Evaluation of Embrittlement Models for Regulatory Use: Comparing RG 1.99 Rev.2 and an Intercept-Adjusted ASTM E900-15 Approach

Abstract

This study evaluates the regulatory applicability of embrittlement trend curve (ETC) models for reactor pressure vessel (RPV) steels by comparing RG 1.99 Rev.2 with an intercept-adjusted ASTM E900-15 model. A statistically grounded additive adjustment method was applied to the E900-15 model to improve its prediction accuracy using plant-specific surveillance data. The analysis utilized a combined dataset of 1,034 data points from Korean and U.S. nuclear power plants, covering a broad range of product forms, notch orientations, and fluence levels. Quantitative comparisons were conducted with and without model-specific margins to assess each model’s prediction performance and conservatism under regulatory conditions. Results showed that the adjusted E900-15 model significantly reduced residual bias and root-mean-square deviation (RMSD), particularly at high fluence. The margin behavior of the adjusted model remained stable and conservative without excessive overestimation, while RG 1.99 Rev.2 tended to underestimate embrittlement in the long-term fluence regime. Although RG 1.99 Rev.2 remains widely used due to its simplicity, the findings suggest that the intercept-adjusted E900-15 model provides a more accurate and flexible framework for evaluating RPV embrittlement, especially for life extension assessments. Future improvements should address variance scaling in margin estimation to further enhance regulatory robustness.

**Keywords**: Reactor Pressure Vessel (RPV), Irradiation Embrittlement, Embrittlement Trend Curve (ETC), ASTM E900-15 Adjustment, Regulatory Guide 1.99 Rev. 2, Regulatory Margin Evaluation

# 1. Introduction

Low alloy steels used for reactor pressure vessels (RPVs) experience irradiation embrittlement due to exposure to neutron flux, which leads to a degradation in fracture toughness. To quantitatively model this behavior, various embrittlement trend curve (ETC) models have been developed based on the transition temperature shift (TTS) measured from Charpy V-notch impact tests under neutron irradiation. These ETC models serve as essential tools in reactor design and regulatory assessments [1].

Historically, ETC models have evolved along two major approaches. One is the development of physically based formulations grounded in mechanistic understanding of neutron embrittlement phenomena [2–5]. The other involves empirically based models derived from surveillance test data using statistical methods [6–8]. While both approaches capture the average irradiation behavior of materials reasonably well, regulatory applications typically require plant-specific adjustments based on surveillance data [1].

In both the United States and South Korea, Regulatory Guide 1.99 Revision 2 (RG 1.99 Rev.2), issued in 1988, remains the standard ETC used in regulatory practice [7]. This model was developed based on approximately 177 surveillance data points available at the time. This model was developed from approximately 177 surveillance data points available at the time. Despite its simple formulation, RG 1.99 Rev.2 continues to be widely used due to its compatibility with plant-specific adjustment procedures [9].

More recently, ASTM E900-15 was developed using a much larger international database comprising over 1,800 data points collected from light water reactors worldwide [10]. As a statistically refined empirical ETC, E900-15 has demonstrated improved accuracy over RG 1.99 Rev.2 [11]. However, for regulatory implementation, E900-15 also requires plant-specific adjustment, and various adjustment methods have been proposed and evaluated [12,13].

In previous work by the authors, a mixed-effects modeling framework was introduced to derive statistically robust adjustment methods for the E900-15 model, particularly for heat-specific groups [14]. Additive and multiplicative forms of adjustments were compared, and a mathematically formalized intercept-only adjustment model was identified as a particularly practical for regulatory applications [15].

Although earlier studies improved the quantitative performance of E900-15 adjustments, relatively little attention has been given to their practical applicability in regulatory contexts—particularly regarding plant-specific adjustment procedures and the treatment of prediction margins [16].

