A Wide-Range Embrittlement Trend Curve for Western RPV Steels

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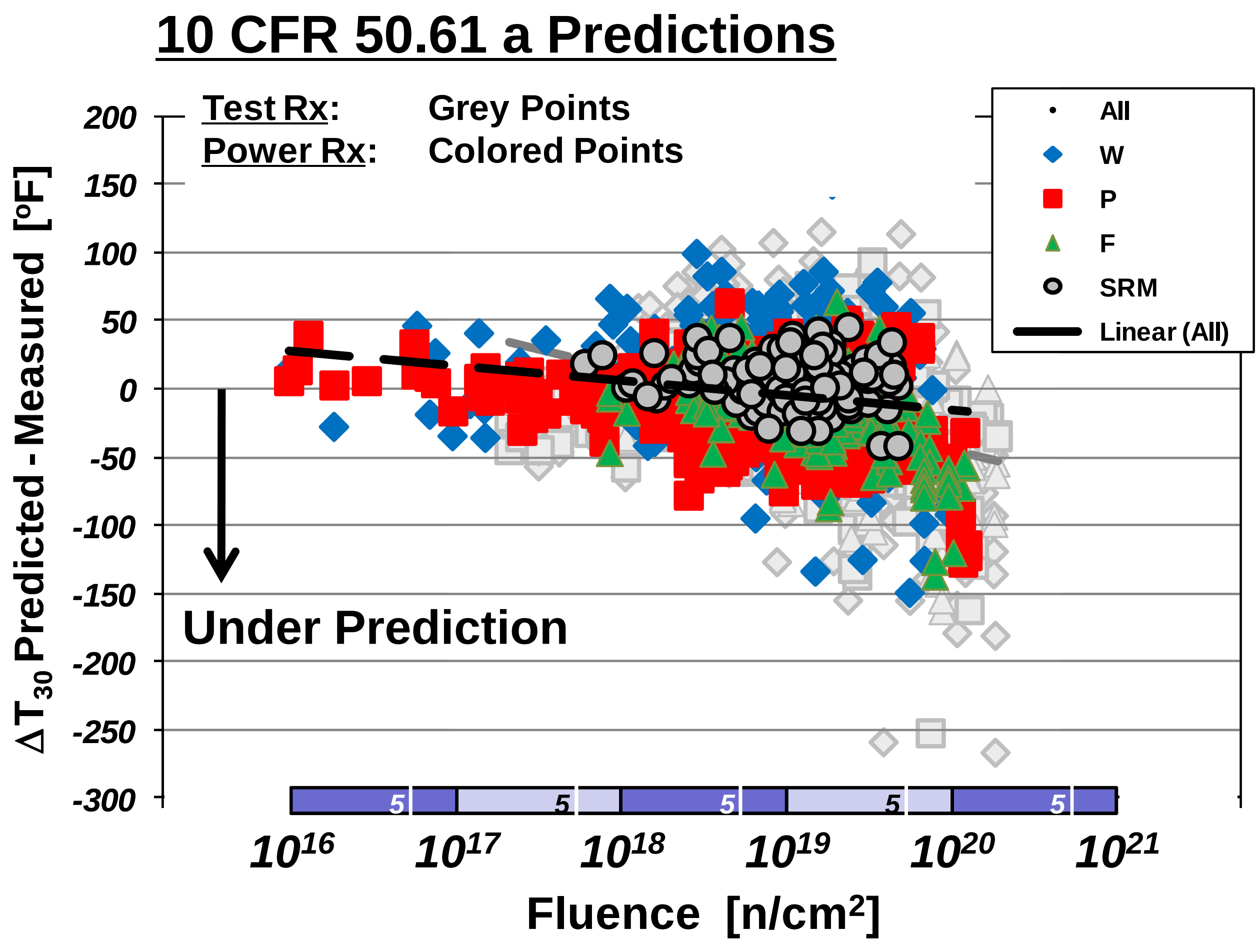
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Motivation

- Existing trend curves
  - RG 1.99 Rev. 2
  - 10 CFR 50.61a

  represent well data used in fitting, but
- do not extrapolate well
  - High fluence
  - Low Cu



Observations

- Most trend curves intended for practical use are, in the end, calibrated to data (claims regarding their "physical basis" notwithstanding)
- Regarding equations fit to data trends
  - Interpolation within the range of fit variables works well
  - Extrapolation outside of this range produces issues
- Therefore, this study expands the empirical dataset used for calibration … to expand the variable range over which interpolation occurs

Outline

- Fitting database
- Fitting process
- Final model
- Assessment of predictability of different data sub-sets
- Conclusion

Fitting Database

- **Traditional data source** (in the USA)
  - US data ***only***
  - Power reactor surveillance data ***only***
  - ΔT_{30} data ***only***
- Considerable data currently exists from **non-traditional sources**
  - Test reactors
  - Non-US reactors overseas
  - Other embrittlement metrics (e.g., ΔYS)
- These greatly expand the fit variable range into areas where traditional data is lacking
  - High fluence
  - Low copper

Fitting Database

- **Traditional data source** (in the USA)
  - US data ***only***
  - Power reactor surveillance data ***only***
  - ΔT_{30} data ***only***

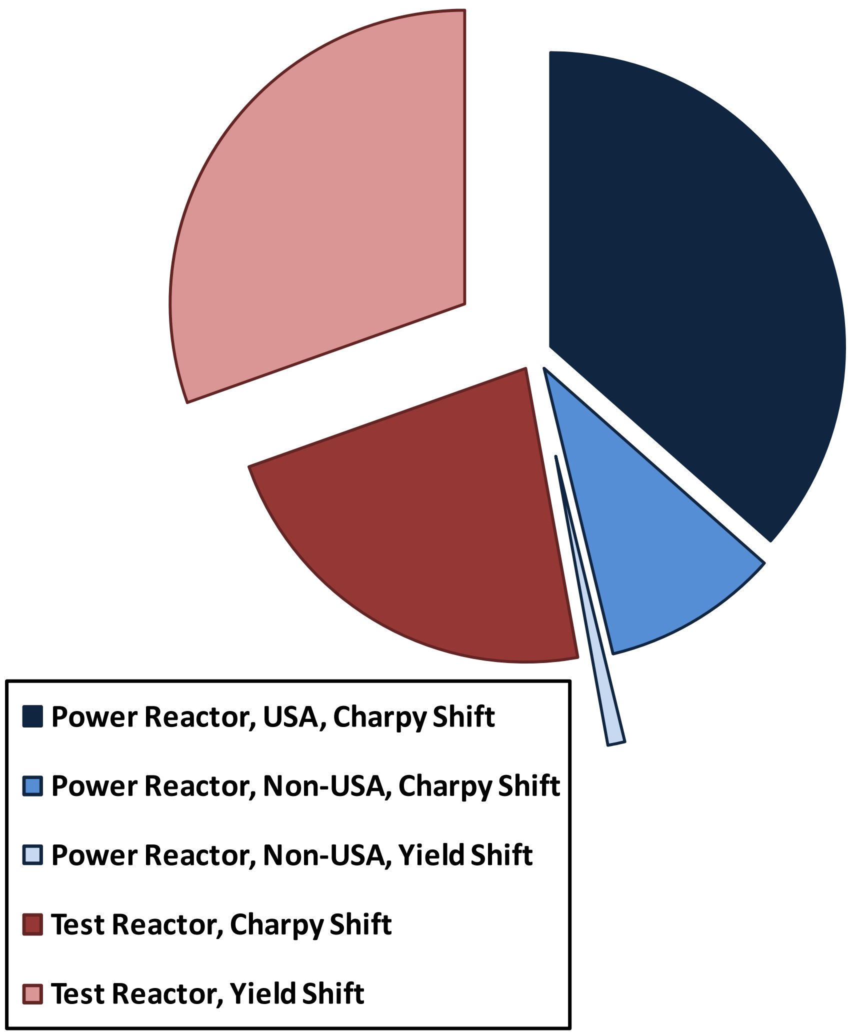
- Currently there is no consensus on how to use together **traditional** and **non-traditional** data, however
- We examine them together here to estimate embrittlement trends in advance of any new testing program

- Considerable data currently exists from **non-traditional sources**
  - Test reactors
  - Non-US reactors overseas
  - Other embrittlement metrics (e.g., ΔYS)
- These greatly expand the fit variable range into areas where traditional data is lacking
  - High fluence
  - Low copper

