Revised 1/06 Embrittlement Shift Correlation

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ATTACHMENT 2

Motivation for Model Update

- Draft NRC (7/2000) and ASTM E900 embrittlement correlations for predicting Charpy transition temperature shift ( ) TTS_{30}) were calibrated to U.S. surveillance data available in 5/2000 (736 shifts)
- Additional U.S. surveillance data (~150 shifts, 62 in low flux BWR) became available in early 2003, another ~50 shifts in 2004
- This addition more than doubled the available BWR low flux data and the long exposure time data
- Preliminary comparisons found neither the 7/2000 draft NRC nor the ASTM E900 models predicted the new data as well as anticipated – particularly the BWR low flux data

Database Update

- **Increase in Size**
  - NUREG/CR-6551 database (~1996) 609 shifts
  - Draft 7/2000 & E900 model database 736 shifts
  - 1/2006 model database 936 shifts

    (775 of the 936 available shifts were used for calibration of most constants, the rest are available for validation)

- **Better Balance**
  - Increased percentage of low Cu, low flux (BWR) & long time-high fluence data in the calibration set
  - Randomly sampled the SRM data to produce comparable influence as other heats (otherwise 3 plates would have undue influence on the fit due to the number of points)

Database Update, cont'd

- **Better Quality Data**
  - Reviewed all data (old and new) for duplicates, discrepancies, missing information
  - Resolved some discrepancies in both old and new data with help from ASTM E10.02 members
  - EPRI (Carter) reviewed BWR temperatures (filling in data for new points and correcting several errors and generic values previously used)
  - Corrections are documented in database and will be documented in revised Surveillance Reports

Database Update, cont'd

- Better Validation
  - 10% of non-SRM data were randomly selected before model development and set aside for validation
  - Most terms in the model were calibrated to the 90% random subset of non-SRM data plus the random sample of SRM data
  - All available low flux data were used to develop the flux terms because of scarcity of low flux data
  - The 10% subset not used for calibrating most constants was used to validate the predictive capability of the model

Issues that Affect Modeling Procedure

- 82% of the calibration data are from PWR, so PWR data will dominate any overall calibration
- All long time, high fluence data are at higher flux
- All low flux data are low fluence BWR at low Tc
- The first term applies at all Cu levels, the second term at higher Cu levels – not numerically independent domains
- Some variables (e.g. fluence, flux, product form, chemistry, Tc) could appear in both terms and could trade off numerically

Modeling Procedure Overview

- PWR data were modeled first, then the PWR model was adjusted to estimate BWR shifts
  - avoids PWR data overwhelming & masking BWR trends
  - avoids confounding Tc and flux, both low in BWR data
  - the only needed adjustment is flux (by effective fluence)
- Low Cu data were initially used to calibrate the "MD" term, then that term was held fixed while working on the "CRP" term
  - makes the domains temporarily numerically independent
- Flux and P*Mn fitting parameters were calibrated to the full range of Cu, then the MD and CRP terms were refined on low & high Cu subsets holding those 4 parameters fixed

Modeling Procedure Overview, cont'd

- The first term fluence effect was fixed at $\sqrt{\phi t}$
  - accepted theoretical approach
  - supported by prior empirical calibrations
  - avoids possible numerical trade-offs between fluence effects in first and second terms
- SRM plates were considered a separate product form category
  - avoids affecting the plate categories for materials actually used in vessels
  - by this change and roughly doubling the number of long time points, the "long time bias" noted in 2000 is no longer evident
- Allowed different Tc effects in both terms
  - MD temperature effect same form as Jones et al, calibrated on low Cu data
  - CRP temperature effect is a fix-up term relative to the MD effect

Revised 1/06 Embrittlement Shift Model

$$TTS = MDterm + CRPterm$$

$$MDterm = A\left(1 - 0.001718T_c\right)\left(1 + 6.130PMn^{2.471}\right)\sqrt{\phi t_e}$$

$$A = \begin{Bmatrix} 1.140x10^{-7} \quad for\ forgings \\ 1.561x10^{-7} \quad for\ plates \\ 1.417x10^{-7} \quad for\ welds \end{Bmatrix}$$

$$\phi t_e = \begin{Bmatrix} \phi t \quad for\ \phi \geq 4.3925\times10^{10} \\ \phi t\left(\dfrac{4.3925\times10^{10}}{\phi}\right)^{0.2595} \quad for\ \phi < 4.3925\times10^{10} \end{Bmatrix}$$

Revised 1/06 Embrittlement Shift Model, cont'd

$$CRPterm = B\left(1 + 3.769 Ni^{1.191}\right)\left(\frac{T_c}{543.1}\right)^{1.100} f\left(Cu_e, P\right) g\left(Cu_e, Ni, \phi t_e\right)$$

$$B = \begin{Bmatrix} 102.3 \;\; for\;\; forgings \\ 102.5 \;\; for\;\; plates\; in\; non\text{-}CE\; mfg.\, vessels \\ 135.2 \;\; for\;\; plates\; in\; CE\; mfg.\, vessels \\ 155.0 \;\; for\; welds \end{Bmatrix}$$

$$128.2\; for\; SRMs$$

$$g\left(Cu_e, Ni, \phi t_e\right) = \frac{1}{2} + \frac{1}{2}\tanh\left[\frac{\log_{10}\left(\phi t_e\right) + 1.1390 Cu_e - 0.4483 Ni - 18.12025}{0.6287}\right]$$

Revised 1/06 Embrittlement Shift Model, cont'd

$$f\left(Cu_e, P\right) = \begin{cases} 0 \quad for\ Cu \le 0.072 \\ \left[Cu_e - 0.072\right]^{0.6679} \quad for\ Cu > 0.072\ and\ P \le 0.008 \\ \left[Cu_e - 0.072 + 1.359(P - 0.008)\right]^{0.6679} \quad for\ Cu > 0.072\ and\ P > 0.008 \end{cases}$$