Building on previous results, this study quantitatively compares RG 1.99 Rev.2 and the adjusted E900-15 model using surveillance data from both Korean and U.S. nuclear power plants, focusing on plant-specific applicability. Importantly, model margins were incorporated into the analysis to reflect realistic regulatory conditions. This study provides a comprehensive evaluation of the adjusted E900-15 model as a regulatory ETC framework.

# 2. Methodology

## 2.1 Surveillance test data

The surveillance data used in this study were collected from two primary sources. The first includes final surveillance reports from South Korean nuclear power plants, covering 20 units through 2024. The second is the Baseline22 dataset, included in the Plotter-22 software provided by the ASTM E10.02 committee [10]. This dataset compiles surveillance and specific reference material (SRM) data from pressurized and boiling water reactors across 15 countries. For this study, only U.S. data with clearly identifiable plant-level information were selected and combined with the Korean dataset.

Each surveillance data point was assigned to a plant-specific material group defined by plant ID, product form, and notch orientation. In the Korean dataset, base materials include forgings and plates with LT and TL orientations, while weld materials are limited to TL. For example, Kori-2, which uses forgings, includes the groups KO2-F-LT, KO2-F-TL, and KO2-W-TL. In the U.S. dataset, a few weld samples were labeled as LT or LS, but for consistency in analysis, all such welds were standardized to the TL orientation.

In several U.S. plants, one plant-specific group included multiple heat-specific groups. A heat-specific group shares the same chemical composition and unirradiated Charpy V-notch results T41J. For example, DR3-W-TL may include DR3-W1-TL and DR3-W2-TL.

A summary of the dataset composition and key statistical characteristics is provided in [Table 1](#tbl-dataset-summary).

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| Table 1. Summary of plant count, material groups, data points, and maximum fluence by country.   |  | Korean | US | total | | --- | --- | --- | --- | | Number of plants | 20 | 99 | 119 | | Number of materials group | 58 | 245 | 303 | | Number of data points | 170 | 864 | 1034 | | Maximum fluence (1019 n/cm2) | 7.01 | 1.07 |  | |

## 2.2 ART Calculation Using RG 1.99 Rev.2

In RG 1.99 Rev.2, the adjusted reference temperature (ART) is calculated as:

Here, the Initial RTNDT is the reference temperature of the unirradiated material, and ΔRTNDT is determined using the RG 1.99 Rev.2 ETC. Depending on the context, ΔRTNDT can also be expressed as ΔT30, ΔT41J, or TTS. The variable CF denotes the chemistry factor, and *f* represents the neutron fluence (n/cm2, E > 1 MeV). Margin is typically defined as twice the standard deviation (SD) of the ETC, denoted as . In most cases, is considered zero, as test results from unirradiated specimens are usually available.

TTS is calculated using one of two methods, depending on the availability of surveillance test data. The first method, outlined in Position 1.1 of RG 1.99 Rev.2, applies when there are no surveillance results or only one data point is available. In this case, the CF is selected from a table based on the Cu and Ni content and whether the material is base or weld metal. The of the ETC is fixed at 9.44°C(17°F) for base metals and 15.56°C(28°F) for welds.

The second method, described in Position 2.1, can be applied when at least two reliable surveillance test results exist for a given plant-specific material group. In this case, the CF is determined using a fluence-weighted average of the measured surveillance data, enabling more plant-specific adjustment than the general ETC prediction.

The margin is calculated after the TTS has been determined at the target fluence level. If all surveillance results within the group are considered credible, the margin may be reduced by half. However, if the calculated margin exceeds the TTS value itself, the final margin is capped and cannot exceed the value of TTS.

Detailed equations and procedures are provided in RG 1.99 Rev.2 [7].

## 2.3 Adjustment of ASTM E900-15 Model

To adjust the E900-15 model, the intercept-only adjustment model AM3 was applied [15]. For each heat-specific group, the intercept is estimated as the mean residual between measured and predicted TTS, scaled by the number of observations plus one. The unirradiated T41J serves as an additional data point.