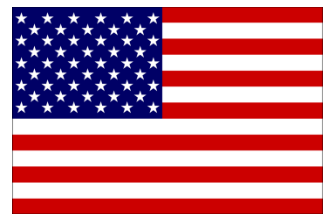
Fitting Database

All Data

> 2500 Shift Values



Power Reactor Data



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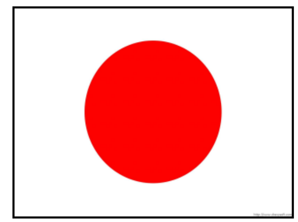

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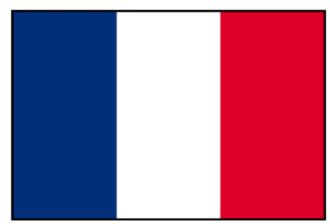
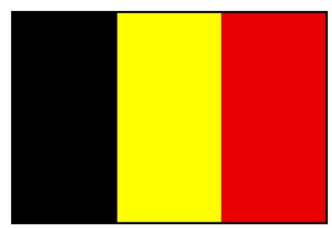
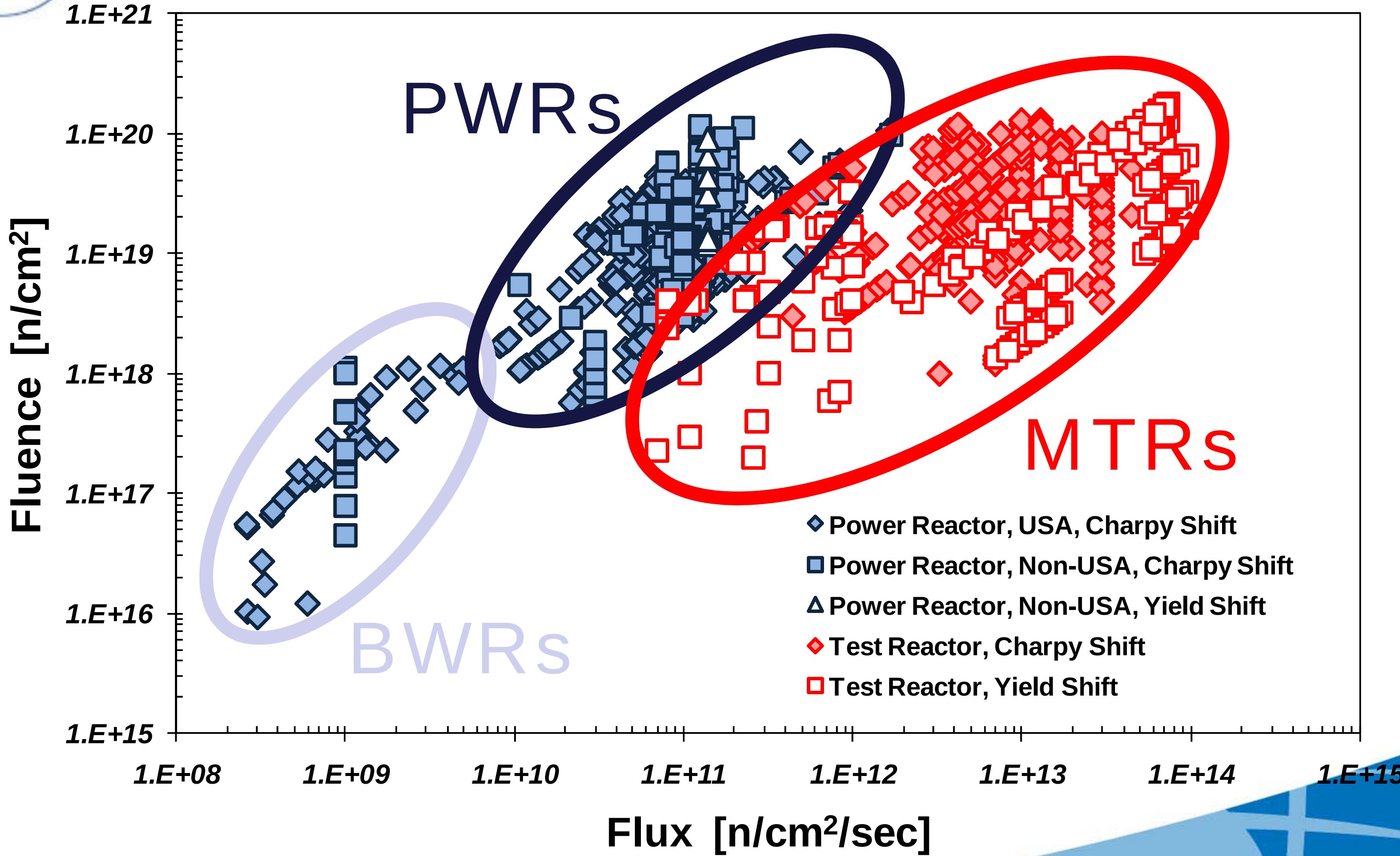


