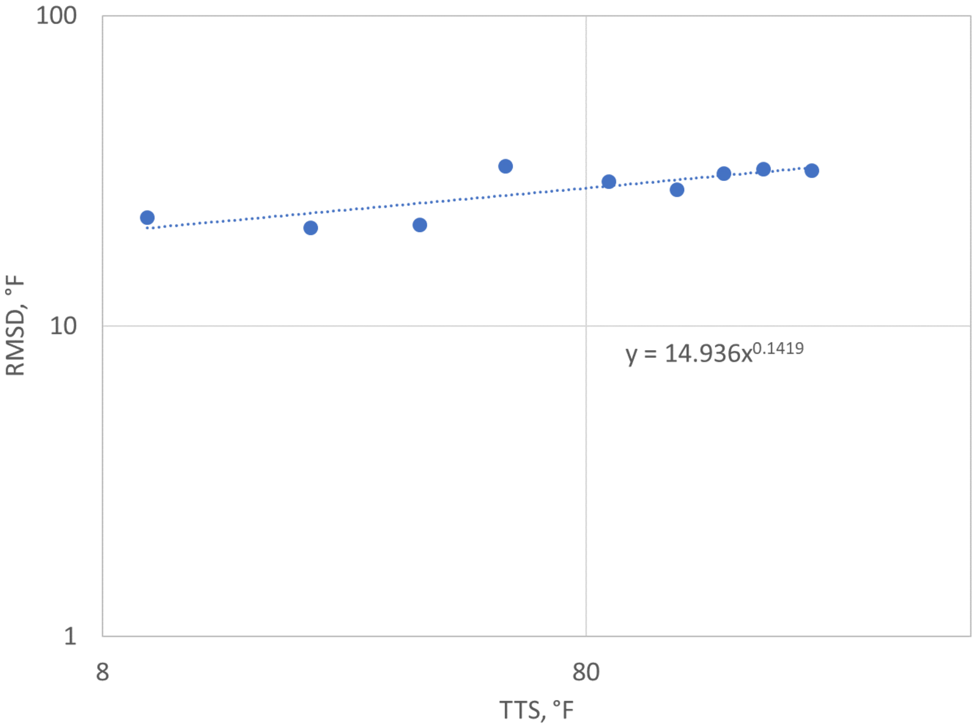

Figure 3-10 RMSD versus TTS fit to U.S. weld data

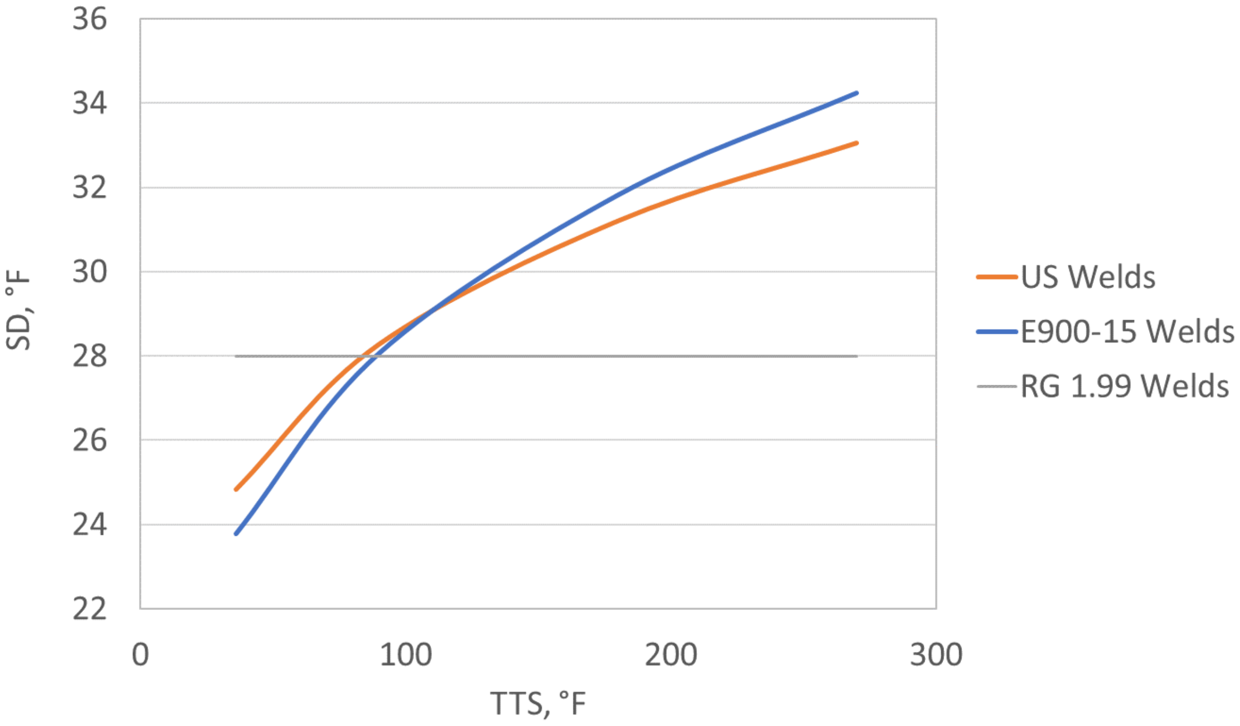

Figure 3-11 Comparison of TTS determined using E900-15 and fit to U.S. welds only

Forgings

Figure 3-12 shows the determination of the fit equation for U.S. forgings. Figure 3-13 shows a comparison of the SDs predicted as a function of TTS for the E900-15 equation (blue), the fit to the U.S. data (red), and a constant value determined from the RMSD of all the U.S. forging data (orange). The constant value of 21.49 degrees F was determined by combining all the U.S. forging data (144 pieces of data) into a single bin and calculating the average RMSD for the single bin. In Figure 3-13, the line for the constant value for all U.S. forgings and the values from the fit equation in Figure 3-12 lie almost on top of one another.