The reference TTS is calculated using the standard equation with seven input variables: product form, Cu, Ni, Mn, P, irradiation temperature, and fluence [10]. Average values per group are used for simplicity.

The additive adjustment term is then calculated as the mean residual between the measured TTS and the E900-15 reference prediction within each group. The denominator includes one additional term to account for the use of a single unirradiated T41J baseline in each heat-specific group.

The standard deviation of E900-15 is defined as a power function of TTS, specific to product form. Notably, the ASTM E900-15 standard does not provide an official formula for calculating the margin used in ART evaluations.

All calculations were performed using R software [17].

# 3. Results and Discussion

## 3.1 Evaluation Using Korean Surveillance Data

[Fig. 1](#fig-01) presents representative examples of plant-specific material groups from a Korean nuclear power plant. Each panel corresponds to a combination of plant, product form, and notch orientation. Data points represent measured TTS values at various fluence levels. Dashed lines show unadjusted reference curves from each ETC, while solid lines indicate adjusted trend curves based on surveillance data.

In the Korean data, each plant-specific material group shares a single unirradiated T41J reference value. Thus, all ΔT41J values in a group are referenced to the same baseline, simplifying adjustment and facilitating statistical interpretation.

Red dashed and solid lines represent the RG 1.99 Rev.2 ETC. The dashed line corresponds to Position 1.1 (P1.1), which uses a CF based on Cu and Ni content and product form. The solid red line shows Position 2.1 (P2.1), where CF is recalculated using fluence-weighted surveillance results. Because P2.1 applies a multiplicative adjustment, it retains the origin-intersecting property while shifting the curve to better match the data.

Green lines indicate the E900-15 ETC. The dashed line is the unadjusted reference curve based on average material properties. The solid green line shows the adjusted curve which applies an additive group-specific intercept, translating the reference curve vertically without changing its slope.

RG 1.99 Rev.2 shows a steep TTS increase in the low-fluence region, which becomes more gradual above ~4×1019 n/cm2. In contrast, E900-15 captures embrittlement trends more closely, likely due to its inclusion of extensive Korean surveillance data under low-Cu conditions.

Notably, for the same base material with different notch orientations (e.g., LT and TL), the reference curves from both ETCs remain unchanged, as they are calculated solely from chemical composition. However, the adjusted curves differ, reflecting variations in unirradiated T41J across material groups.

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| Fig. 1. Comparison of RG1.99 Rev.2 and E900-15 ETCs for a sample unit from Korean surveillance data, showing reference (dashed) and adjusted (solid) curves. |

[Fig. 2](#fig-02) shows residuals between measured and predicted TTS values versus fluence. Blue curves represent quadratic fits to the residual trends. Weld data from Kori-1 were excluded due to extreme TTS values considered outliers. These samples had exceptionally high Cu content compared to the rest of the Korean dataset.

Unadjusted models—RG 1.99 Rev.2 P1.1 and the E900-15 reference—show a wide residual spread, whereas the adjusted models—RG 1.99 Rev.2 P2.1 and the adjusted E900-15—exhibit significantly reduced scatter. This improvement is clearly reflected in the root-mean-square deviation (RMSD) values: 13.17°C for RG 1.99 P1.1, reduced to 7.63°C in P2.1; and 12.55°C for the E900-15 reference, reduced to 7.68°C after adjustment.

The residual trends indicate that RG 1.99 Rev.2 P1.1 tends to underestimate TTS at high fluence, resulting in positive residuals and non-conservative bias. A similar pattern is seen in P2.1, despite using actual surveillance data. In contrast, the E900-15 reference model shows more stable residuals across fluence levels, with even better agreement in the adjusted version. These findings support the use of E900-15 ETC for improved embrittlement predictions, particularly in the high-fluence regime.