≈ 100

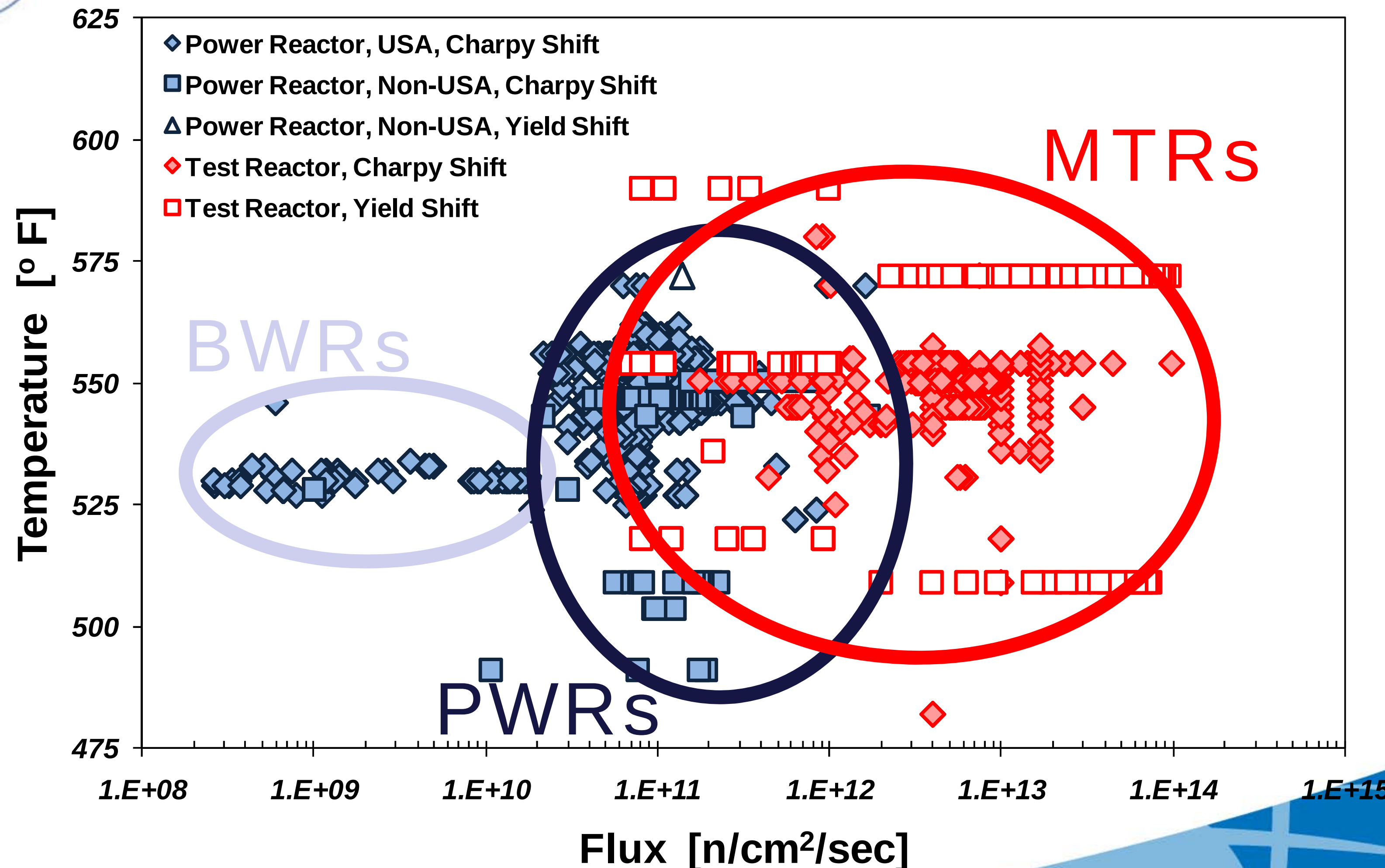


≈ 50

Fitting Database



Fitting Database

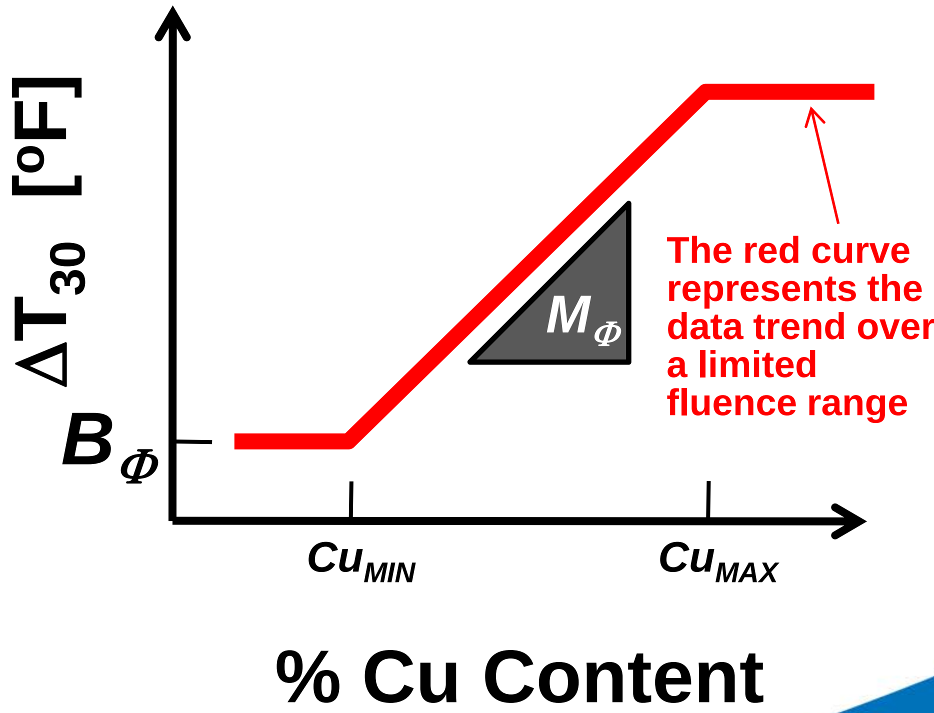


Fitting Process

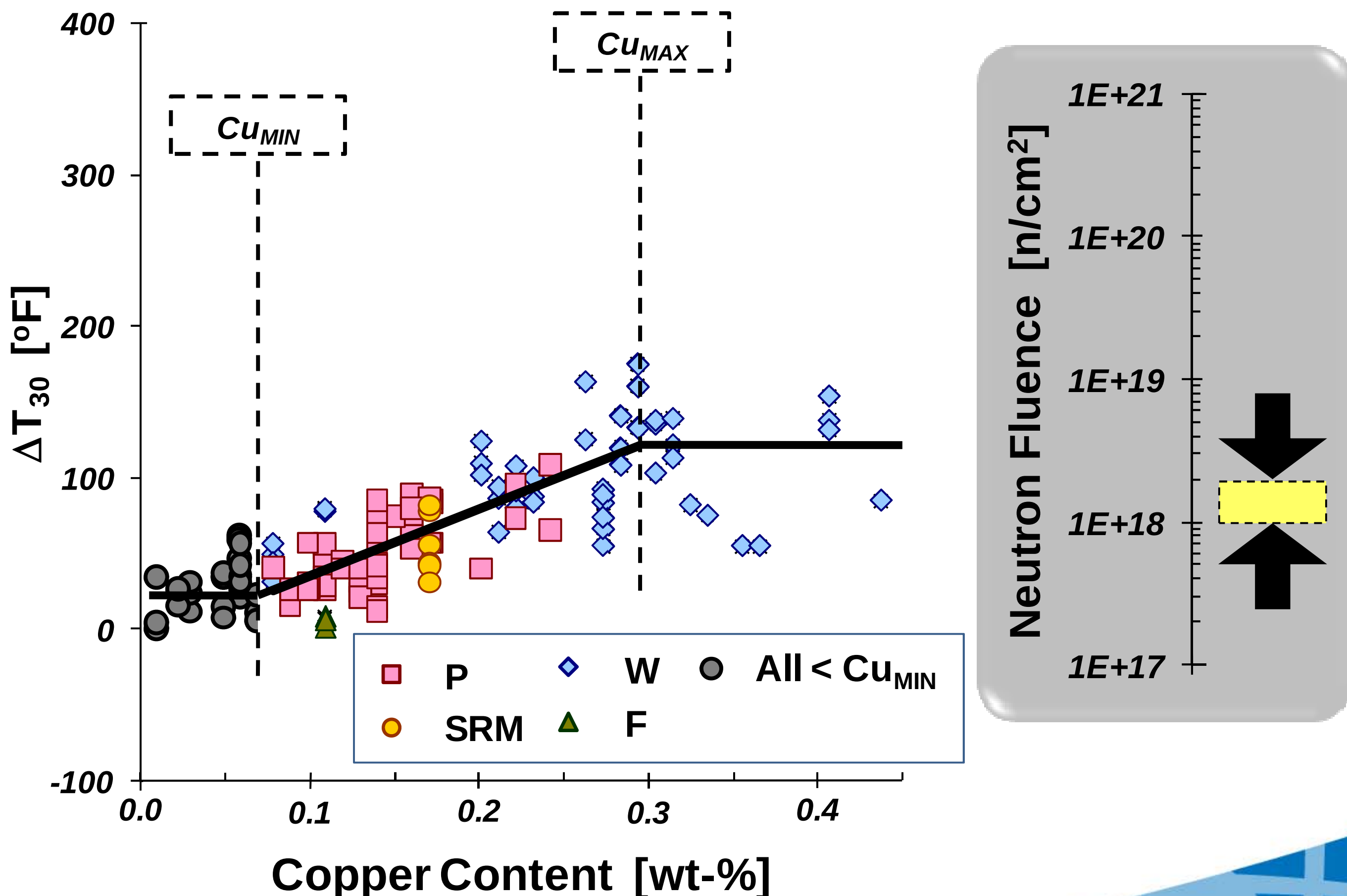
Empirically Motivated

- These trends stand out ***strongly*** in the empirical database

M_{Φ}	**Increases with increasing fluence up to a limit, then saturates**
B_{Φ}	**Characterizes embrittlement below Cu_{MIN}**
	Is independent of Cu
	Increases with increasing fluence, with no apparent limit
Cu_{MAX}	**Above this value, embrittlement does not increase with increasing Cu**