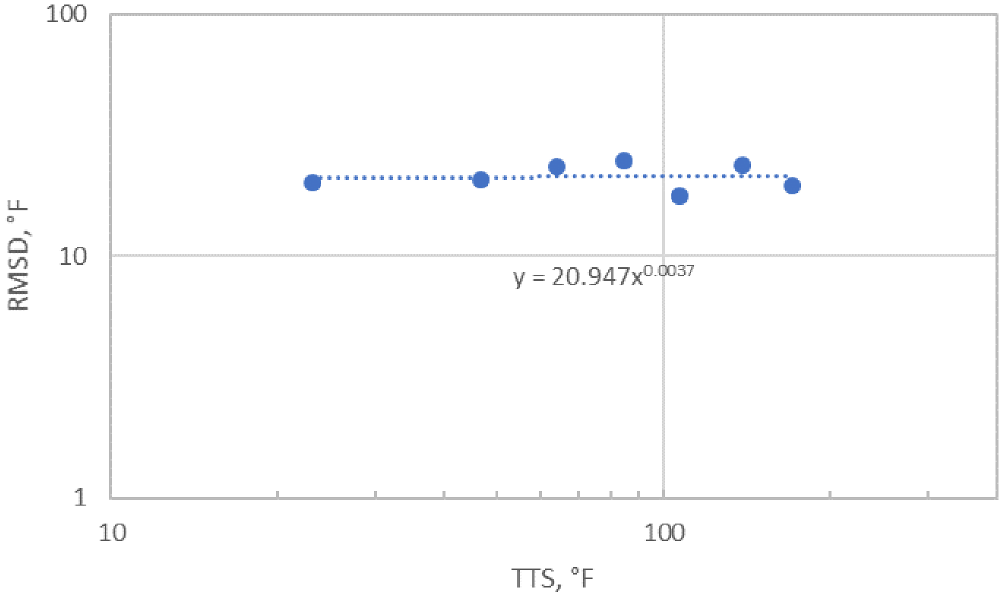

Figure 3-12 RMSD versus TTS fit for U.S. forging data

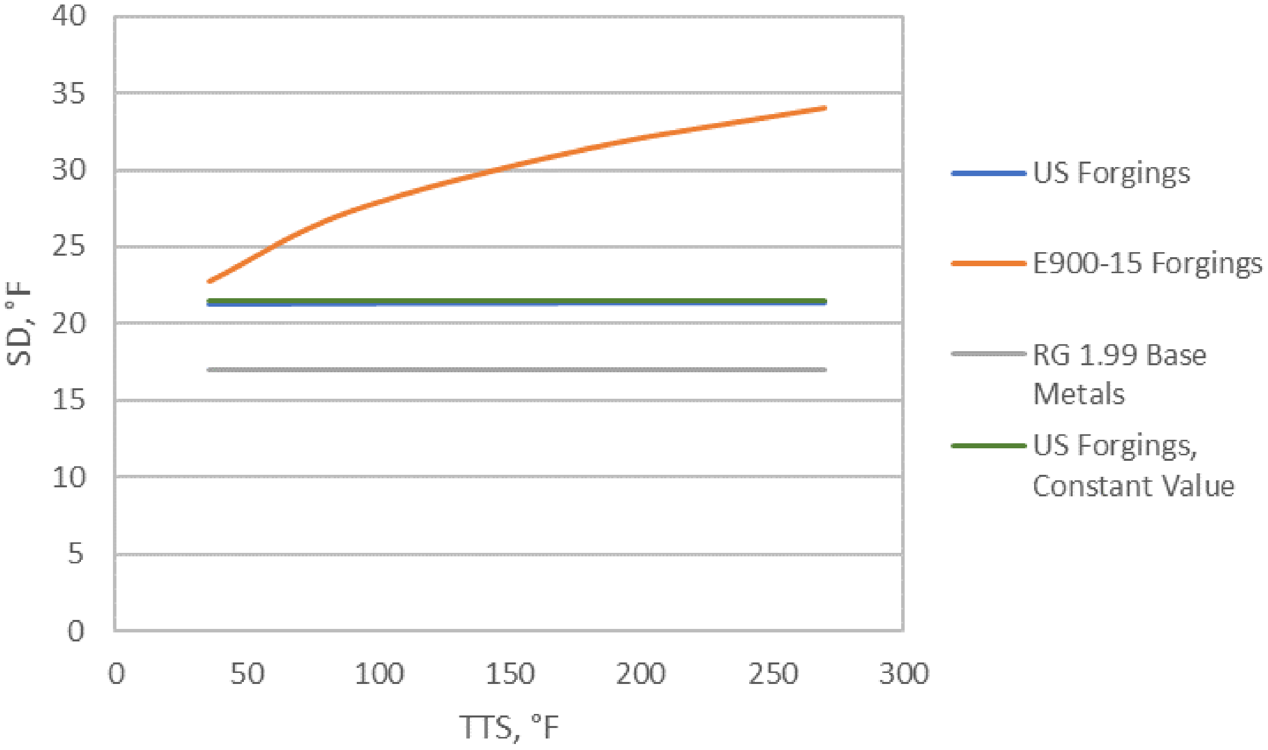

Figure 3-13 Comparison of forging fits for U.S. only, E900-15, and RG 1.99 base metals

3.4 Default Values

Default values are needed for the ΔRT_{NDT} calculation when certain data are missing. This includes chemistry composition values in weight % of Cu, Ni, Mn, P, and irradiation temperature. Default values should be conservative such that their use is biased toward calculating a higher ΔRT_{NDT}. Therefore, default chemistry values should be on the high side of the possible range and irradiation temperature values should be on the low side of the possible range.

3.4.1 Need for Default Values

It is expected that missing chemistry values will be rare for beltline materials in U.S. commercial nuclear power plants, particularly Cu and Ni. For most plants, the irradiation temperature should also be known, since it is considered equivalent to the reactor inlet or cold-leg temperature for PWRs and equivalent to the reactor recirculation loop temperature in BWRs.

3.4.2 Approach

To determine the default values, the staff examined the distribution of values for each variable in BASELINE. Histograms were created for each chemistry variable, and the quartiles of the distribution were determined. Figure 3-14 shows an example of a histogram for Cu for BWR forgings from BASELINE. The objective was to determine whether the values for each variable conformed to a uniform, normal, or other identifiable distribution that could be used to define percentiles, such that the default values could be defined in terms of a certain percentile (e.g., 95th). A similar approach was used for SA-508, Class 2 nozzle forgings as described in BWRVIP-173NP-A, “BWR Vessel and Internals Project, Evaluation of Chemistry Data for BWR Vessel Nozzle Forging Materials,” dated July 31, 2011 (Ref. 13), in which a $+2\sigma$ value, corresponding to a 97.8 percent confidence interval, determined from available industry data, was used as the default value for Cu, Ni, Mn, and P when actual values were missing.

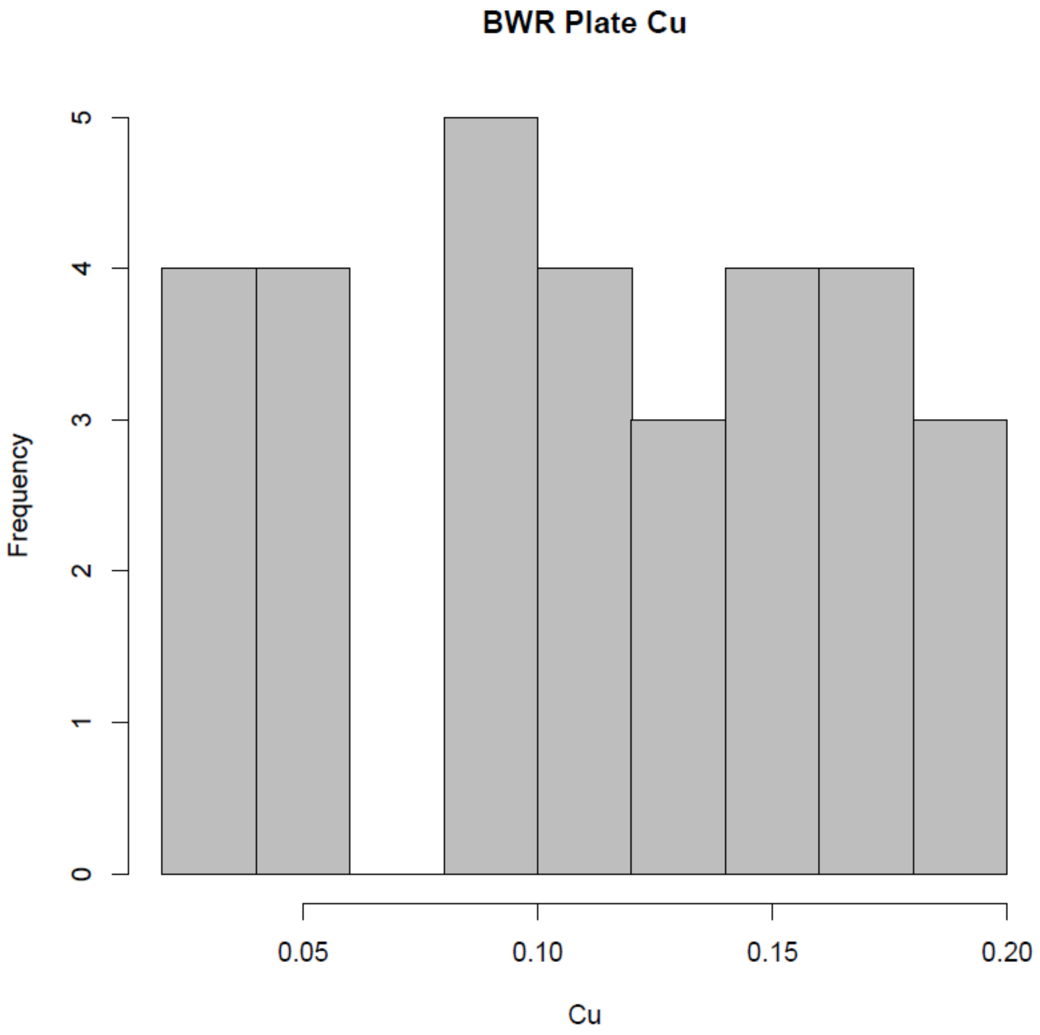

Figure 3-14 Distribution of Cu (weight %) values for BWR forgings from BASELINE

3.4.3 Results/Recommendations

The distributions did not consistently conform to any recognized distribution such as normal or uniform.

