

## Evaluation of Irradiation Embrittlement Models for SA508 Gr.3 Class 2 RPV Steels: RG 1.99 vs. ASTM E900-15

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### 1. Introduction

Innovative Small Modular Reactors (i-SMRs) are emerging as pivotal technologies targeting an operational life of over 80 years [1]. The i-SMR design led by Korea Hydro & Nuclear Power (KHNP) adopts an integral reactor design where the introduction of high-strength SA508 Gr.3 Class 2 (Cl.2) steel is being considered for the reactor pressure vessel (RPV) and containment vessel (CV) to replace conventional Class 1 (Cl.1) steel. While higher unirradiated yield strength (YS) has been found to potentially reduce irradiation sensitivity [2,3], the regulatory applicability of current embrittlement trend curves (ETCs), such as RG 1.99 Rev.2, must be verified for Cl.2 materials because existing regulations were primarily developed using Cl.1 data.

Irradiation test data for Cl.2 steels are limited, and publicly available surveillance results are scarce. In this work, the available surveillance (SV) dataset was classified into lower-strength (~Cl.1) and higher-strength (~Cl.2) groups based on their unirradiated room-temperature tensile properties. The study evaluates whether RG 1.99 Rev. 2 shows statistically similar behavior for the two strength groups and compares these results with the ASTM E900-15 model.

### 2. Methodology

To evaluate the statistical behavior of different strength groups, the SV dataset was classified based on unirradiated tensile properties. Materials with an unirradiated YS of at least 450 MPa and an UTS of at least 620 MPa were categorized as 'Class 2' regardless of their product form. This classification resulted in a total of 848 data points, consisting of 607 Cl.1 points and 241 Cl.2 points. The dataset was compiled from 170 Korean surveillance test results and 678 data points from the U.S. Reactor Embrittlement Archive Project (REAP) and the ASTM E900-15 database.

The performance of various evaluation models, including RG 1.99 Position 1.1, Position 2.1, and both the reference and intercept-adjusted versions of ASTM E900-15, was then compared using residual analysis

calculated as the difference between measured and predicted values.

### 3. Results and Discussion

The analysis of residuals for the RG 1.99 Position 1.1 model was initiated with normality testing, which required the implementation of non-parametric statistical methods for cases where the assumption of normality was not met. As illustrated in Fig. 1, these results highlight a slight bias inherent in the chemistry-based model when applied specifically to high-strength base materials. A comparison of the medians revealed a statistically significant difference of approximately 4.4°F between the Class 1 and Class 2 groups within the base materials. Notwithstanding this median shift, further statistical evaluation confirmed that there were no significant differences in variance between the two classes for either base or weld materials.

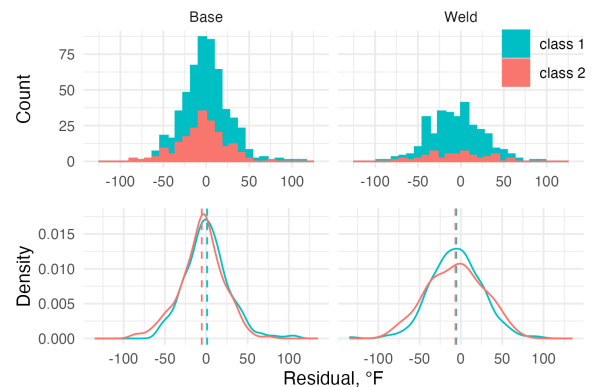


Fig. 1. Residual distributions (measured – predicted TTS) for base and weld materials based on the RG 1.99 Position 1.1 model, comparing Class 1 and Class 2 strength groups.

In a regulatory context, the RG 1.99 Position 2.1 (P2.1) model determines the Chemistry Factor (CF) as a weighted average of measured SV data for material groups where at least two credible results are available. Applying this procedure to the dataset demonstrated that recalculating the CF based on P2.1 eliminates

statistically significant differences in both median and variance between Class 1 and Class 2 materials. Fig. 2 illustrates these residual distributions, confirming that the P2.1 adjustment effectively harmonizes predictive performance across different strength groups, thereby supporting its reliability for regulatory evaluations.

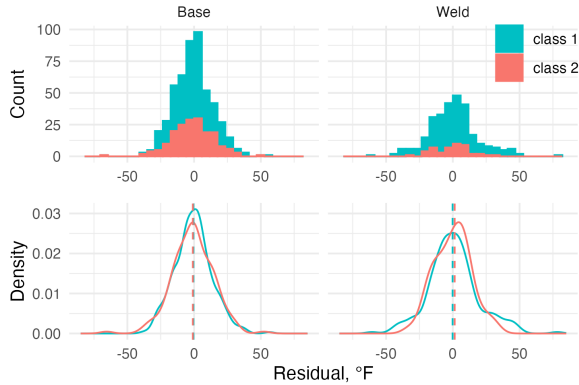


Fig. 2. Residual distributions of the RG 1.99 Position 2.1 model, showing harmonized predictive performance across Class 1 and Class 2 materials for both base and weld product forms.

Residual analysis was conducted for all evaluation models, including the ASTM E900-15 Reference and Adjusted models, and the resulting residual distributions are consolidated in Fig. 3, where Class 1 and Class 2 materials are distinguished by green and red lines, respectively. While the overall distribution patterns for ASTM E900-15 are qualitatively similar to those of RG 1.99, the E900-15 model exhibits consistently smaller RMSD values. Notably, the intercept-adjusted E900-15 model [4] demonstrates significantly reduced residuals, effectively eliminating both the high-fluence bias and the performance gap between strength classes. Furthermore, the E900-15 model shows no high-fluence underestimation, as such data were integral to its development process. This adjustment approach provides a statistically robust framework that outperforms traditional models in the high-fluence regimes critical for SMR life-extension.

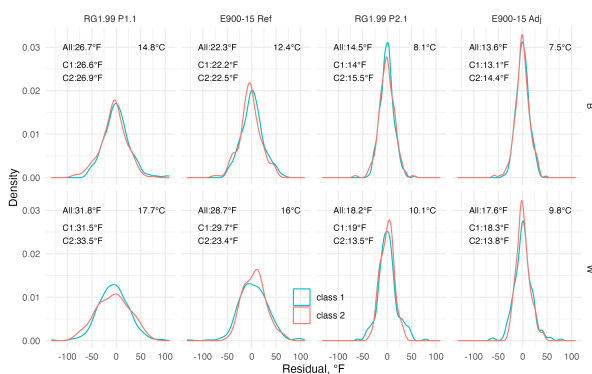


Fig. 3. Consolidated residual distributions for RG 1.99 P1.1 and P2.1 and ASTM E900-15 Reference and Adjusted models, comparing Class 1 and Class 2 materials for base and weld products.

#### 4. Conclusions

The investigation concludes that RG 1.99 Rev.2 Position 2.1 is statistically applicable to high-strength SA508 Gr.3 Class 2 steels as it yields no significant residual differences compared to Class 1. Nevertheless, ASTM E900-15 provides a more robust framework for long-term operation due to its superior stability at high fluence and lack of class-specific bias. Future research plans include manufacturing actual Class 2 materials to conduct neutron-irradiation capsule tests and evaluate fracture toughness directly.

#### REFERENCES

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