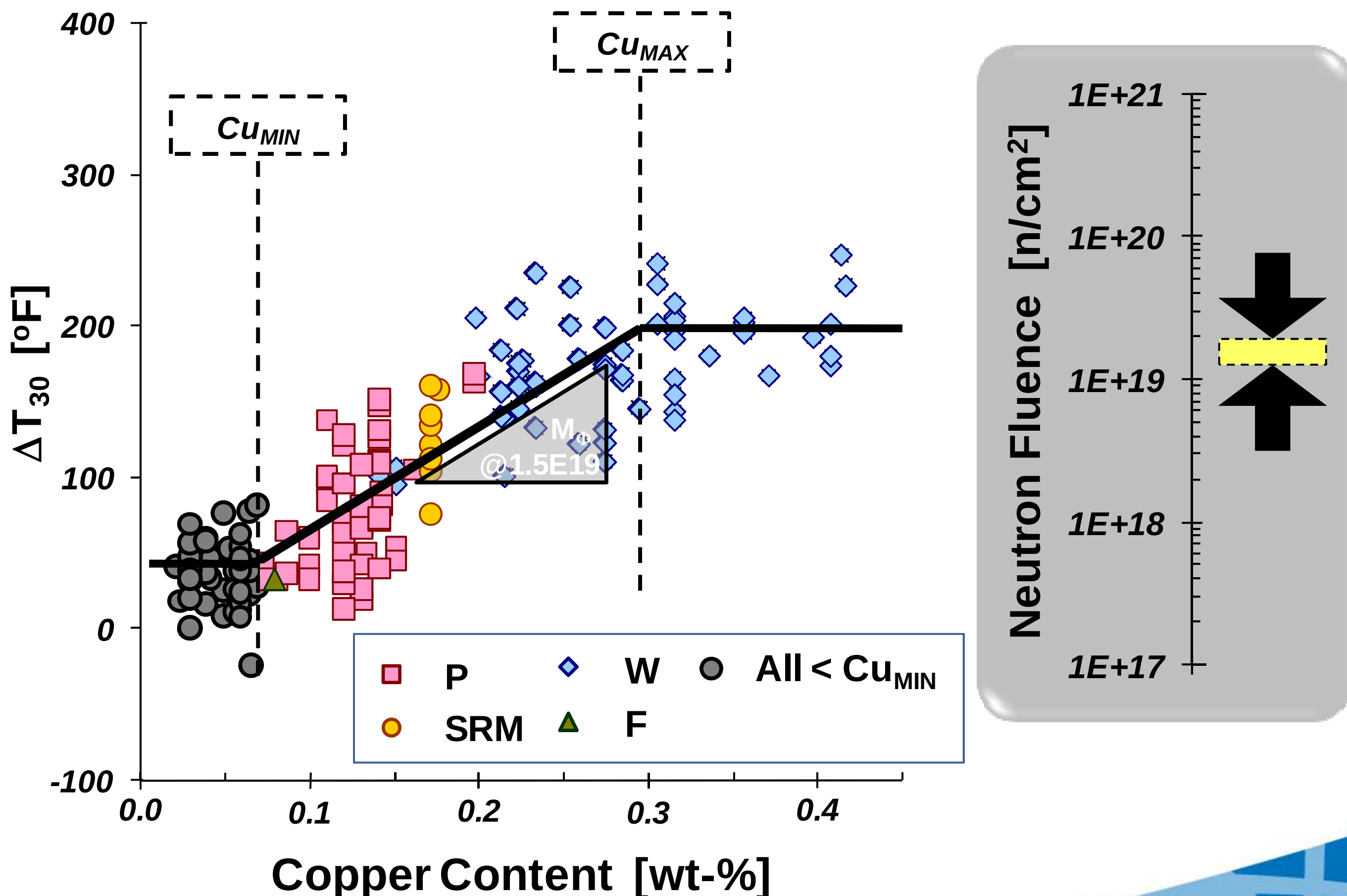


Fitting Process
Φ = 1 to 2×10^{18} n/cm^2



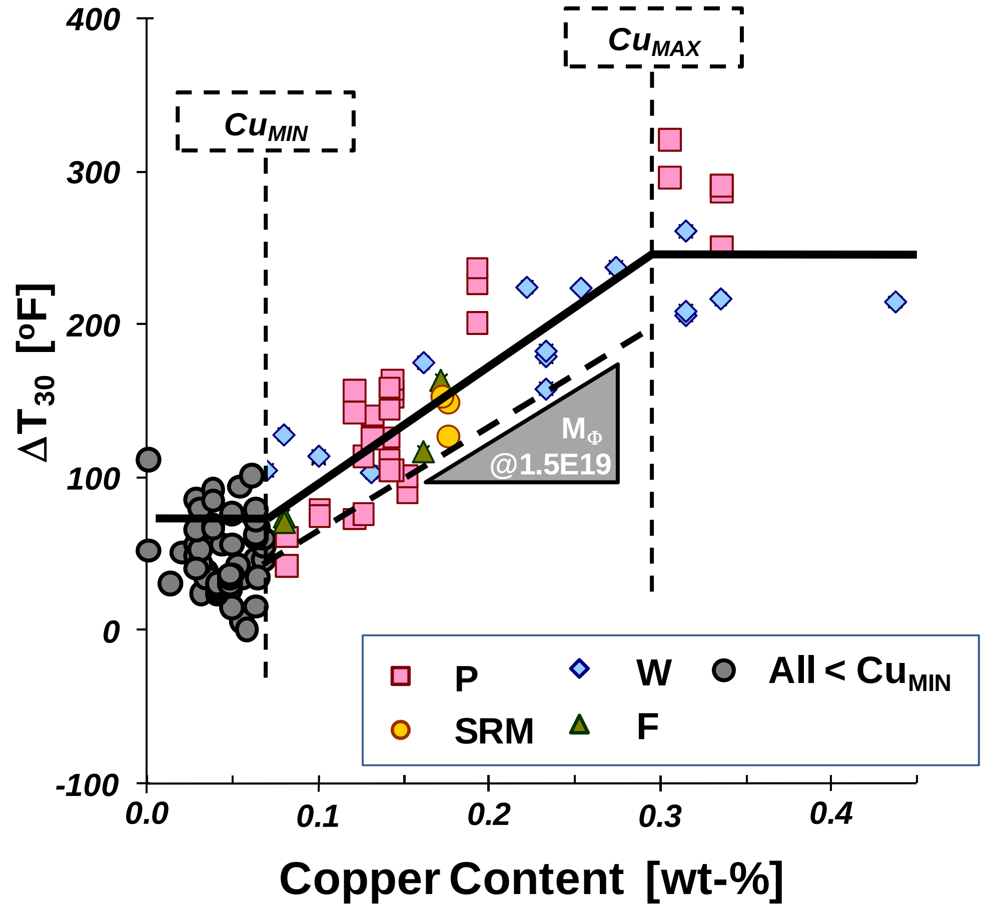
Fitting Process

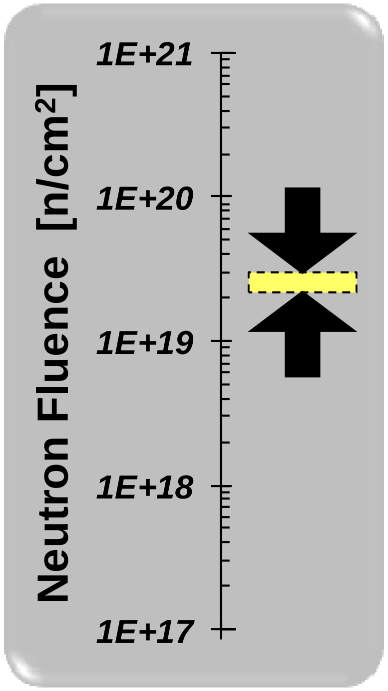
Φ = 1.3 to 1.7x10^{19} n/cm^2



Fitting Process

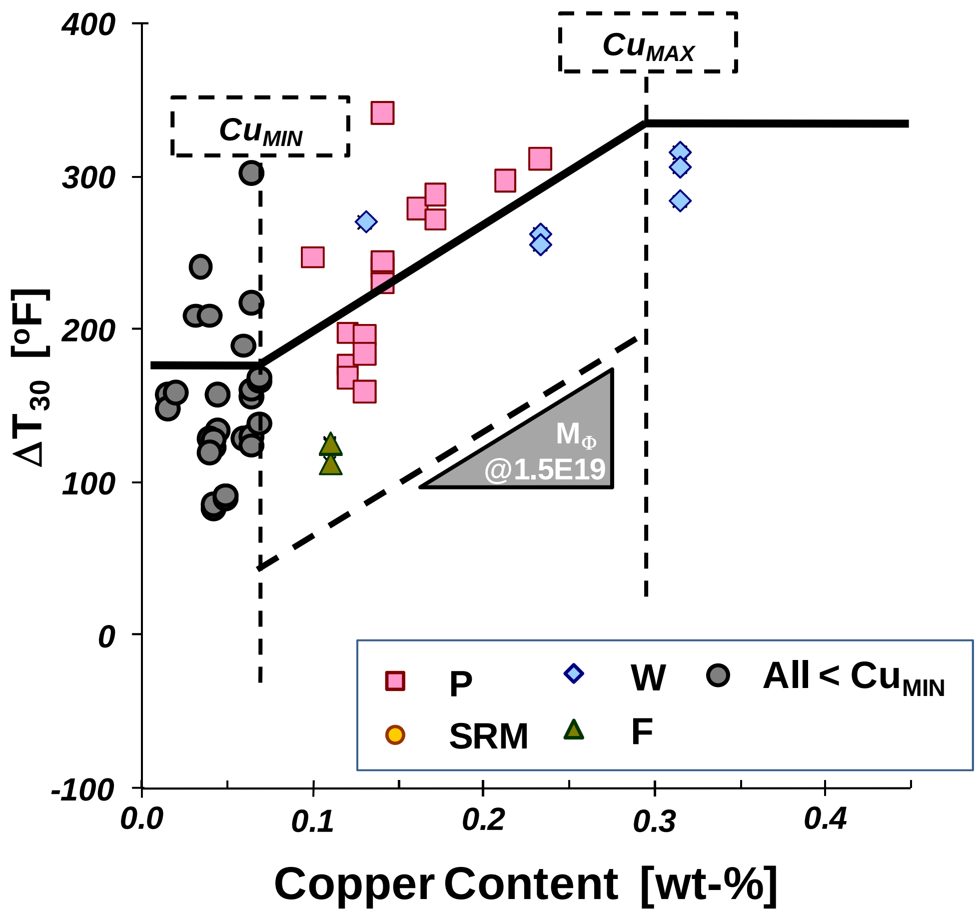
Φ = 2.2 to 2.6x10^{19} n/cm^2

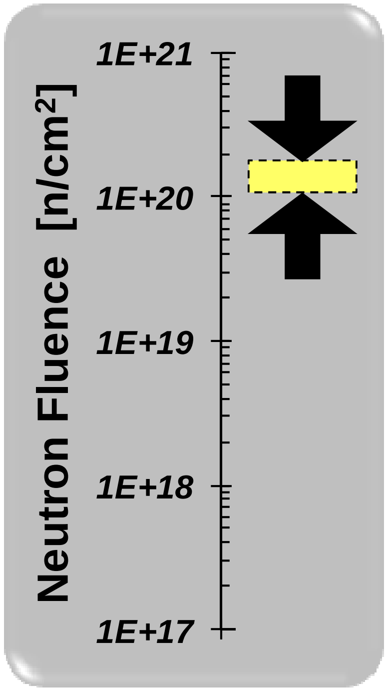




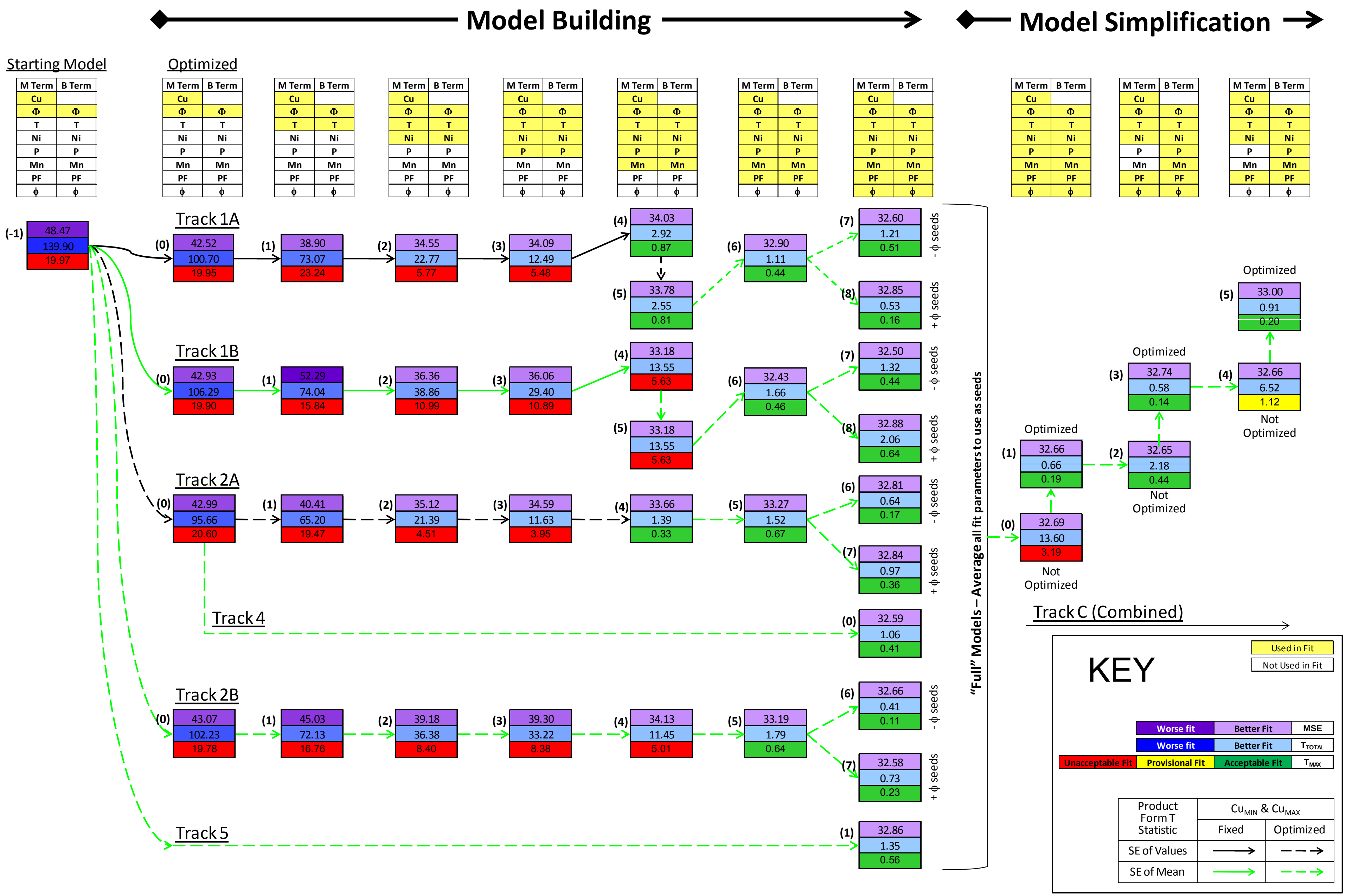
Fitting Process

Φ = 1 to 1.8×10^{20} n/cm^2





Fitting Process



Final Model

WR-C(5)

$$\Delta T_{30} = MAX\begin{Bmatrix} MIN(Cu, 0.35) - 0.05 \\ - \\ 0 \end{Bmatrix} \times M + B$$

$$M = \begin{bmatrix} M_W = 0.93 \\ M_P = 0.96 \\ M_F = 0.68 \end{bmatrix} MAX\langle MIN\{[ln(\Phi) - ln(1.67 \times 10^{17})] \cdot 171.3, 733.5\}, 0\rangle \left[\frac{T}{550}\right]^{-3.84} \cdot \left[\frac{(Ni)^{1.155}}{0.63}\right]^{0.28}$$

$$B = \begin{bmatrix} B_W = 1.12 \\ B_P = 1.056 \\ B_F = 0.925 \end{bmatrix} \cdot \{9.78 \times 10^{-10} \cdot \Phi^{0.5564}\} \cdot \left[\frac{T}{550}\right]^{-4.74} \cdot \left[\frac{P}{0.012}\right]^{0.24} \cdot \left[\frac{(Ni)^{0.865}}{0.63}\right]^{0.48} \cdot \left[\frac{Mn}{1.36}\right]^{0.15}$$

$$\sigma = 0.073\Phi^{0.138}$$

Copper dependent term

- ✓ **Operates over restricted range of Cu**
- ✓ **Saturates at 1.2×10^{19} n/cm^2**
- ✓ **Depends also on Ni, temperature, product form**
- ✓ **Does not depend on flux**

Final Model

WR-C(5)

$$\Delta T_{30} = MAX\begin{Bmatrix} MIN(Cu, 0.35) - 0.05 \\ - \\ 0 \end{Bmatrix} \times M \boxed{+\, B}$$

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Copper in-dependent term

- ✓ **No fluence saturation, roughly $\sqrt{\Phi}$ dependence**
- ✓ **Depends also on Ni, temperature, P, Mn, product form**
- ✓ **Does not depends on flux**