3.4.4 Recommendation—Chemistry

For the default chemistry values, it is recommended to use the maximum values from the database for Cu, Ni, Mn, and P. The staff considered using an upper 95 or 75 percentile value; however, since values do not appear to be normally distributed, the staff decided to use maximum values from distribution. These values are conservative, and missing chemistry values are expected to be a rare case. Table 3-17 gives the recommended default chemistry values.

Another option considered was the use of a specification maximum; however, specifications do not contain ranges for all elements. For example, SA-533, a commonly used specification for RPV plates, does not specify a range for Cu.

Table 3-17 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

3.4.5 Recommendation—Temperature

PWRs

The reactor inlet or cold-leg temperature should be used as the irradiation temperature for PWRs. A weighted average should be used if the temperature changed for different cycles, such as due to power uprates. The default value for PWRs is 523 degrees F (272.8 degrees C) based on the U.S. fleet minimum from BASELINE.

BWRs

The recirculation loop temperature should be used as the irradiation temperature of BWRs. A time-weighted average should be used if the temperature changed for different cycles, such as due to power uprates. The default value for BWRs is 530 degrees F (276.7 degrees C) based on the minimum value from BASELINE.

3.5 Limitations

3.5.1 Background

ASTM E900-15, Section 1.1.2.1, lists A533 Type B Class 1 and 2, A302 Grade B, A302 Grade B (modified), and A508 Class 2 and 3, and European and Japanese steel grades that are equivalent to these ASTM grades, as the applicable grades. These grades are essentially equivalent to those listed in RG 1.99 except that RG 1.99 also lists SA-336. Therefore, this alternative is considered to be applicable to the material grades listed in RG 1.99 and ASTM E900-15 and grades other than those listed should be justified.

ASTM E900-15, Section 1.1, provides the range of material and irradiation conditions in the database for variables used in the embrittlement correlation. These maxima and minima do not restrict the use of E900-15 within these bounds; however, ASTM E900-15, Section 1.2, recommends caution when using the E900-15 ETC near these maxima and minima, and requires the user to ensure that the ETC is appropriate for the conditions. Table 3-18 provides these maxima and minima.

Table 3-18 Chemistry, Temperature, and Fluence Limits of the E900-15 Database (BASELINE)

Parameter	Minimum	Maximum
Cu, weight %	None	0.4
Ni, weight %	None	1.7
Mn, weight %	0.55	2.0
P, weight %	None	0.03
Irradiation Temperature	491 °F (255 °C)	572 °F (300 °C)
Neutron Fluence (n/cm^2)	1×10^{17}	1×10^{20}

3.5.2 Methodology

Comments during the ASTM voting process for ASTM E900-15 expressed concerns about the range of applicability, with one commenter recommending more restrictive limitations based on +/- 3σ, and “warning levels” based on +/- 2σ (see comments related to Negative Vote by Tim Williams on E900-14 in Appendix E to the E900 adjunct, Ref. 8). The staff evaluated the need for similar limits. The approach for each individual variable was to divide the BASELINE database into two populations based on the percentile of all data (for example, upper 5th percentile versus the entire data set). Then the staff performed the surveillance data consistency checks (Type A, B, C, D) on both populations to determine whether there was a statistically significant difference in the proportion of the data passing and failing the consistency checks, for the different percentiles. Fisher’s exact test for count data and Pearson’s Chi-square test with a simulated p-value (based on 2,000 replicates) were performed on the upper 5th, 4th, 3rd, 2nd, and 1st percentiles of RPV chemistry and lower 5th, 4th, 3rd, 2nd, and 1st percentiles of irradiation temperature. A 95-percent confidence level was used, meaning a p-value < 0.05 would indicate a statistically significant difference. The resulting p-values for either test were never below 0.249, demonstrating that there was no statistically significant difference in performance for the ETC between the entire population and any of the other percentiles for any of the variables. Therefore, the staff concluded, based on the statistical tests, that it was not necessary to impose limitations more restrictive than the limitations described in ASTM E900-15.

However, a review of the irradiation temperature data in BASELINE for all U.S. plants (Figure 3-15) shows that data are very sparse below 523 degrees F (272.8 degrees C), which is relatively consistent with the lower limit of 525 degrees F (273.8 degrees C) in RG 1.99. Therefore, the minimum temperature limit for this alternative is 523 degrees F (272.8 degrees C). ASTM E900-15 has an upper temperature limit of 572 degrees F (300 degrees C), which is slightly lower than the upper limit in RG 1.99 of 590 degrees F (310 degrees C). Since embrittlement should be less as temperature increases, the staff finds it acceptable to use the alternative up to the RG 1.99 upper limit of 590 degrees F (310 degrees C). Correction factors for temperatures outside of these limitations should be justified.

The limitations on chemistry and neutron fluence specified by ASTM E900-15 are less restrictive than those of RG 1.99, at least with respect to Ni content. The procedures of RG 1.99 are described as being applicable to the neutron fluence levels, Cu content, and Ni content within the ranges given in Figure 1 and Tables 1 and 2 of RG 1.99, respectively. These limitations are a maximum Cu content of 0.4 percent, maximum Ni content of 1.20 percent, and a maximum fluence of $1x10^{20}$ n/cm^2. As these chemistry limits are well within the limitation of E900-15, all materials acceptable for use with RG 1.99 are acceptable for use with ASTM E900-15.

3.5.3 Conclusions and Recommendations

The staff’s evaluation of limitations concludes that it is acceptable to use the potential alternative described in this report within the following limitations:

- The alternative may be used with A533 Type B Class 1 and 2, A302 Grade B, A302 Grade B (modified), and A508 Class 2 and 3, European and Japanese steel grades that are equivalent to these ASTM grades, and SA-336.
- The range of Cu, Ni, Mn, and P, and neutron fluence values must be within the maxima and minima listed in Table 3-18.
- The maximum irradiation temperature of 590 degrees F (310 degrees C) is consistent with RG 1.99.
- The minimum irradiation temperature is 523 degrees F (272.8 degrees C), which is more restrictive than the maxima and minima of the E900-15 database.

Correction factors for temperatures outside of these limitations should be justified. This alternative may also be used with other material grades if justification is provided of equivalency to the listed grades.

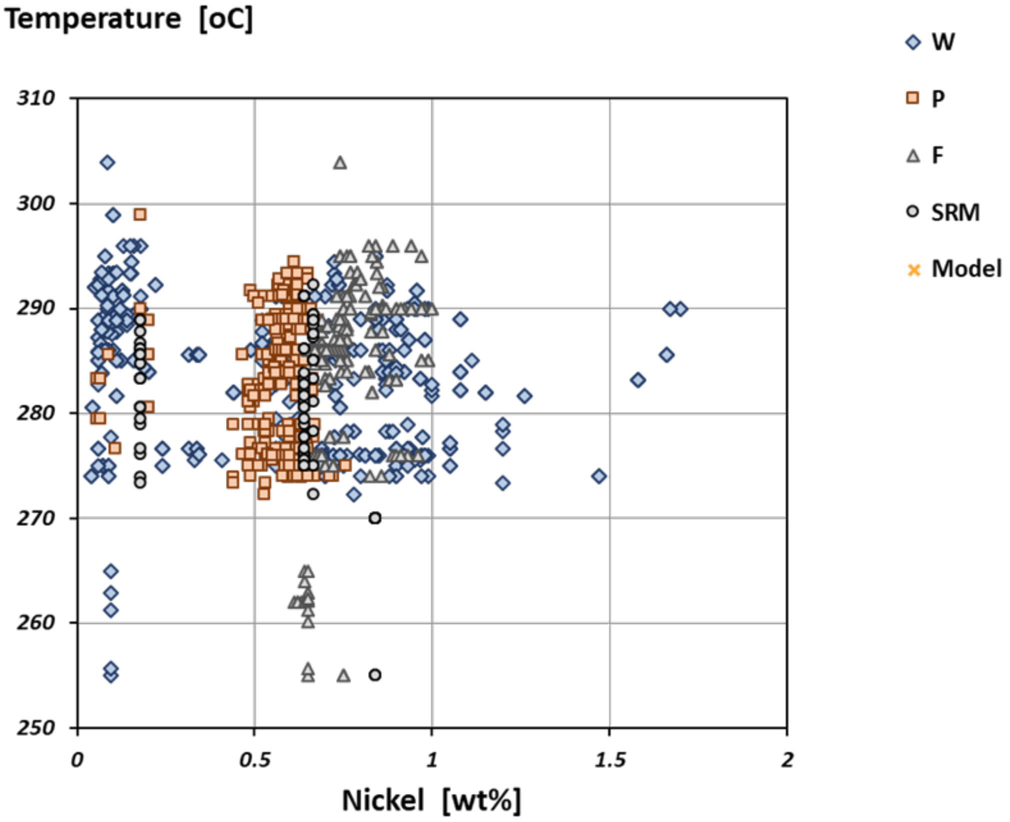

Figure 3-15 Distribution of U.S. reactor temperature data from the BASELINE database versus Ni content