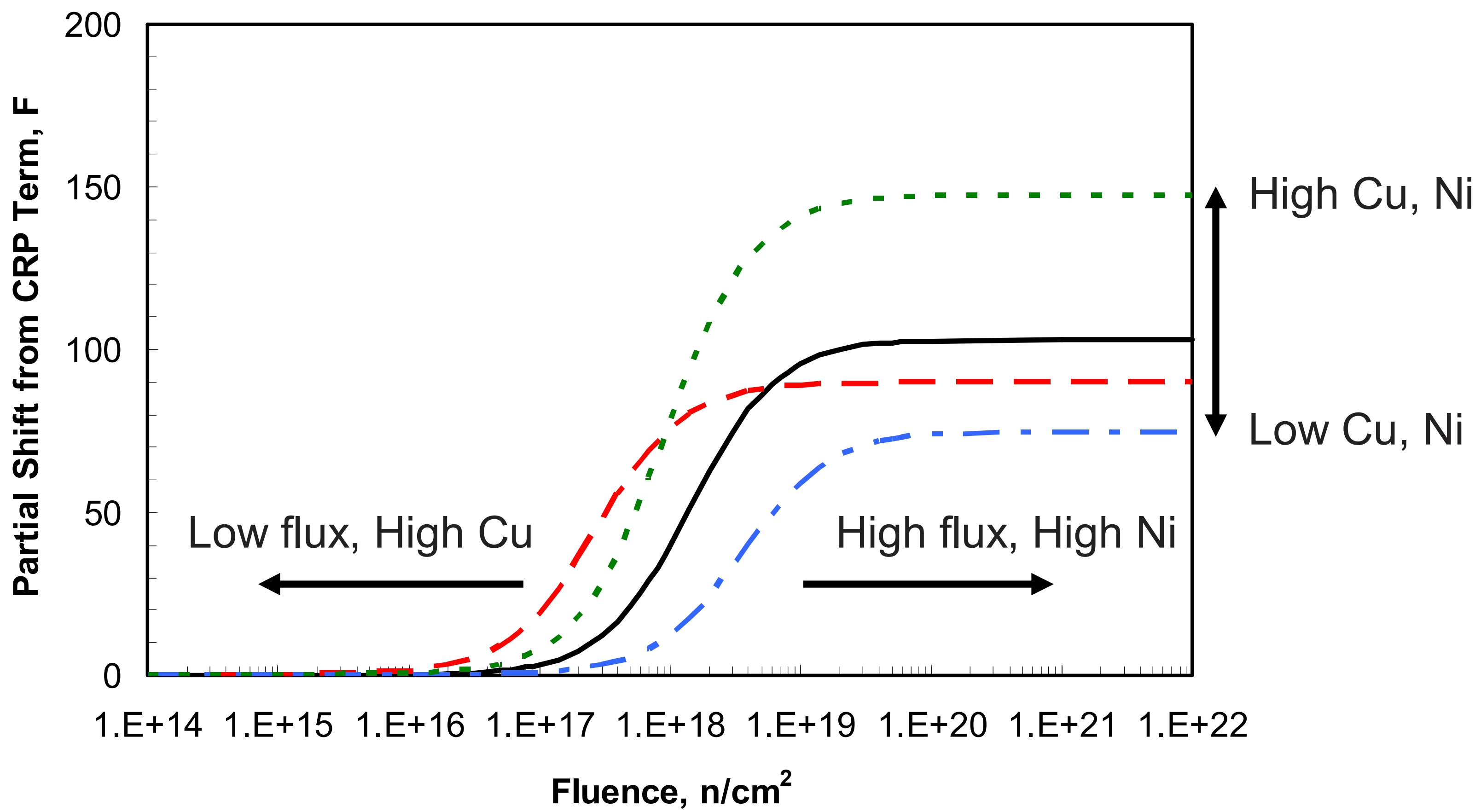
$$Cu_e = \begin{cases} 0 \quad \text{for } Cu \le 0.072 \text{ wt\%} \\ Cu \quad \text{for } Cu > 0.072 \text{ wt\%} \end{cases}$$

$$Max(Cu_e) = \begin{cases} 0.370 \quad for\ Ni < 0.5\ wt\% \\ 0.2435 \quad for\ 0.5 \le Ni \le 0.75\ wt\% \\ 0.301 \quad for\ Ni > 0.75\ wt\%\ (all\ welds\ with\ L1092\ flux) \end{cases}$$