Final Model

WR-C(5)

$$\Delta T_{30} = MAX\begin{Bmatrix} MIN(Cu, 0.35) - 0.05 \\ - \\ 0 \end{Bmatrix} \times M + B$$

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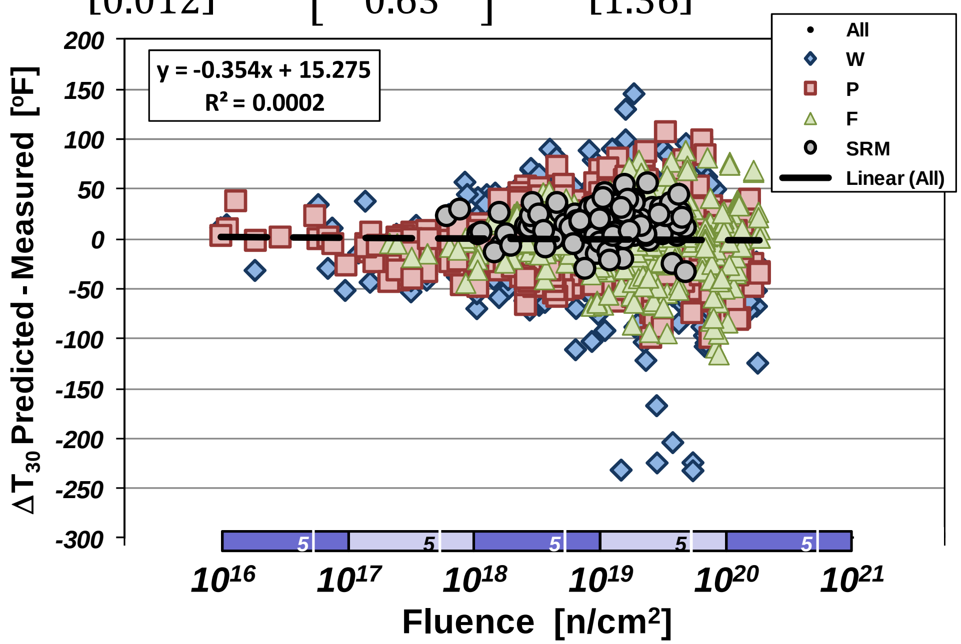
$$\boxed{\sigma = 0.073\Phi^{0.138}}$$