4. Fleet Impact Evaluation

4.1 Methodology of Fleet Impact Evaluation

The NRC staff recognized that using an alternative RG based on the E900-15 ETC could impact the operating fleet by resulting in increased ARTs. To better understand the extent to which the ARTs would change, the staff performed a fleet impact study on a “smart sample” of 21 reactors to determine the change in ART and RT_{PTS} resulting from a change from RG 1.99 to an alternative ETC. This change in ART is designated the “embrittlement shift delta (ESD).” The equation for ESD is:

$$ESD = ART_{E900-15} - ART_{RG\ 1.99} \quad (4\text{-}1)$$

Where:

$$ART_{E900-15} = RT_{NDT(u)} + \Delta T_{41J} + M$$

$$\text{where } \Delta \mathrm{T}_{41\mathrm{J}} \text{ is determined using the E900} - \text{15 ETC,}$$

$$\mathrm{M} = \text{margin determined in accordance with Section 3.3}$$

$$RT_{NDT(u)}\ is\ the\ unirradiated\ licensing\ basis\ RT_{NDT}$$

$$ART_{RG\ 1.99} = adjusted\ reference\ temperature\ determined\ in\ accordance\ with\ RG\ 1.99$$

The fleet impact study was conducted for a hypothetical change from RG 1.99 to the E900-15 ETC. The number of materials experiencing increases or decreases in ART and the amount of these increases and decreases were not used to inform the decision on which ETC should be chosen. However, this information was used to qualitatively assess the impact that would be expected with adopting the E900-15 ETC.

Another important purpose of the fleet impact study was to determine the range of the changes in ART resulting from switching from the RG 1.99 ETC to the E900-15 ETC. This range of ESDs was used as an input to the PFM evaluation licensing basis ARTs from the plant data searches used to calculate the ESD. Licensing basis ARTs are generally based on RG 1.99, Position 2.1, for materials having credible surveillance data, and RG 1.99, Position 1.1, for materials without credible surveillance data.

E900-15

$$ART = RT_{NDT(u)} + TTS + M \quad (4\text{-}2)$$

The TTS is calculated using Equation 1 of E900-15, as modified using the refit procedure described in Section 3.2. The refit procedure used the available surveillance data in the Reactor Embrittlement Archive Project (REAP). The surveillance data consistency checks used a program written in the R computer language for those materials with available and sufficient surveillance data in REAP (three or more surveillance data points). The refit term thus determined was added to the TTS calculated as described above. Only three materials in the fleet impact smart sample actually required a refit.

For determining the ARTs, the 1/4T fluence was used; that is, the fluence estimated at ¼ of the thickness of the vessel from the inner surface. The 1/4T fluence was calculated using the attenuation formula of RG 1.99, based on the end-of-life RPV inner surface fluence for the material of interest. For calculating RT_{PTS}, the RPV inner surface fluence was used without attenuation. The 1/4T location was chosen since the ART at this location usually supports regulatory criteria related to the pressure-temperature limits for normal cooldowns.

The margin, M, was previously determined as described in Section 3.3.

Calculations of the ARTs were executed in an Excel spreadsheet.

4.2 Results

Figure 4-1 shows the distribution of ESDs for all materials in the smart sample. At the 1/4T location, the median ESD is in the bin for 10–25 degrees F, with few materials having ESDs greater than 70 degrees F. For the inner diameter (ID) location, the values are somewhat higher, as expected. For the ID location, the highest ESD for any material was 123 degrees F, while at the 1/4T location, the highest ESD was 102 degrees F. In Figure 4-1 through Figure 4-9, the numbers on the X-axis represent the highest value for the bin. For example, in Figure 4-1, the bars adjacent to the number 0 on the X-axis (on the left side) represent the numbers of ESDs having values > -25 and ≤ 0.

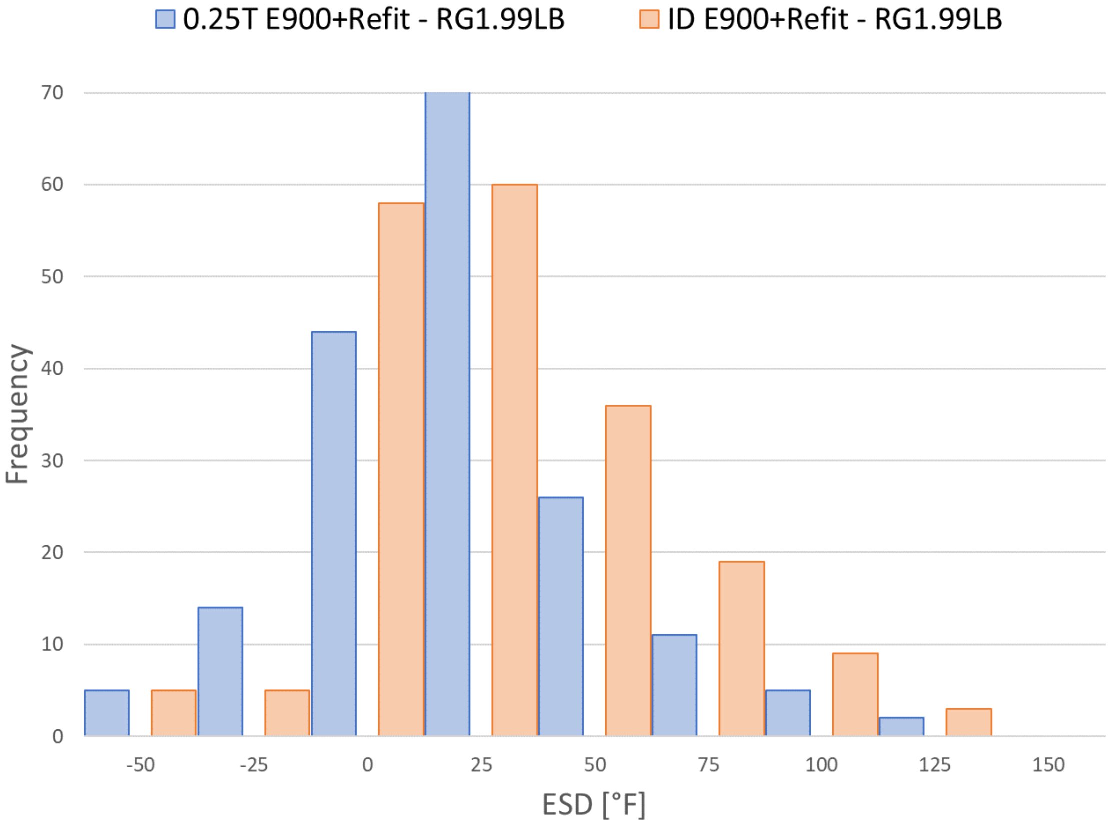

Figure 4-1 Distribution of ESDs, all materials in fleet impact smart sample

Figure 4-2 shows the distribution of ESDs for the limiting materials only for the 1/4T location; in other words, those materials with the highest ART or RT_{PTS} for a given reactor at the 1/4T location. In Figure 4-2, the light blue bars represent the ESDs for materials that are limiting when the same material remains limiting, whether RG 1.99 or ASTM E900-15 is used, while the dark blue bars show the ESDs for those materials that have a change in limiting material when the E900-15 ETC is used. In Figure 4-2, the ESD for those materials that had a change in limiting material is calculated on the difference in ARTs for old and new limiting materials:

$$ESD = ART_{E900-15(new\ limiting\ material)} - ART_{RG\ 1.99(old\ limiting\ material)})$$

This situation occurred for 5 of 21 reactors in the smart sample. Thirteen reactors had positive ESDs for the limiting materials, and nine reactors had negative ESDs, for the 1/4T location.[f] For those reactors with positive ESDs at the 1/4T location for limiting materials, only two reactors had increases in ESD at the 1/4T location of 50 degrees F (10 degrees C) or greater.