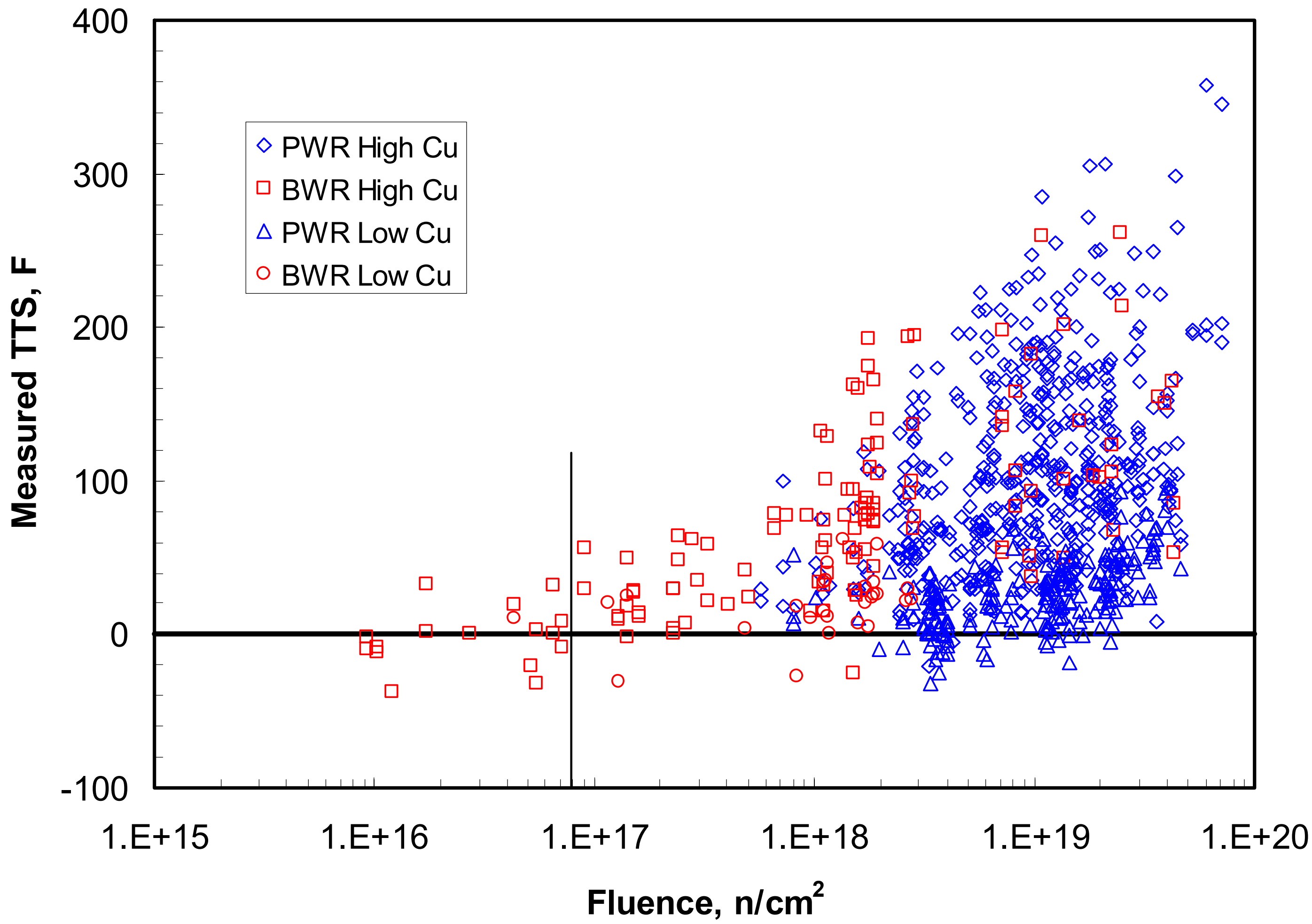
Notes on 1-06 Shift Model

- Units are:
  - Weight percent for all chemical concentrations,
  - n/cm^2 and $n/cm^2/s$, E > 1MeV for fluence, ϕt, and flux, ϕ
  - Degrees Fahrenheit for Tc and calculated shift TTS
- Definitions:
  - Tc is the estimated coolant temperature at the capsule location, used as the best available estimate of irradiation temperature
  - TTS is the transition temperature shift at 30 ft-lb
  - The vessel manufacturer is used to separate CE and non-CE plates
  - Standard Reference Materials (SRMs) are the three plates (ASTM, HSST-01, and HSST-02) irradiated in multiple plants
- Cu limits for welds by Ni and weld flux group:
  - The L1092 welds are placed as a group in the high Ni category, including a few with Ni values somewhat below the lower limit on the high Ni category
  - L80 welds are categorized solely by Ni; most fall in the medium Ni category, a few are in the low Ni category with Ni values well below the lower limit on the medium Ni category
  - Other weld flux groups did not have sufficient high Cu data for separate consideration as a group – they are categorized solely by Ni

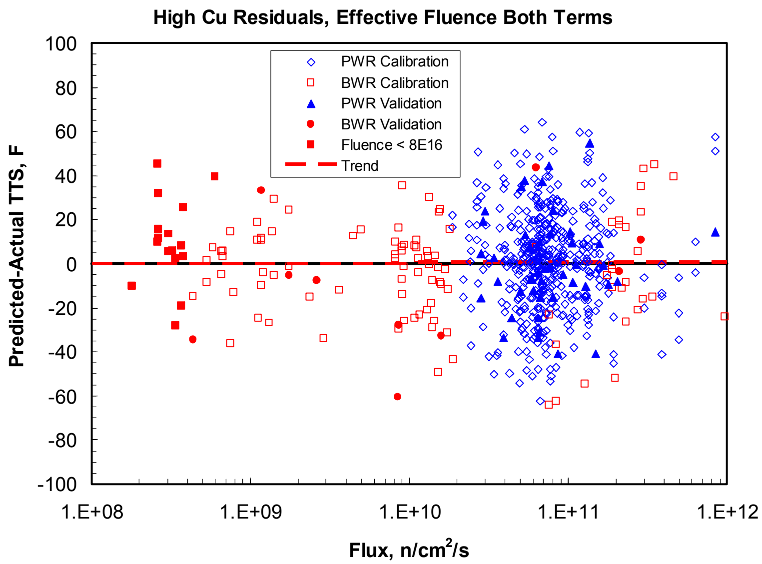
Effect of CRP Term (Schematic)

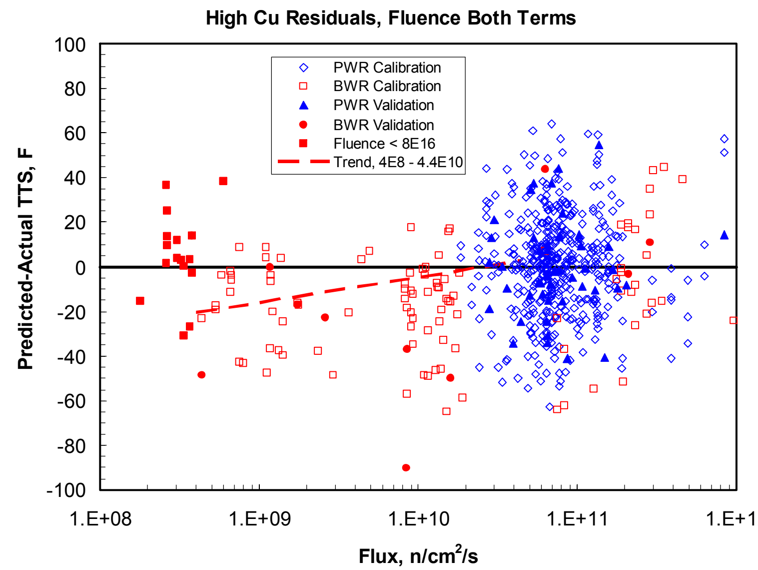


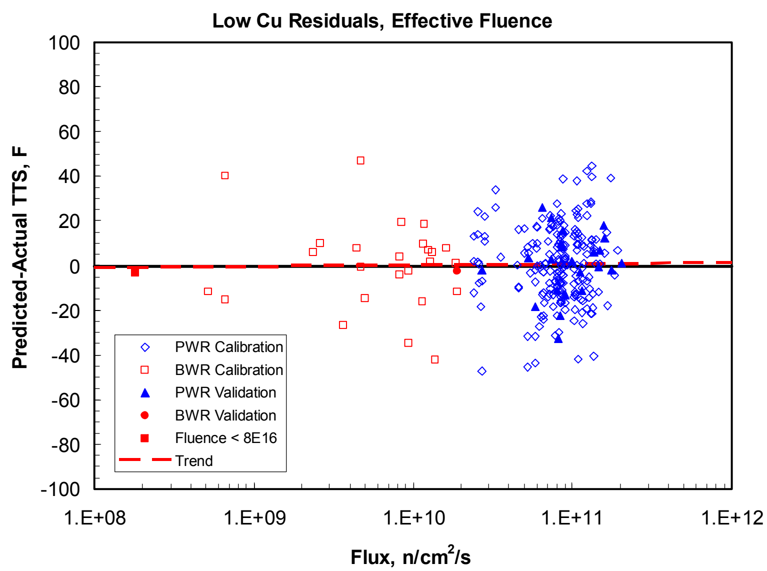
~Zero Average Shift for Fluence < $8x10^{16}$