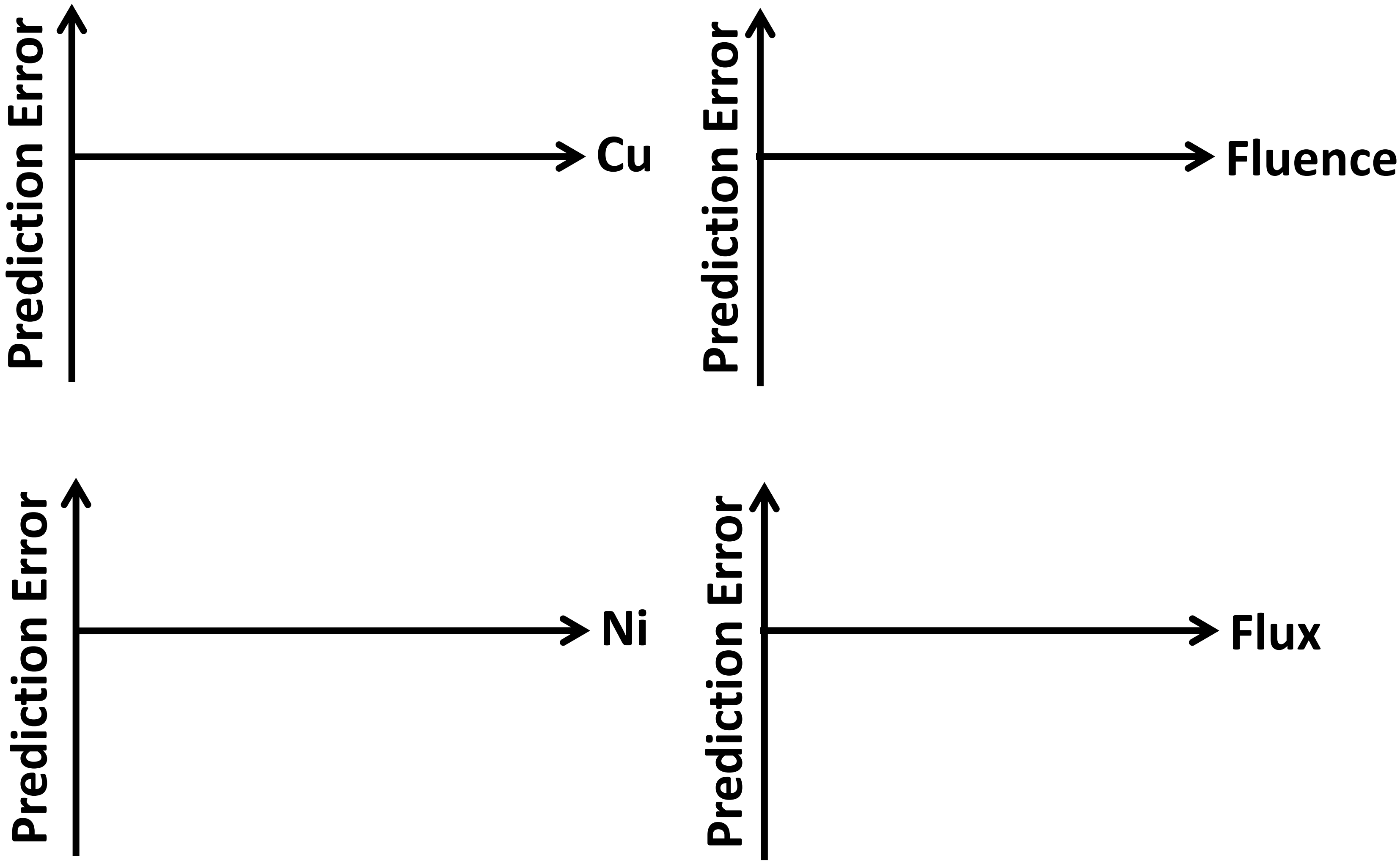
Uncertainty / scatter

- ✓ **Increases with fluence**



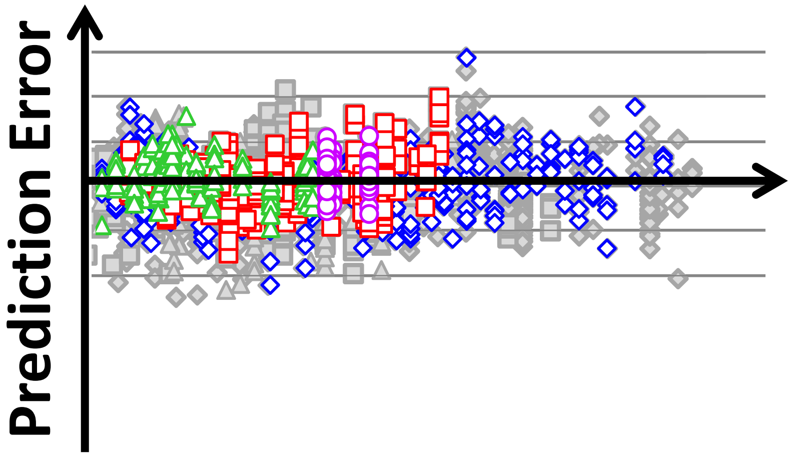
Accuracy for Data Subsets

Subset Name



Accuracy for Data Subsets

Subset Name



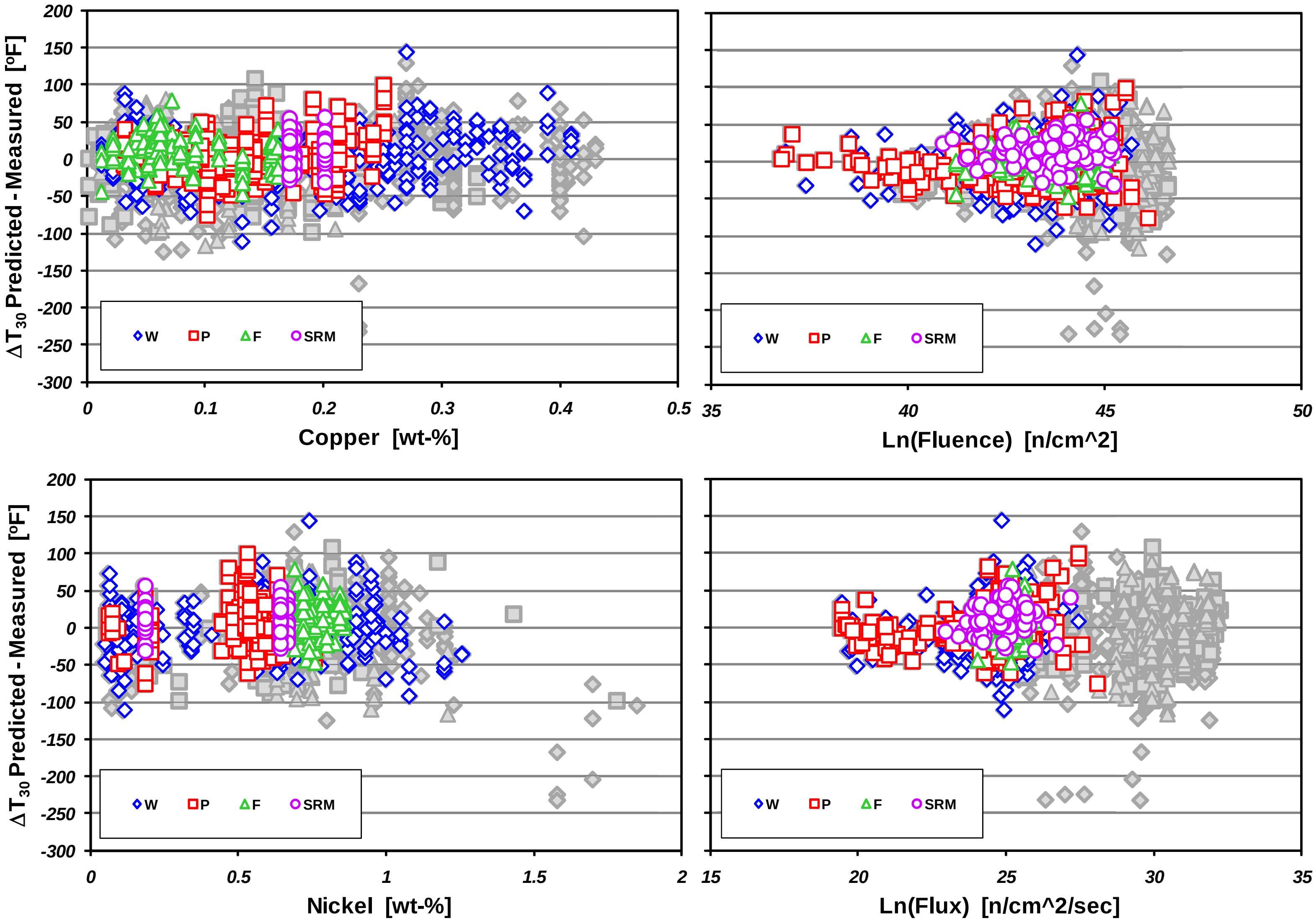
- Subsets assessed
  - USLWR surveillance data
  - Non-US surveillance data
  - Test reactor – ΔT_{30} data
  - Test reactor – ΔYS data

- Color Key
  - Bright points – stated subset