Figure 4-3 shows the distribution of ESDs for the limiting materials only for the ID location; in other words, those materials with the highest ART or RT_{PTS} for a given reactor at the ID location.

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[f] One reactor had two limiting materials identified in the plant data searches. One material is a longitudinal weld and one material is a circumferential weld. Therefore, the total number of limiting materials in Figures 4-2 and 4-3 equals 22 rather than 21.

In Figure 4-3, the light orange bars represent the ESDs for materials that are limiting when the same material remains limiting whether RG 1.99 or ASTM E900-15 is used, while the dark orange bars show the ESDs for those materials that have a change in limiting material when the E900-15 ETC is used. This situation occurred for 5 of 21 reactors in the smart sample. Thirteen reactors had positive ESDs for the limiting materials, and nine reactors had negative ESDs for the ID location. For those reactors with positive ESDs at the ID location for limiting materials, only three reactors had increases in ESD at the ID location of 50 degrees F (10 degrees C) or greater.

For limiting materials, the maximum ESD was 60 degrees F at the ID and 46 degrees F at the 1/4T location. Figure 4-2 and Figure 4-3 do not show the ESD for the original limiting material if the limiting material changed, since the ESD for the former limiting material would no longer be relevant.

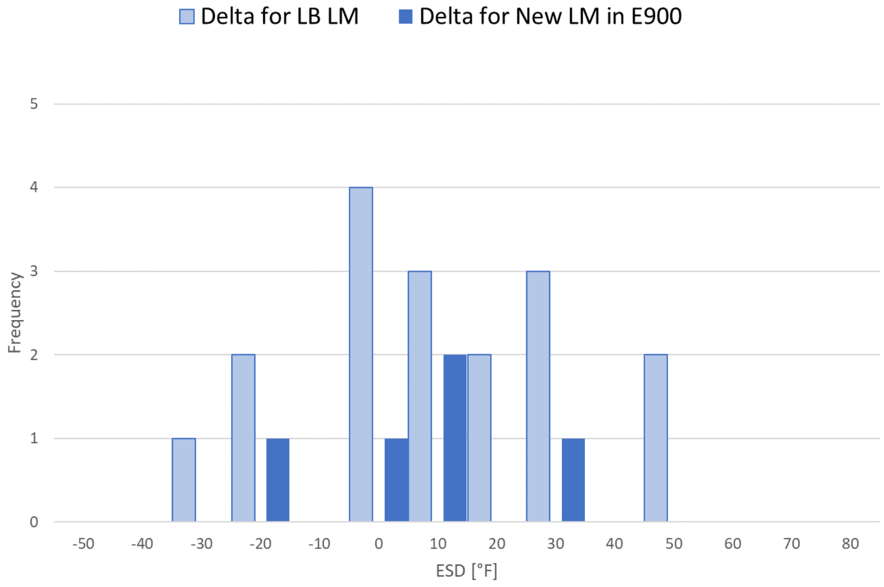

Figure 4-2 Distribution of ESDs for limiting materials only, at 1/4T location

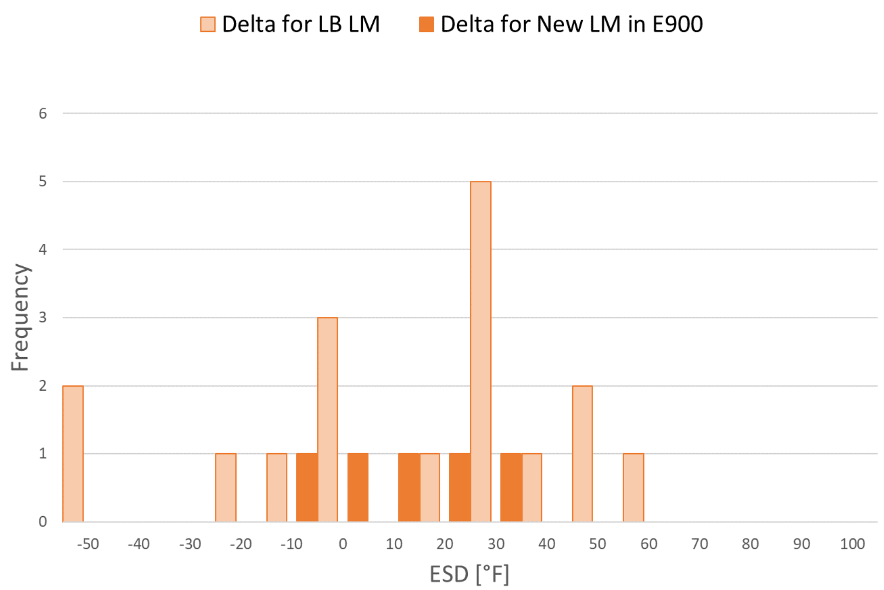

Figure 4-3 Distribution of ESDs for limiting materials only at ID location

Figure 4-4 shows the distribution of ESDs as a function of neutron fluence for both the ID and 1/4T locations. A trend toward higher ESDs occurs as fluence increases. The ID location tends to have higher ESDs, which is not surprising, since neutron fluences are higher at the ID, and the RG 1.99 ETC is known to be nonconservative at higher fluences. Figure 4-5 shows the distribution of ESDs for limiting materials only. For both limiting and nonlimiting materials, a similar trend is observed with an increase in ESDs as fluence increases.

For base materials (plates and forgings), Figure 4-6 and Figure 4-7 show the distribution of ESDs versus fluence for all materials and limiting materials only, respectively. Both figures show a trend of increasing ESDs as neutron fluence increases.

For weld materials, Figure 4-8 and Figure 4-9 show the distribution of ESDs versus fluence for all materials and limiting materials only, respectively. The weld materials show a less pronounced trend of increasing ESDs with neutron fluence than the base materials, and approximately equal numbers of materials have positive and negative ESDs. For limiting weld materials, more materials actually have negative ESDs than positive ESDs.

The results of the fleet impact study showed the following, if the potential alternative RG framework were implemented:

- There is a tendency for material reference temperatures to increase, particularly for base metals.
- 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 $< 4 \times 10^{19}$ n/cm^2.

- Based on the smart sample, only a handful of plant limiting materials will have increases in reference temperatures > 50 degrees F (30 degrees C), and these tend to be at fluences ~$6x10^{19}$ n/cm^2.

- Approximately 20 percent of plants would experience a change in the plant limiting material.