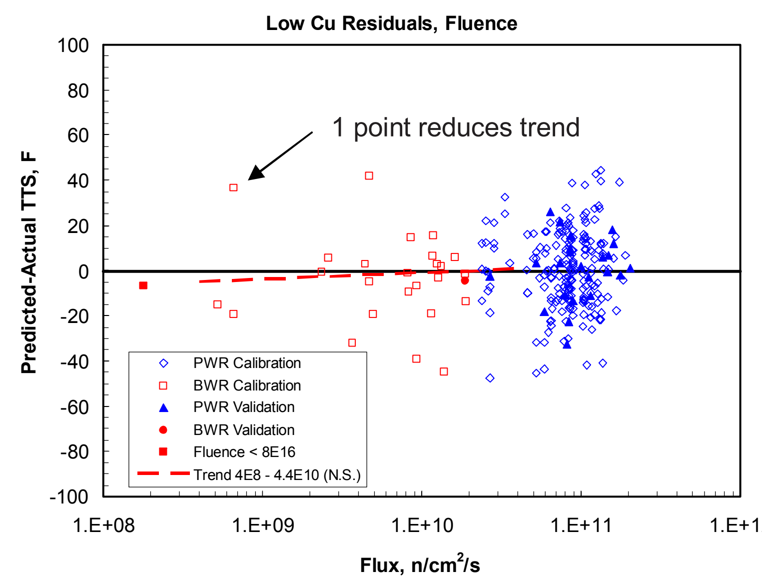


Effect of Effective Fluence, ϕt_e









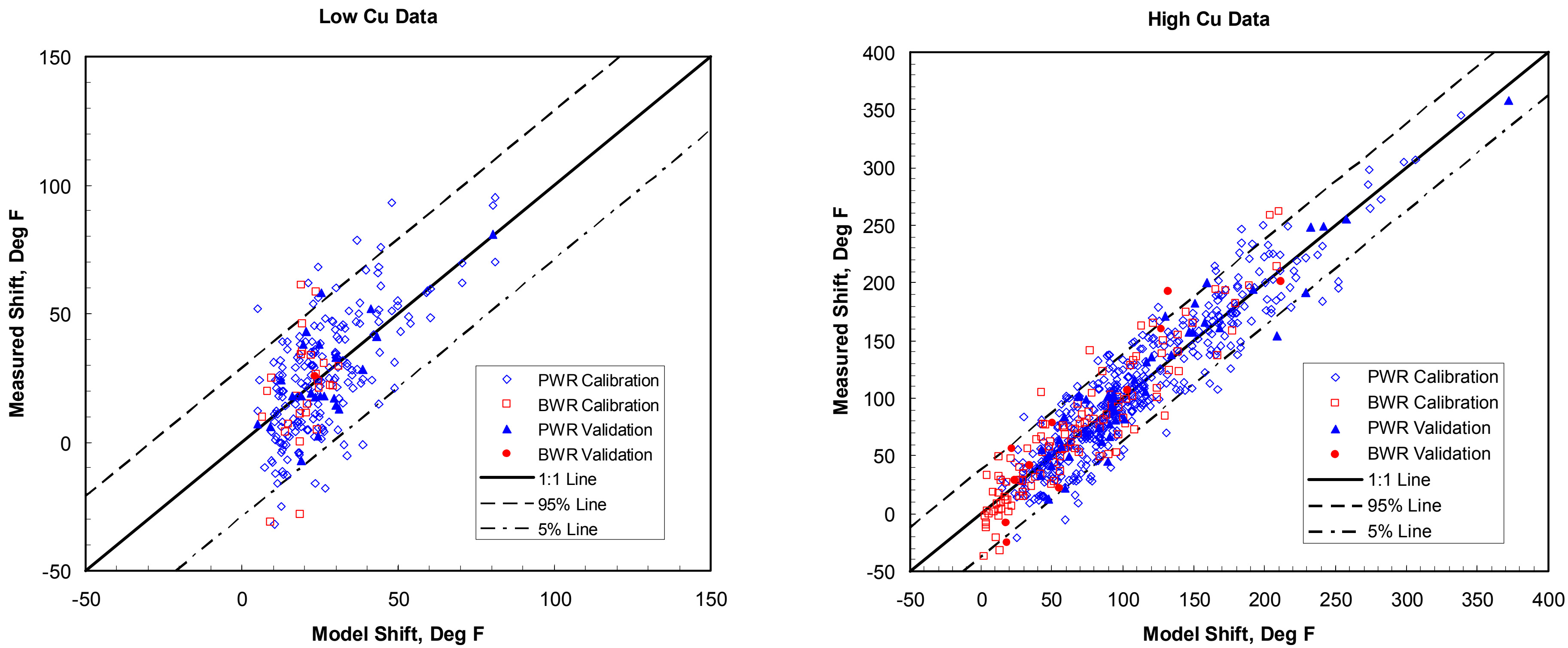
Statistics on Least Squares Fit

Standard deviation of residuals (Sd) about the embrittlement shift model in various subsets, all PWR and BWR calibration and validation data except SRM