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| Fig. 2. Residuals between measured and predicted TTS for Korean surveillance data, showing improved accuracy after model adjustment as indicated by reduced RMSD. |

[Fig. 3](#fig-03) plots residuals versus predicted TTS. For RG 1.99 Rev.2 P1.1, the regression slope is nearly zero, indicating no systematic bias with respect to TTS, but the positive intercept (+4.6°C) reveals underprediction. P2.1 shows a reduced slope (−0.03) and intercept (+1.22°C), indicating improved prediction accuracy.

The E900-15 Reference model shows a steeper negative slope (−0.35), suggesting overprediction at high TTS values, which, while introducing systematic error, may be favorable from a conservative standpoint. The Adjusted model reduces the slope to −0.12 and the intercept to +3.56°C, indicating a reduction in bias and improved regulatory applicability.

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| Fig. 3. Residuals vs. predicted TTS showing bias reduction after model adjustment. |

For regulatory use, ART values must include appropriate margins. RG 1.99 Rev.2 defines margins based on ETC standard deviations, with potential reductions when surveillance data are credible [7]. However, the ASTM E900-15 standard does not specify how margins should be calculated.

MRP-462 suggests that if a material group includes three or more data points, the margin can be approximated as 68% of the E900-15 standard deviation [13]. In contrast, the intercept adjustment method employed in this study yields a prediction interval (PI) for the adjusted TTS that continuously shrinks as the number of measurements increases [15]. Accordingly, the margin can be calculated as:

Here, *N* is the number of data points within each group. The value 9.54 represents the within-group standard deviation estimated using the AM3 model based on the Baseline22 dataset. The denominator value 13.49 corresponds to the maximum PI when *N* = 0.

[Fig. 4](#fig-04) illustrates the adjusted results considering model margins for the same cases shown in [Fig. 1](#fig-01). Most surveillance test results fall below the margin-adjusted predictions.

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| Fig. 4. TTS predictions and margin bounds for selected cases using RG1.99 Rev.2 P2.1 and E900-15 Adjusted; dashed lines indicate margin-added predictions. |

[Fig. 5](#fig-05) shows residuals after applying model-specific margins. The blue lines represent the smoothed trend of the residuals using the LOESS method [18]. For RG1.99 Rev.2, 12 data points exceed the margin. The blue trend line decreases rapidly in the low fluence region; however, it begins to increase when fluence exceeds 2×1019 n/cm2. This implies that RG1.99 Rev.2 can become non-conservative at high fluence, even when margins are considered.

For E900-15, only four points exceed the margin at low fluence, and residuals remain consistently negative across the fluence range, indicating sustained conservatism. This suggests that E900-15 provides better support for integrity evaluations extending through long-term operation.

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| Fig. 5. Residuals between measured and margin-adjusted predicted TTS for Korean surveillance data, with smoothed trend lines indicating bias across fluence. |

## 3.2 Evaluation Including U.S. Surveillance Data

To broaden the scope of the analysis, U.S. surveillance test data were incorporated in addition to the Korean dataset. These U.S. nuclear power plants are also subject to the same regulatory guideline, RG 1.99 Rev.2. As with the Korean dataset, the U.S. data were also classified into three material group types per plant: Base-LT, Base-TL (either forgings or plates), and Weld-TL. For consistency, weld materials with notch orientations recorded as LT or LS were standardized to TL.

Among the U.S. data, 22 plant-specific material groups were identified to include multiple heat-specific groups, each characterized by distinct chemical compositions and unirradiated T41J values. Since the AM3 intercept-only adjustment model was originally formulated for single heat-specific groups (i.e., with a common unirradiated T41J value), two extended approaches were considered to adapt it for multi-heat material groups.