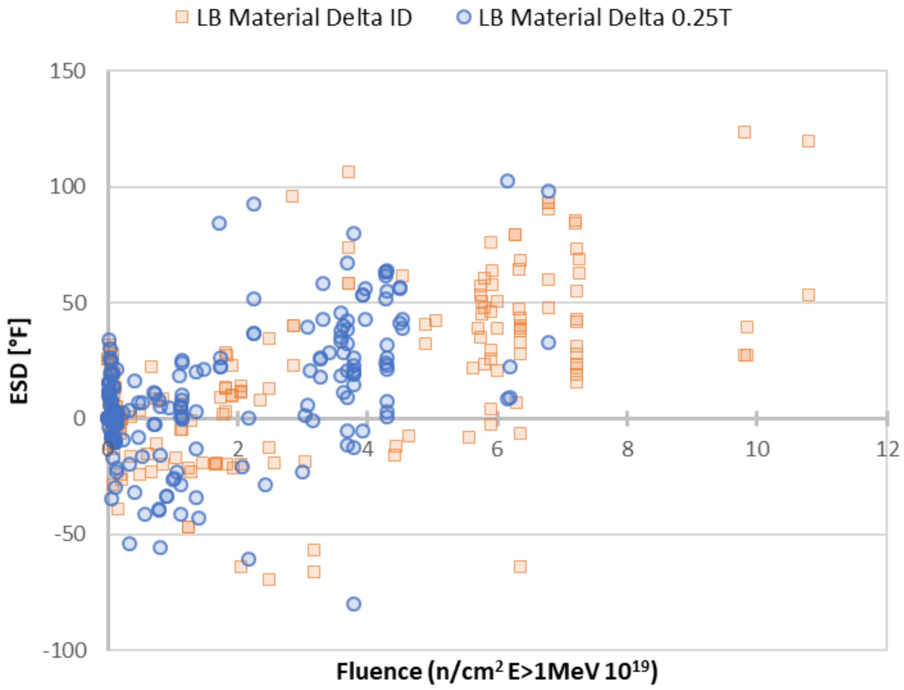

Figure 4-4 Distribution of ESDs versus fluence for all materials

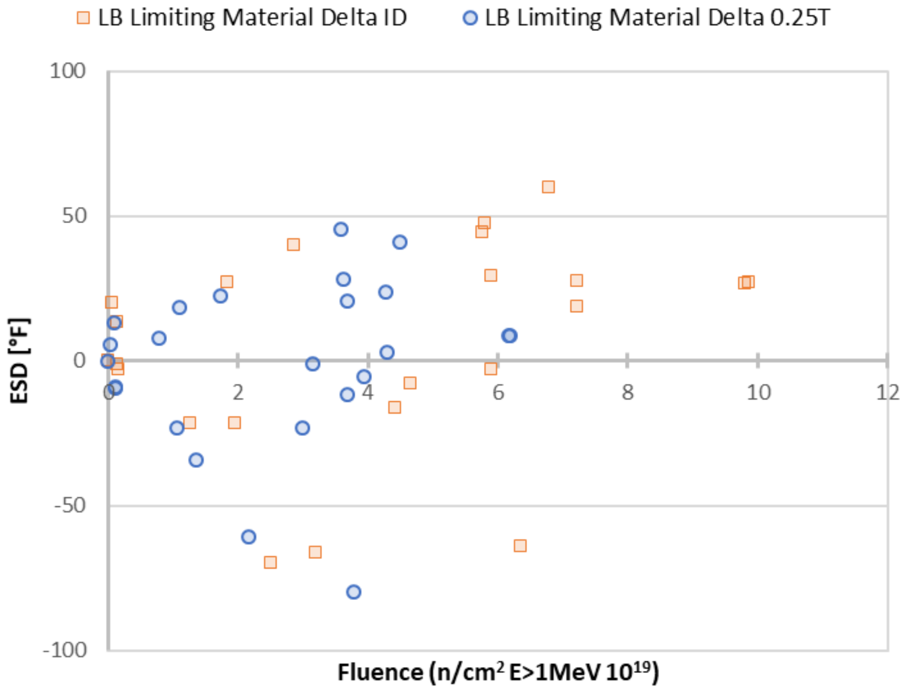

Figure 4-5 Distribution of ESDs versus fluence for limiting materials only

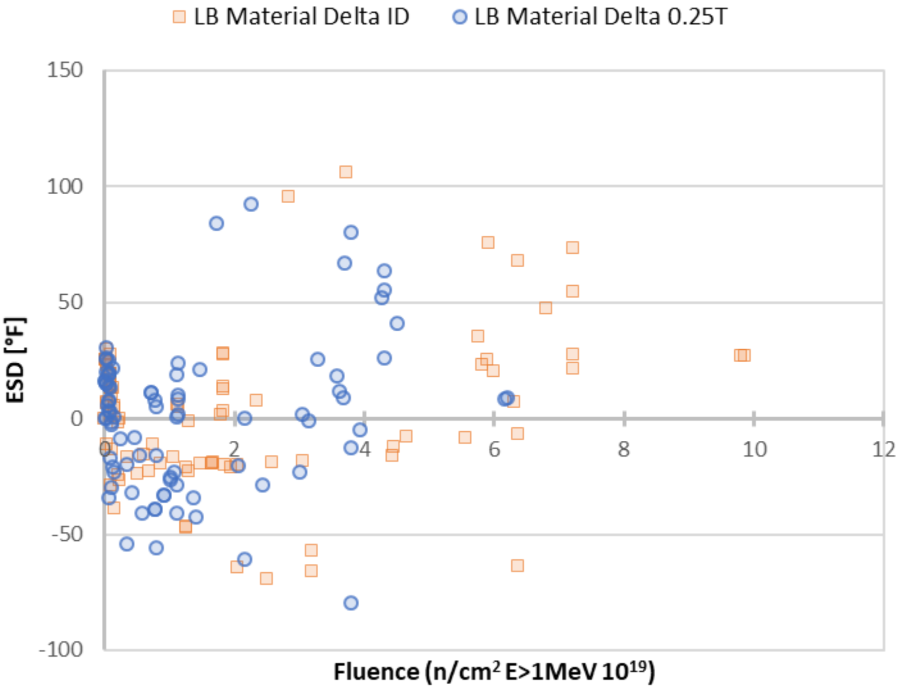

Figure 4-6 Distribution of ESDs versus fluence for all base materials

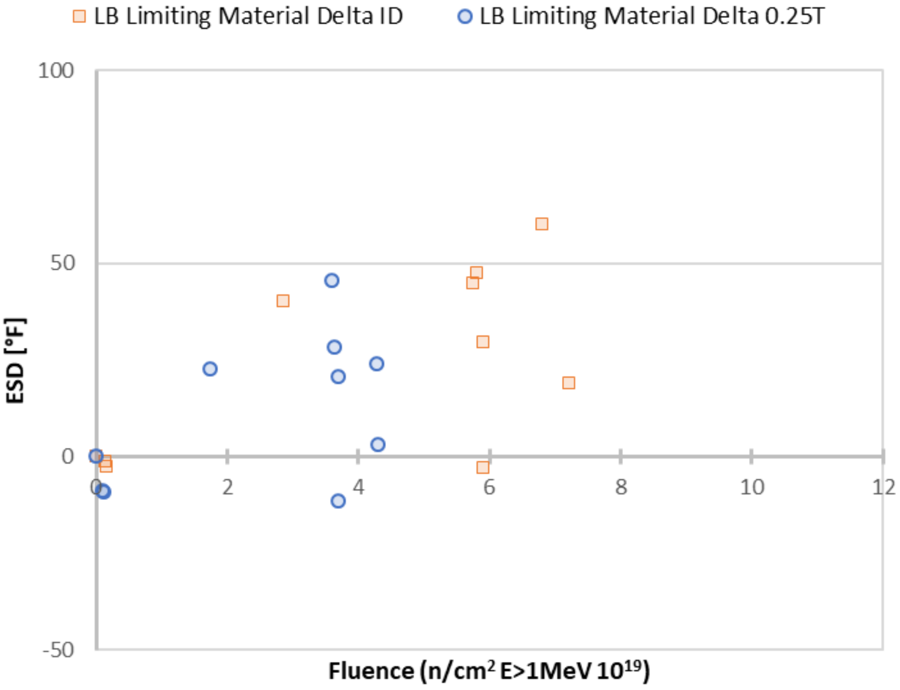

Figure 4-7 Distribution of ESDs versus fluence for limiting base materials only

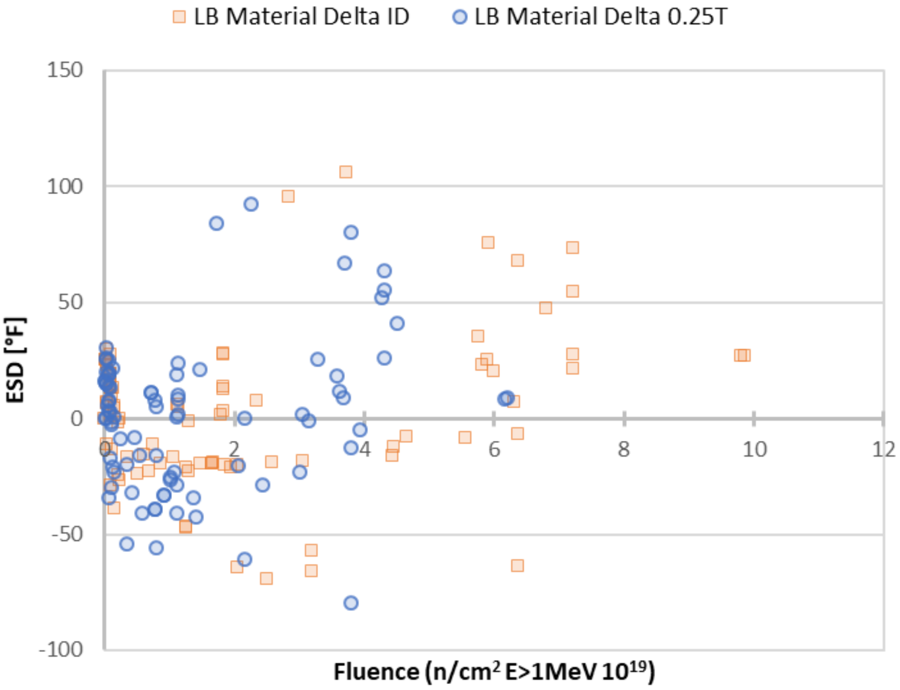

Figure 4-8 Distribution of ESDs versus fluence for all weld materials

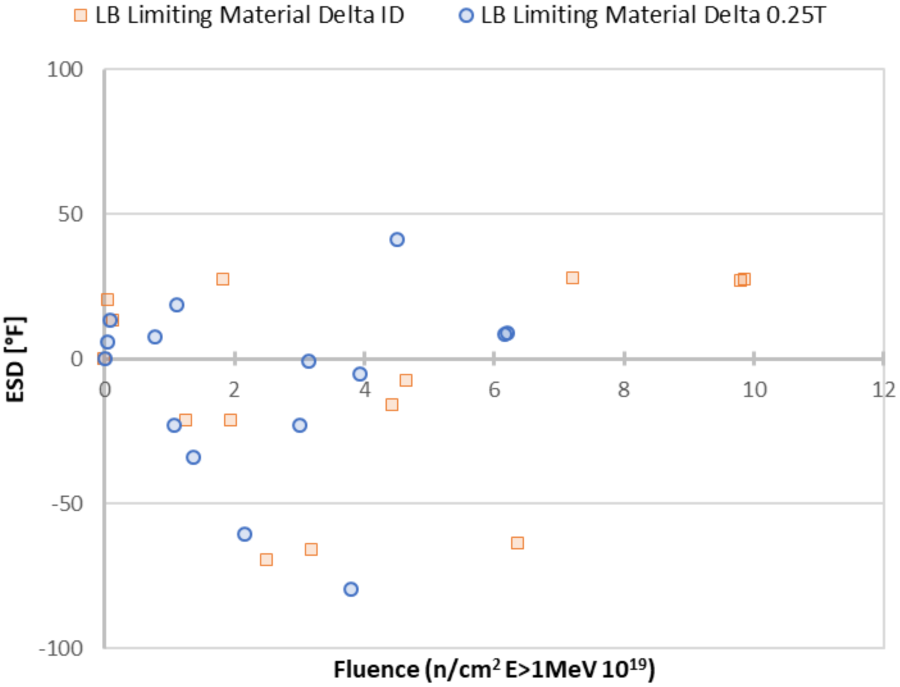

Figure 4-9 Distribution of ESDs versus fluence for limiting weld materials only

5. Conclusions

As a result of the 2019 evaluation of the adequacy of RG 1.99 (Ref. 2), the staff initiated an effort to evaluate a potential alternative to RG 1.99, and whether formal implementation of such an alternative was necessary, based on both technical adequacy and PFM considerations. This report documents the technical basis of a potential alternative to RG 1.99 that was developed to address the issues for further consideration identified in Reference 2. This report also documents the results of a study of the fleet impact if the potential alternative were implemented. This report does not address whether implementation of a revision or alternative to RG 1.99 is necessary from a safety or risk perspective. The results of the related risk assessment contained in TLR-RES-DE-CIB-2020-09—"RG-1.99R2 Update FAVOR Scoping Study," dated October 26, 2020 (Ref. 14), supported the decision by the staff not to pursue implementation of a potential alternative to RG 1.99, Revision 2, at this time.

5.1 Elements of Alternative

This report documents the technical basis for the elements of a potential alternative or revision to RG 1.99. This alternative consists of a methodology for estimating the ART or RT_{PTS} based on the E900-15 ETC. The potential alternative has the following elements:

- **ETC**—Section 3.1 of this report documents the staff's evaluation of two candidate alternative ETCs to RG 1.99 ETC: the E900-15 and 10 CFR 50.61a ETCs. A statistical evaluation of the performance of the two candidate ETCs against surveillance data (consisting of both U.S. and international LWR surveillance data) in the BASELINE database aided in selecting the ETC. The staff considered the statistical evaluation results in addition to nonquantitative factors in selecting the E900-15 ETC as the basis for this alternative framework.

- **Use of surveillance data**—Section 3.2 of this report describes the method for using plant-specific surveillance data:

    - Four surveillance data consistency checks are evaluated, known as Type A (bias test), Type B (slope test), Type C (scatter test), and Type D (outlier test). The staff recommended only Types A, C, and D for the proposed alternative.

    - If the Type A, C, and D tests are passed, then the E900-15 ETC is used without adjustment; if one or more tests failed, a refit procedure is performed based on a bias adjustment. The checks are then performed on the refit curve. If the refit passes, the refit curve is used with the same margins as the nonrefit curve (2 SDs). If the refit curve fails any checks, the more conservative results between the refit and nonrefit curve are used, with an increased margin of 2.33 SDs.