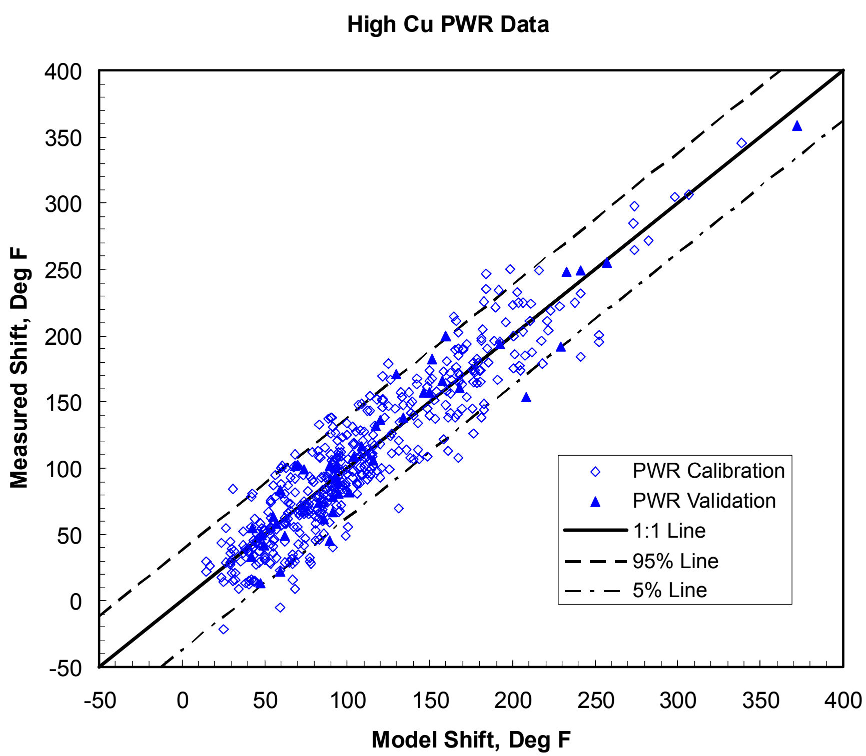
Product Form	Sd for Cu ≤ 0.072 wt%	Sd for Cu > 0.072 wt%
Forging	17.5	19.8
Plate	15.0	20.9
Weld	18.6	26.3

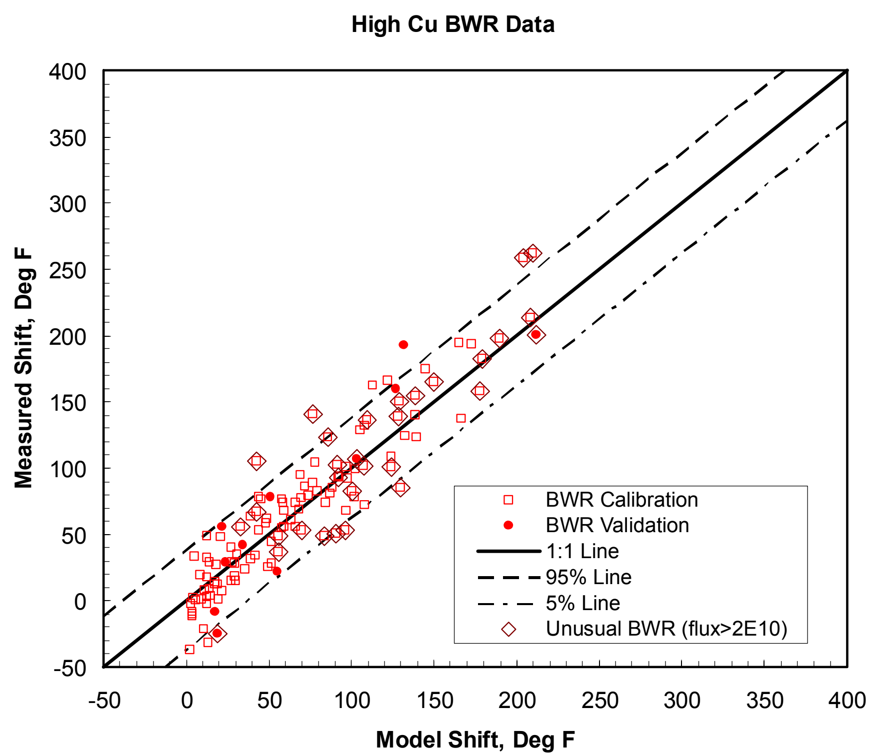
These Sd values by product form should be considered when setting margins.

Model vs. Actual Shift



Model vs. Actual Shift, Cu > 0.072 wt%





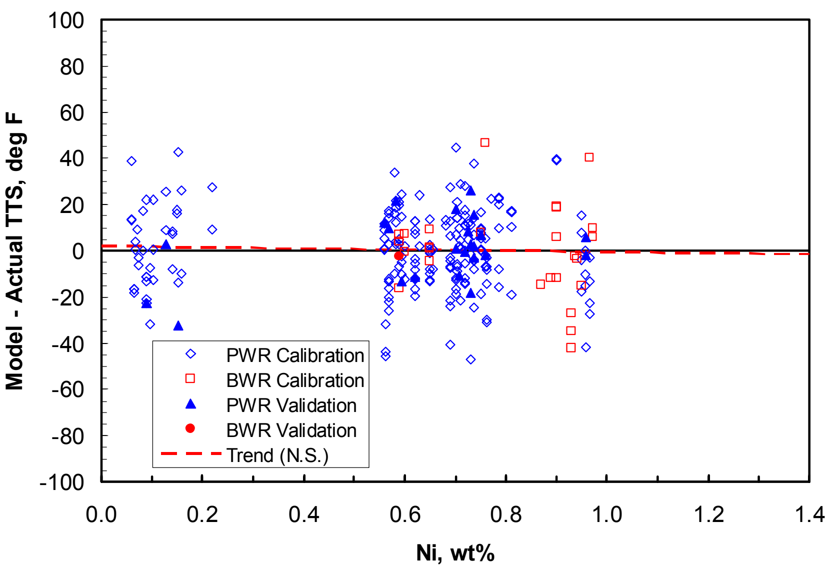
Fit is Comparable on Calibration & Validation Sets

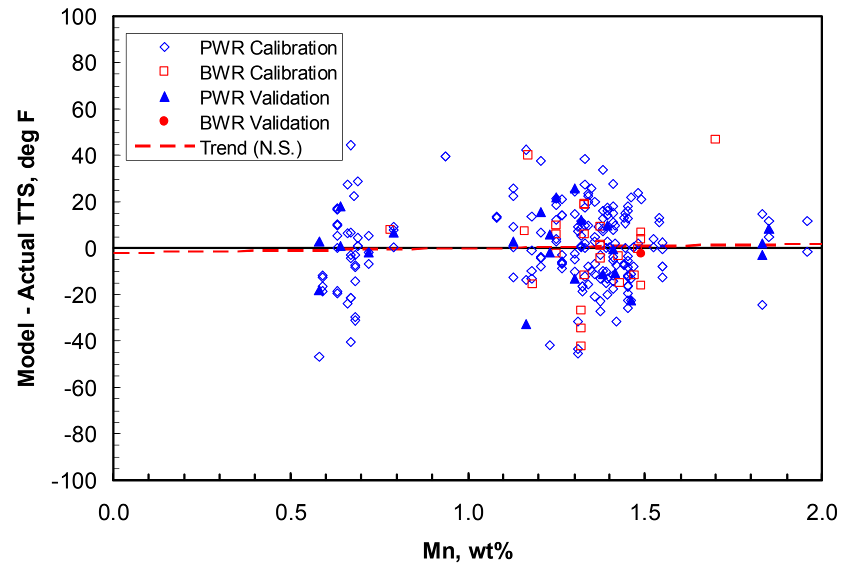
Comparison of Calibration and Validation Subsets by Mean and Standard Deviation (Sd) of Residuals. Number of points shown for subsets smaller than 40 points.