  - Grey points – all data

- Accuracy indicated by
  - Bright points uniformly distributed within overall scatter
  - No residual trends shown by bright points

Accuracy for Data Subsets

USLWR Surveillance Data



Accuracy for Data Subsets

Non-US Surveillance Data

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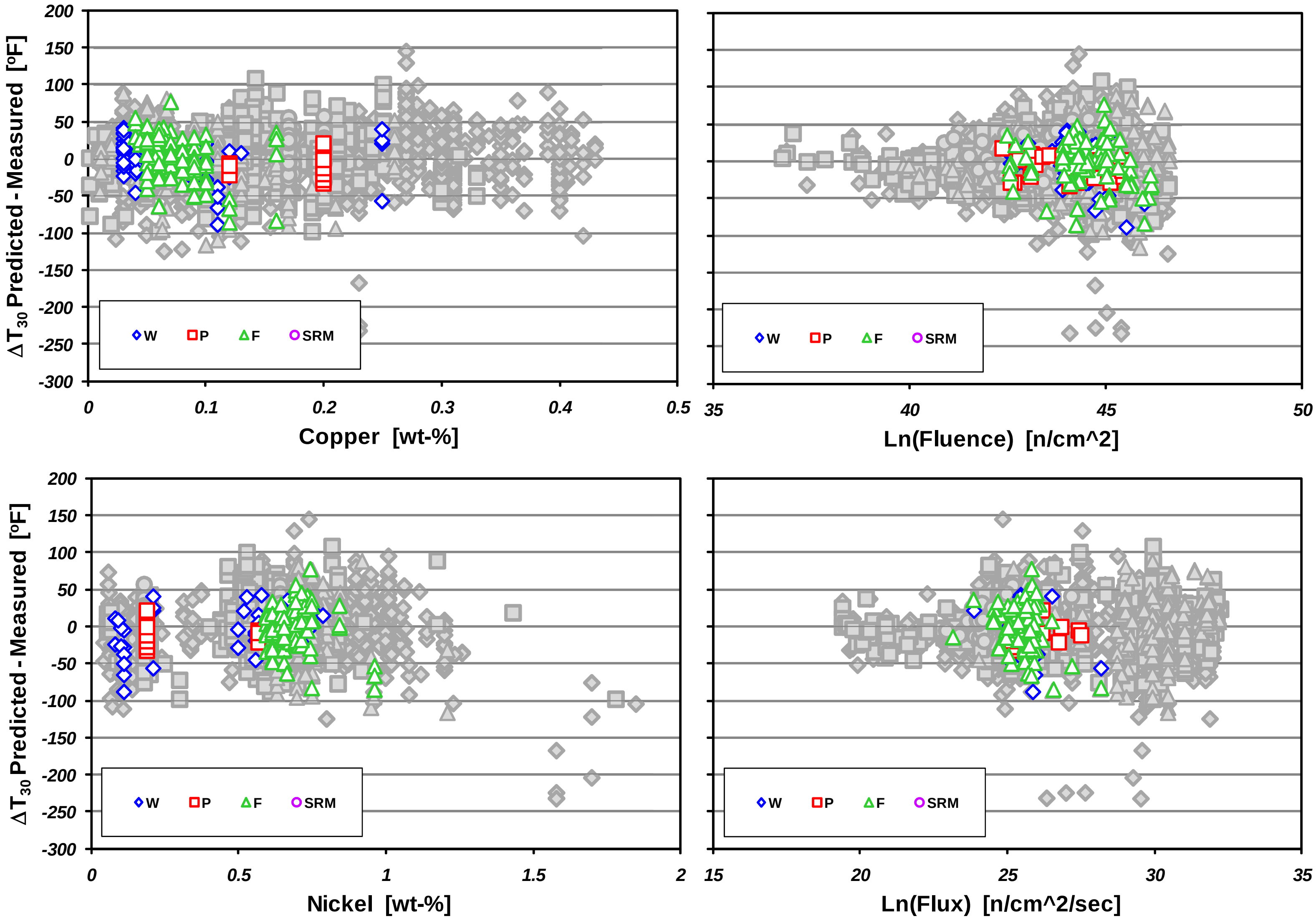
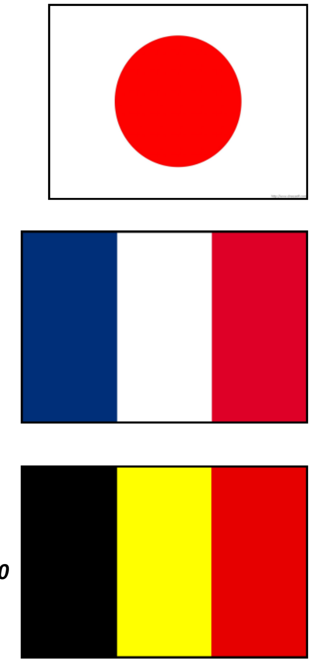
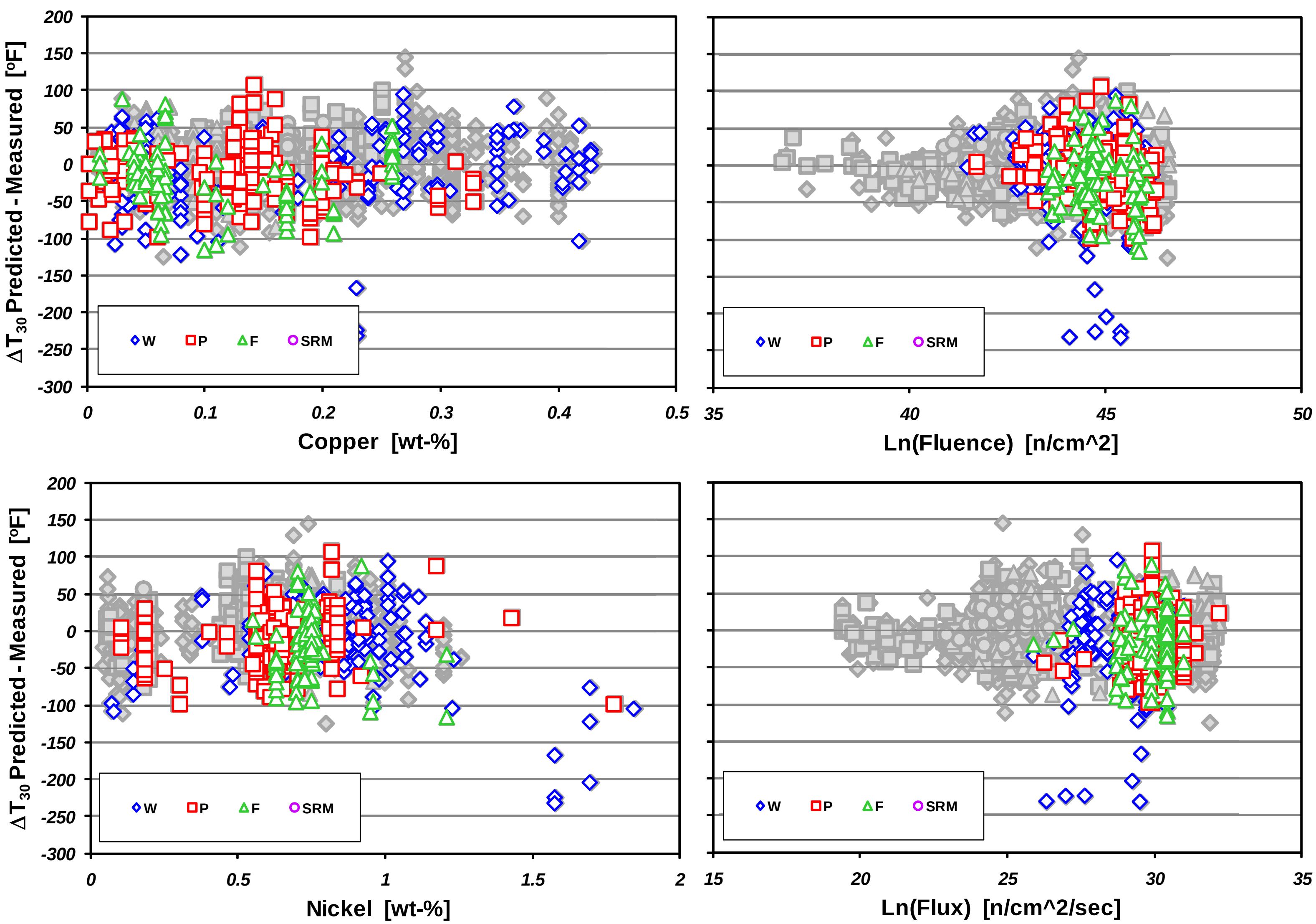