    - The philosophy of use of surveillance data differs from RG 1.99 in that RG 1.99 defaults to the use of the plant-specific surveillance data rather than the generic RG 1.99 ETC, provided the surveillance data meet certain criteria, while the proposed alternative defaults to the use of the generic E900-15 ETC, as long as the surveillance data pass certain tests.

- **Margins**—Section 3.3 of this report describes the determination of the margins to be added to the E900-15 ETC to account for uncertainty. The structure of the margin term is similar to RG 1.99; however, the SD of the ΔRT_{NDT} term (σ_Δ) is derived from U.S. data in the BASELINE database and varies with the magnitude of ΔRT_{NDT}. This results in somewhat larger margins than are currently employed in RG 1.99, which addresses a finding in the RG 1.99 assessment report that found the margins were too small at higher neutron fluences.

- **Default Values**—Section 3.4 of this report describes the default values for the input parameters to the ETC (chemistry values and irradiation temperature). These are to be used if the user cannot determine certain input parameters. The default values are generally based on the highest values in the database for chemistry values (which is conservative), and low values for temperature (which is conservative).

- **Limitations**—The E900-15 standard defined the limits of applicability of the standard with respect to chemistry values, irradiation temperature, and neutron fluence. Section 3.5 of the report describes the staff's evaluation of whether more restrictive limits are needed than those of ASTM E900-15, based on a comparison of the Type A, C, and D test results for the population versus certain more restrictive percentiles. The staff determined the ASTM E900-15 limitations are adequate.

5.2 Fleet Impact Study

Section 4 of the report documents the fleet impact evaluation of a smart sample of 21 plants. The evaluation used licensing basis material inputs to determine the change in ART and RT_{PTS} resulting from a change from RG 1.99 to an alternative ETC. This change in ART associated with switching from RG 1.99 to an alternate ETC is designated the ESD.

The fleet impact study found the following, if the proposed alternative framework based on E900-15 were implemented:

- There is a tendency for material reference temperatures to increase, particularly for base metals.

- Many weld materials see reductions in reference temperatures at fluences $< 4\times10^{19}$ n/cm^2.

- Based on the smart sample, only a handful of plant limiting materials will have increases in reference temperatures greater than 50 degrees F (30 degrees C), and these tend to be at fluences $\sim 6\times10^{19}$ n/cm^2.

- Approximately 20 percent of plants would experience a change in the plant limiting material.

The results of the fleet impact study, with respect to the range of ESDs to be expected, was used to inform a PFM analysis in TLR-RES-DE-CIB-2020-09—"RG-1.99R2 Update FAVOR Scoping Study," dated October 26, 2020 (Ref. 14).