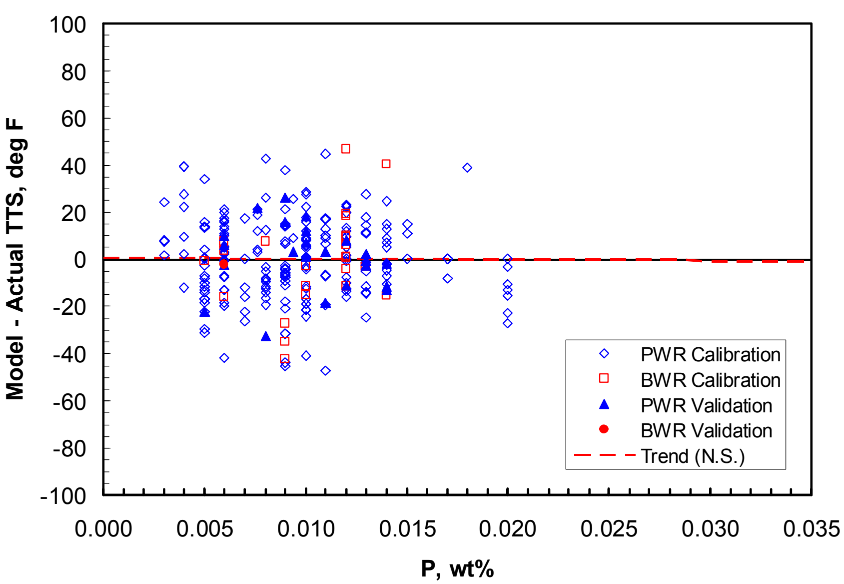
Subset	Calibration Mean	Validation Mean	Calibration Sd	Validation Sd
Cu ≤ 0.072, ϕ > 4.39E10	0.0	0.9 (N.S.) (22 points)	17.0	14.6 (N.S.) (22 points)
Cu ≤ 0.072, ϕ ≤ 4.39E10	1.7	-2.1 (N.S.) (2 points)	19.5	0.2 (2 points)
Cu > 0.072, ϕ > 4.39E10	0.5	1.4 (N.S.)	23.1	22.7 (N.S.)
Cu > 0.072, ϕ ≤ 4.39E10	0.6	-7.9 (N.S.) (15 points)	21.2	26.7 (N.S.) (15 points)

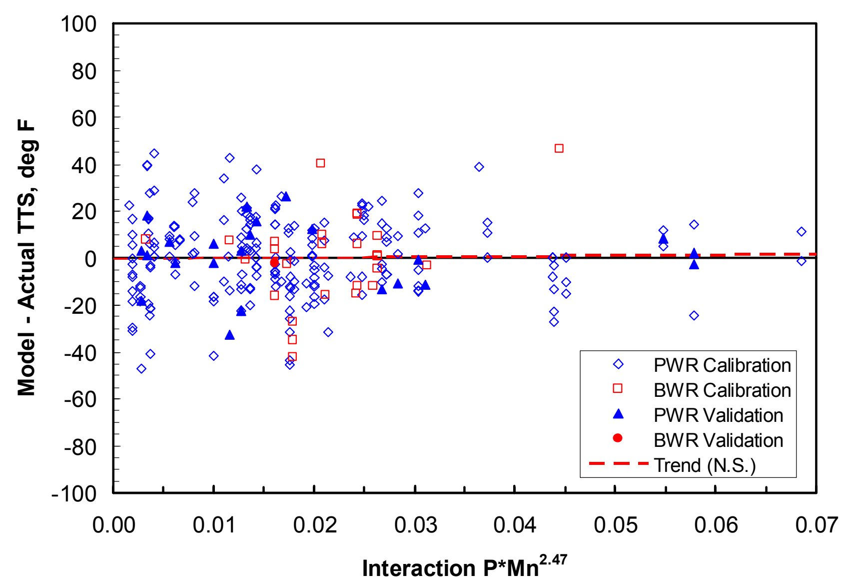
Note: N.S. means the difference from the calibration value is not statistically significant.