The first approach applies the intercept adjustment separately to each heat-specific group, producing individual adjusted TTS predictions. A weighted mean of these predictions is then computed across the entire material group, accounting for the number of data points in each subgroup:

The second approach performs a single, unified adjustment for the entire material group. This is done using the group-averaged E900-15 reference curve, and the residuals from all heat-specific groups are pooled. The adjustment term is modified from the original AM3 form by explicitly incorporating the number of distinct heat-specific groups, *G*, into the denominator:

Here, *N* denotes the total number of data points in the material group, and *G* is the number of heat-specific groups.

[Fig. 6](#fig-06) presents three representative material group cases exhibiting the largest prediction differences between the two approaches. In each case, notable discrepancies in chemical composition and unirradiated T41J values were observed among subgroups. Across all multi-heat material groups, only four cases exhibited a prediction gap greater than 1°C. Therefore, the material group mean approach was adopted for all subsequent analyses in this study.

In parallel, the PI used for margin calculation was also reformulated to reflect both the total number of data points and the number of subgroups:

Although this approach differs from standard regulatory procedures, it was adopted in this study to support a unified comparison and visualization of the Korean and U.S. surveillance data.

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| Fig. 6. E900-15 prediction comparison for multi-heat material groups with large differences between group mean and weighted mean. |

[Fig. 7](#fig-07) compares residual distributions from RG 1.99 Rev.2 P2.1 and E900-15 adjusted across the entire dataset. In the left panel (residual vs. fluence), blue lines are smoothed trends using LOESS method. RG 1.99 model shows increasing residuals at high fluence, indicating underprediction. E900-15 maintains near-zero residual trends across the range, especially at high fluence, demonstrating improved long-term accuracy. Although the RMSD values for the Korean dataset are nearly identical between the two adjusted models ([Fig. 2](#fig-02)), the overall RMSD across the full dataset is lower for E900-15 than for RG1.99R2, confirming improved predictive accuracy of the adjusted E900-15 model.

The right panel (residual vs. predicted TTS) shows near-linear patterns in both models, reflecting consistent improvement from group-specific adjustment. Compared to the slope of the residual trend observed for adjusted E900-15 in the Korean dataset ([Fig. 3](#fig-03)), the slope becomes even smaller when the model is applied to the full dataset, demonstrating that the adjustment procedure for E900-15 generalizes well and performs more effectively across a broader data set.

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| Fig. 7. Residuals between measured and predicted TTS for surveillance data from Korea and the United States. Korean data are marked in red. |

[Fig. 8](#fig-08) presents the residuals between the measured and predicted TTS values after incorporating model-specific margins. The left panels show these residuals as a function of neutron fluence, with blue curves representing smoothed trends. For RG 1.99 Rev.2 P2.1, 53 out of 1,034 data points were found to exceed the margin-adjusted predictions. while the residuals remain stable in the low-fluence region, the margin becomes increasingly insufficient at higher fluence levels. This indicates that RG1.99R2 may not provide adequate conservatism near very high fluence conditions.

In contrast, the adjusted E900-15 model shows only 26 points exceeding the margin. Moreover, the residual trend remains nearly flat across the entire fluence range, indicating that the margin provides consistent conservatism regardless of fluence level. This stability suggests the robustness of the E900-15 adjustment in regulatory applications, especially for long-term operation assessments.

The right panels plot residuals against margin-adjusted predicted TTS. For RG 1.99 Rev.2 P2.1, residuals trend negative as TTS increases, indicating growing overconservatism at high embrittlement levels. Adjusted E900-15 maintains a flat trend, suggesting more consistent predictions with an appropriate level of safety margin across the full range.

These results show that the E900-15 adjustment offers a better balance between accuracy and conservatism, particularly for high-fluence, long-term operation conditions.

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| Fig. 8. Residuals between measured and predicted TTS, including margins, for surveillance data from Korea and the United States. Korean data are shown in red. |

To further examine model differences in regulatory terms, [Fig. 9](#fig-09) compares the predicted ART values from E900-15 and RG 1.99 Rev.2 across all 303 plant-specific material groups. The difference, denoted as ΔART (E900 − RG1.99), is plotted against fluence and segmented by product form. Each gray line represents a single material group, while the solid blue line indicates the average smoothed trend in ΔART.