Acknowledgements

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Appendix A

Comparison of BASELINE ΔT_{41J} Values to REAP ΔT_{41J}

The transition shift temperature is determined by fitting a four-parameter tanh curve to each surveillance capsule data set. The coefficients for Equation A-1 were determined by fitting U.S. surveillance data from the Reactor Embrittlement Archive Project (REAP) surveillance database:

$$\Delta T = A + B(Tanh((Temperature - D)/C)) \qquad \text{(A-1)}$$

The resulting reference temperature, nil ductility transition (RT_{NDT}) values were matched and compared with the RT_{NDT} values from the BASELINE subset of American Society for Testing and Materials (ASTM) E900-15, “Standard Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials.” Records were excluded from analysis where no match between the data in REAP and BASELINE was identified. Unmatched records between the databases were caused by subtle differences in nomenclature. The resulting histogram in Figure A-1 showed that the calculated RT_{NDT} from the REAP surveillance data matched closely with values from BASELINE. The y-values in Figure A-1 represent RT_{NDT}(BASELINE) - RT_{NDT}(REAP).

Figure A-2 shows an example of a significant difference between the ΔT_{41J} in BASELINE versus the ΔT_{41J} calculated from surveillance data in REAP. In the example of Figure A-2, there is no pronounced lower shelf energy. As a result, the algorithm used to generate the characteristic S-curve for the Charpy impact energy data was unable to converge on a mathematical solution and determine T_{41J}, although a T_{41J} can be estimated visually. In such cases, significant differences resulted between the ΔT_{41J} calculated from REAP data and the ΔT_{41J} for the same surveillance data in BASELINE.

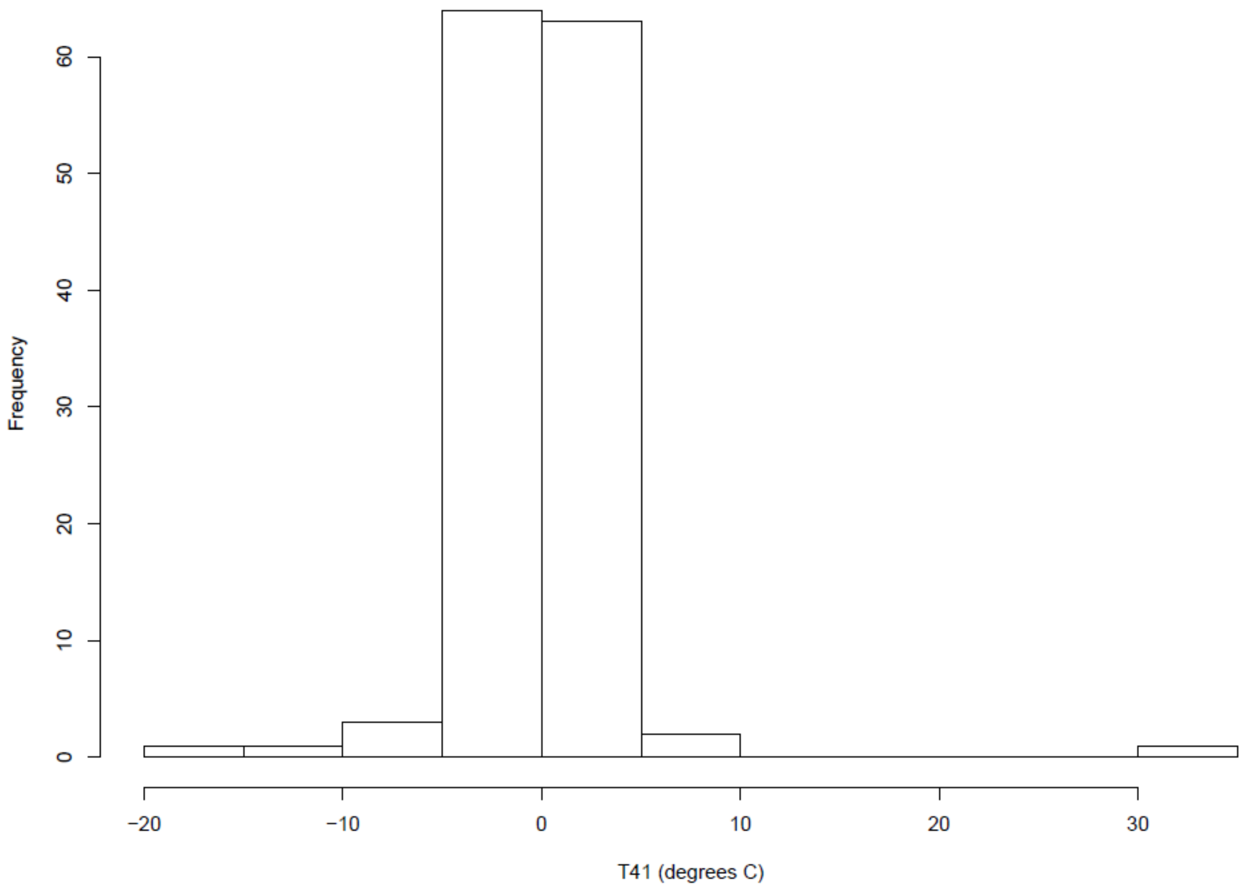

Figure A-1 Comparison of ΔT_{41J} between BASELINE and the REAP surveillance database

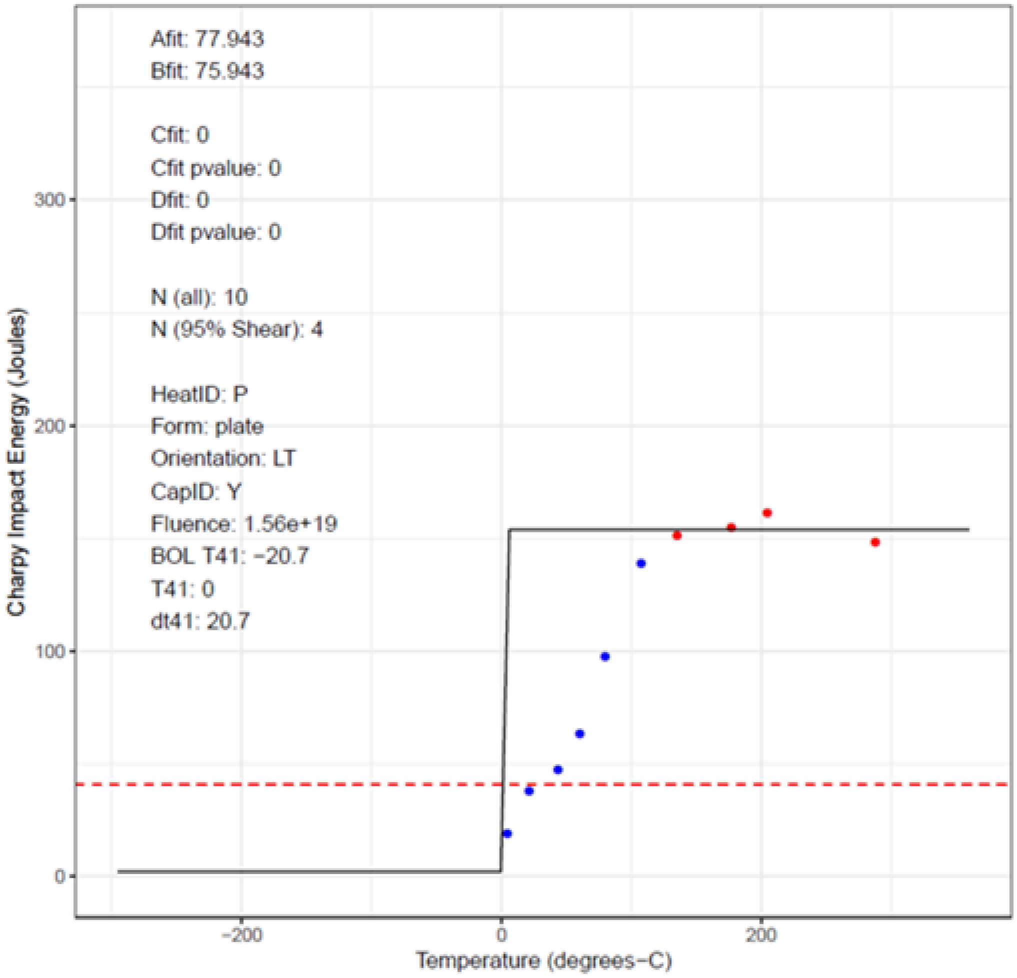

Figure A-2 Example of a lack of mathematical convergence using Equation 1 with the surveillance capsule data for a pressurized-water reactor plant