Residual Plots, Chemistry Variables, Cu ≤ 0.072 wt%

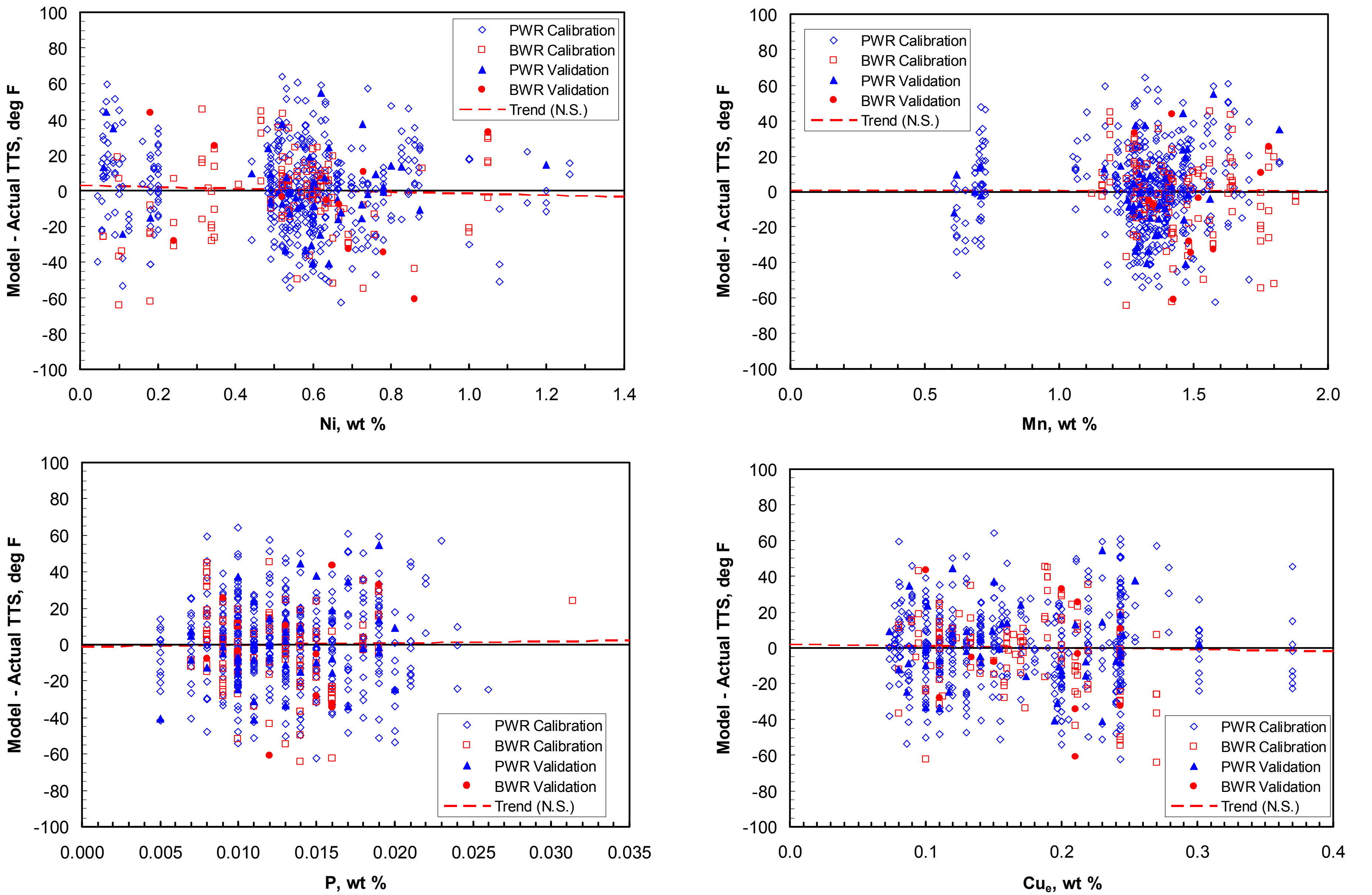




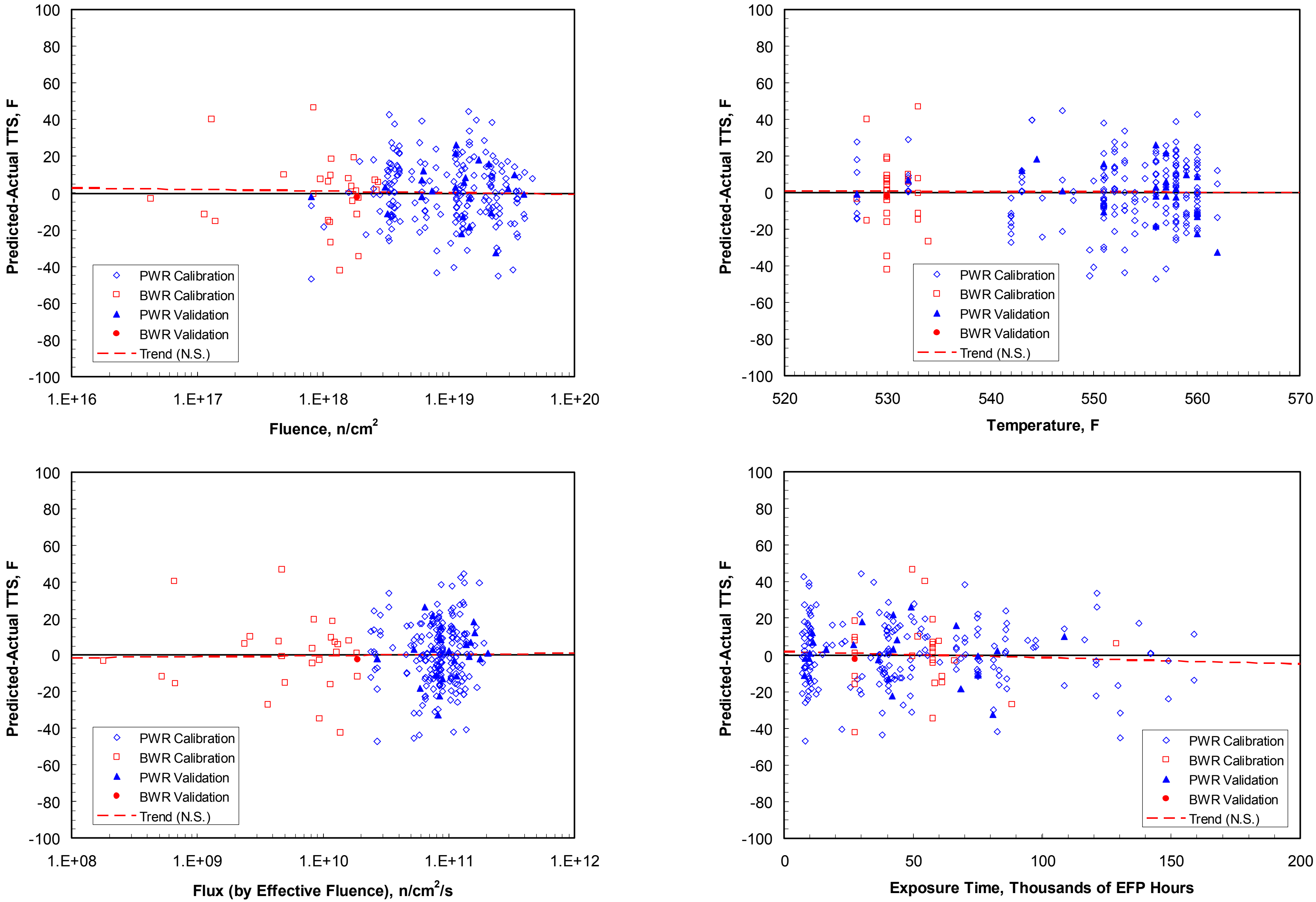




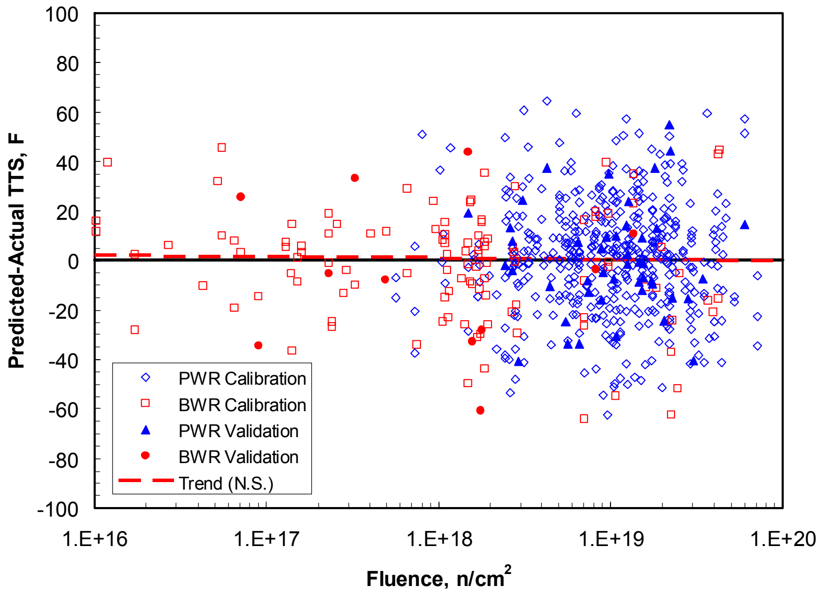
Residual Plots, Chemistry Variables, Cu > 0.072 wt%

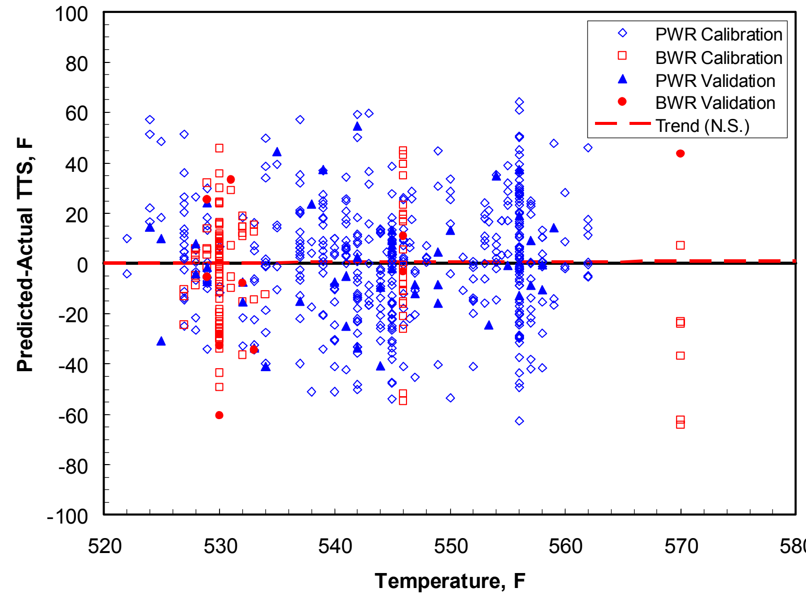


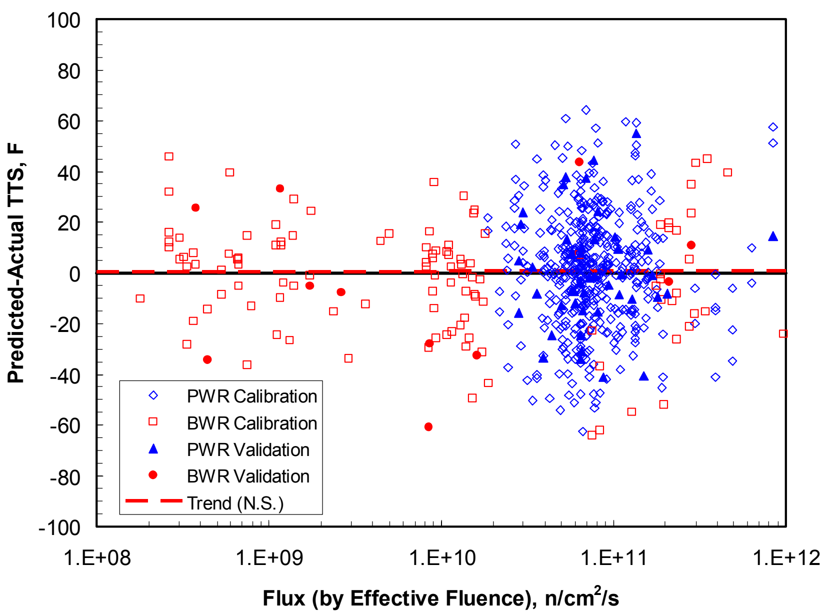
Residual Plots, Exposure Variables, Cu ≤ 0.072 wt%

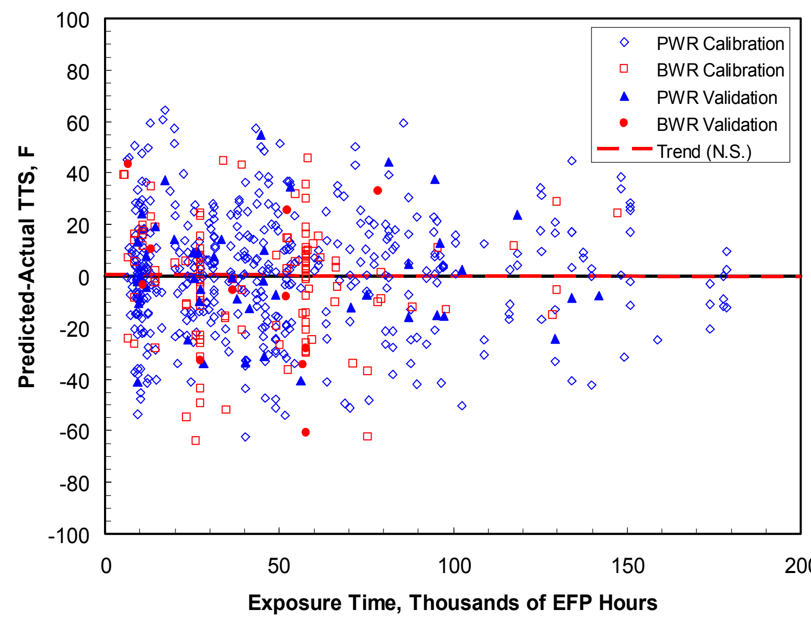


Residual Plots, Exposure Variables, Cu > 0.072 wt%









Conclusions

- The 1/06 revised shift model is a major update of prior models, reflecting
  - Larger, better balanced, higher quality database
  - Improved form based on recent physical insights
  - Modeling procedure based on lessons learned in prior modeling
- The result is a physically-motivated empirical model that has no significant residual trends in the major database subsets
- The predictive capability of the model has been validated on a random sample of data not used for calibrating most model constants