For forgings, the E900-15 model predicts consistently higher ART than RG1.99 from the beginning of irradiation. In plates, the difference between the two models is negligible at low fluence (less than 2×1019 n/cm2), but gradually increases as fluence rises. Weld materials show a more complex behavior: the ΔART tends to decrease slightly at first, up to around 2×1019 n/cm2, and then increases at higher fluence.

To support comparison, the number of material groups for which ΔART exceeds 20°C at a fluence of 6×1019 n/cm2 is noted in each panel. For forgings and plates, a substantial number of groups exceed this threshold, while for welds, the proportion is relatively lower.

Beyond the average behavior, the spread of the individual curves offers further insight. Forgings exhibit relatively tight clustering, while plates show moderate variability. Welds exhibit the widest spread among the three, indicating significant diversity in prediction behavior. Notably, several weld material groups exhibit negative ΔART values even at high fluence, meaning that E900-15 predicts lower ART than RG 1.99 Rev.2. This observation implies that adopting the E900-15 model without caution—particularly for weld materials—could lead to non-conservative assessments.

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| Fig. 9. ΔART between E900-15 and RG 1.99 Rev.2 versus fluence, separated by product form with average trends highlighted in blue. |

## 3.3 Discussion and future work

The findings presented in this work highlight the advantages of the intercept-adjusted E900-15 model over the existing RG 1.99 Rev.2 framework in terms of predictive accuracy and margin consistency. By incorporating plant-specific surveillance data through a statistically grounded additive adjustment, the model better reflects material-specific embrittlement trends, particularly under high-fluence conditions.

Although RG 1.99 Rev.2 remains widely used in regulatory applications due to its simplicity and clearly defined margin rules, the present results suggest that its margin formulation may be insufficient for long-term operation scenarios. In contrast, the E900-15 adjustment model maintains robustness across a broad range of fluence levels, supporting its applicability for life extension assessments. However, overly conservative margins—if not properly tailored—may impose unnecessary operational restrictions, potentially limiting plant management flexibility.

Accurate margin estimation requires proper consideration of the SD structure of the ETC. While the current intercept-only adjustment model improves the mean prediction, it assumes homoscedasticity and does not reflect the heteroscedastic variance behavior specified in ASTM E900-15, where SD increases with TTS. To enhance reliability, future adjustment models should incorporate a heteroscedastic variance function into the intercept estimation framework.

In addition, refitting the original E900-15 model parameters by incorporating the effects of adjustment could help improve consistency between the reference and adjusted predictions. This line of investigation would be particularly valuable in aligning the ETC formulation with plant-specific embrittlement behavior observed in ongoing surveillance programs.

# 4. Conclusion

This study evaluated the applicability of the intercept-adjusted ASTM E900-15 model as an alternative to RG 1.99 Rev.2 for predicting irradiation embrittlement in reactor pressure vessel (RPV) materials. Using surveillance data from South Korean and U.S. nuclear power plants, the E900-15 model was adjusted using a group-specific intercept approach (AM3), and the results were compared with those of RG 1.99 Rev.2 under regulatory conditions. The analysis showed that the adjusted E900-15 model provides improved agreement with measured data and offers more stable margin behavior across a wide fluence range. In particular, it reduces the residual bias observed in RG 1.99 Rev.2, which tends to underestimate embrittlement at high fluence levels. The margin formulation based on E900-15 also maintained conservatism without excessive overestimation, supporting its practical use in extended plant operation assessments. Overall, the results support the E900-15 adjustment framework as a statistically sound and practically applicable method for embrittlement evaluation. Further refinement of the model’s treatment of uncertainty, particularly in connection with standard deviation scaling, may improve its regulatory usability.

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