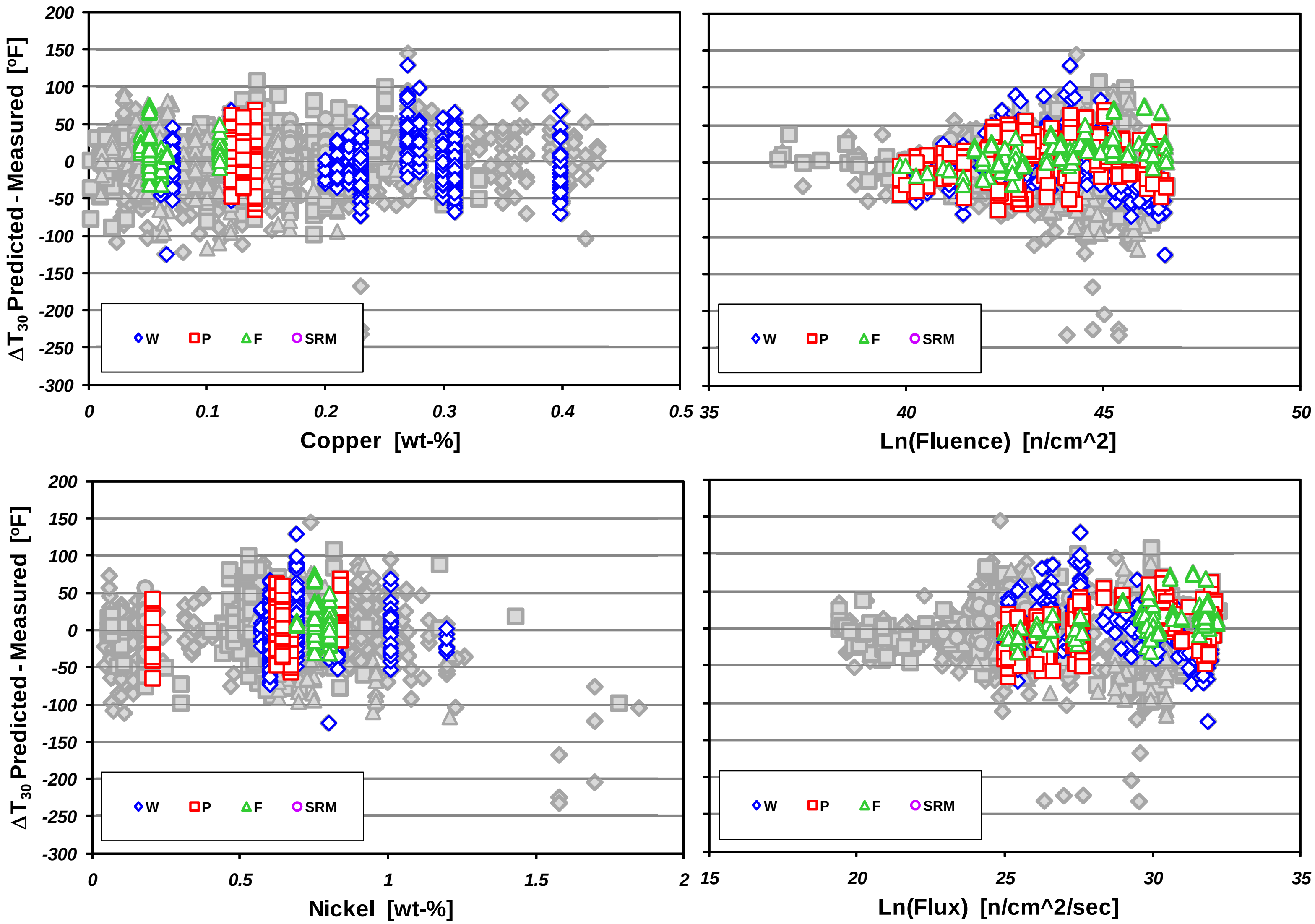
Accuracy for Data Subsets

Test Reactor – ΔT_{30} Data



Accuracy for Data Subsets

Test Reactor – ΔYS Data



Conclusions

- Fit model WR-C(5) developed from a wide range of empirical data
  - Expands variable range in which fit is interpolated
  - Reduces variable range over which fit is extrapolated
- No flux term needed to fit the data
- Fits entire database, and data subsets, well
  - USLWR surveillance data
  - Non-US surveillance data
  - Test reactor data
- Future paper (IAEA meeting, Znojmo, 18-22 October 2010) will demonstrate the enhanced predictive capability of WR-C(5) relative to data not used in fitting