Comparison of Different Embrittlement Trend Curves

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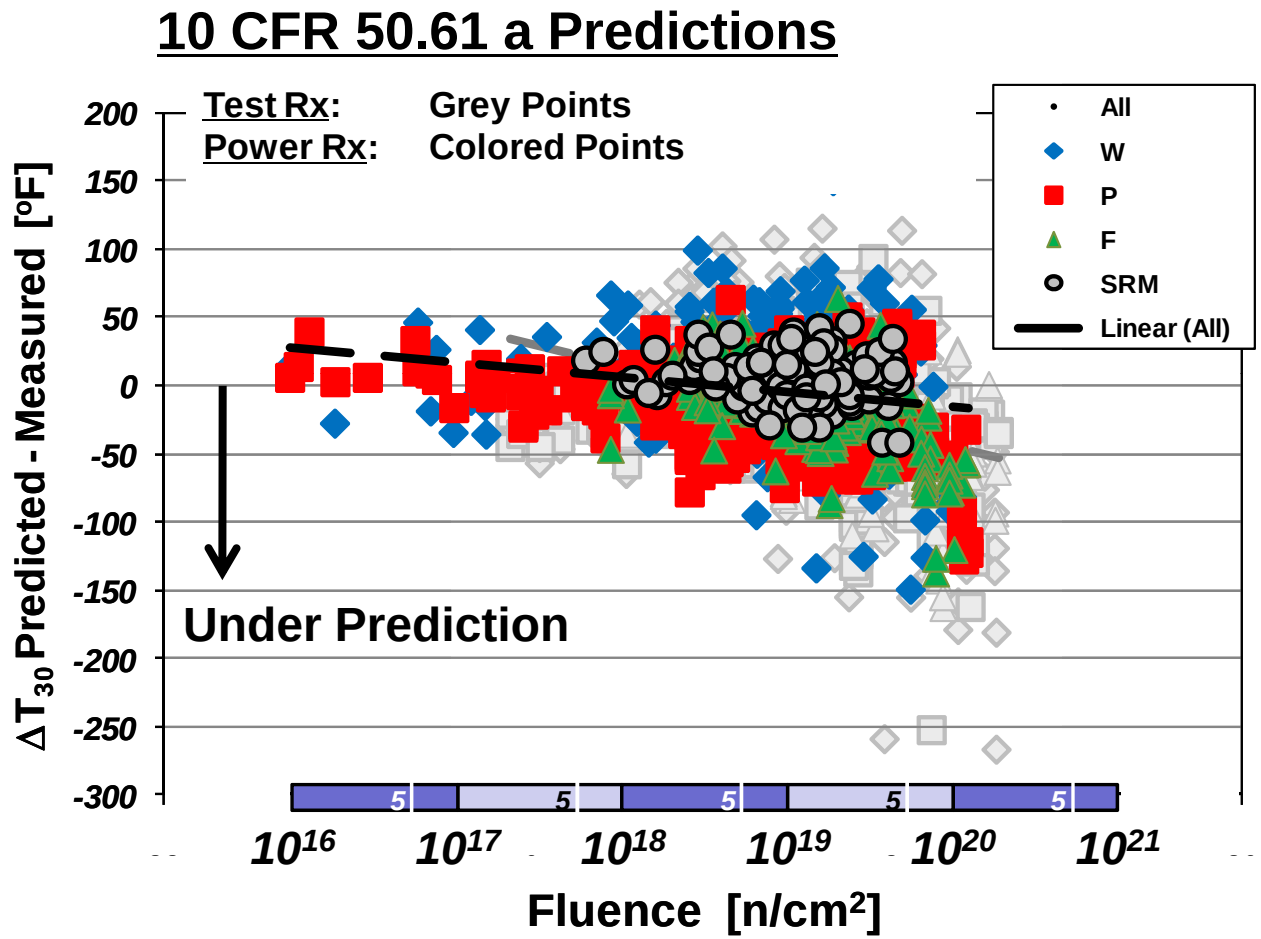
United States Nuclear Regulatory Commission

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



Objective

- Compare trend curves
  - Reg Guide 1.99 Rev 2
  - 10 CFR 50.61(a) (also known as “EONY”)
  - WR-C(5)
- Assess how well they each predict data not used in fitting
- Compare curves to each other

Outline

- Review of trend curve equations
- Databases for assessment of equations
- Assessment of blind predictive capabilities
- Comparison of trend curve predictions to each other
- Conclusions

Reg Guide 1.99 Rev. 2

$$\Delta T_{30} = (CF)\, f^{(0.28 - 0.1 \log f)}$$

- *CF*: Chemistry factor
  - Depends on Cu, Ni, product form
- *f*: Fluence factor
  - Fluence / 10^{19}

- Fit by [Randall 1987] to 177 ΔT_{30} data from power reactor surveillance programs

10 CFR 50.61a (EONY)

$$\Delta T_{30} = MD + CRP$$

$$MD = A\left(1 - 0.001718 \cdot T\right)\left(1 + 6.130 PMn^{2.471}\right)\sqrt{\Phi_e}$$

$$CRP = B\left(1 + 3.769 Ni^{1.191}\right)\left(\frac{T}{543.1}\right)^{1.1} f\left(Cu_e, P\right) g\left(Cu_e, Ni, \Phi_e\right)$$

… terms defined in the paper

- MD: Matrix damage
  - Depends on T, P, Mn, Φ, ϕ, product form
- CRP: Copper-rich precipitates
  - Depends on Cu, Ni, T, P, Mn, Φ, ϕ, product form, vessel manufacturer, weld flux type
- Fit by [Eason 2007] to 936 ΔT_{30} data from power reactor surveillance programs

WR-C(5)

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

- M: Copper dependent term
- B: Copper independent term

- Fit by [Kirk 2010] to 2561 ΔT_{30} and ΔYS data from power reactor surveillance programs (US and non-US), and from test reactor irradiations

WR-C(5)

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

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

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

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

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**

WR-C(5)

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Copper independent term

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

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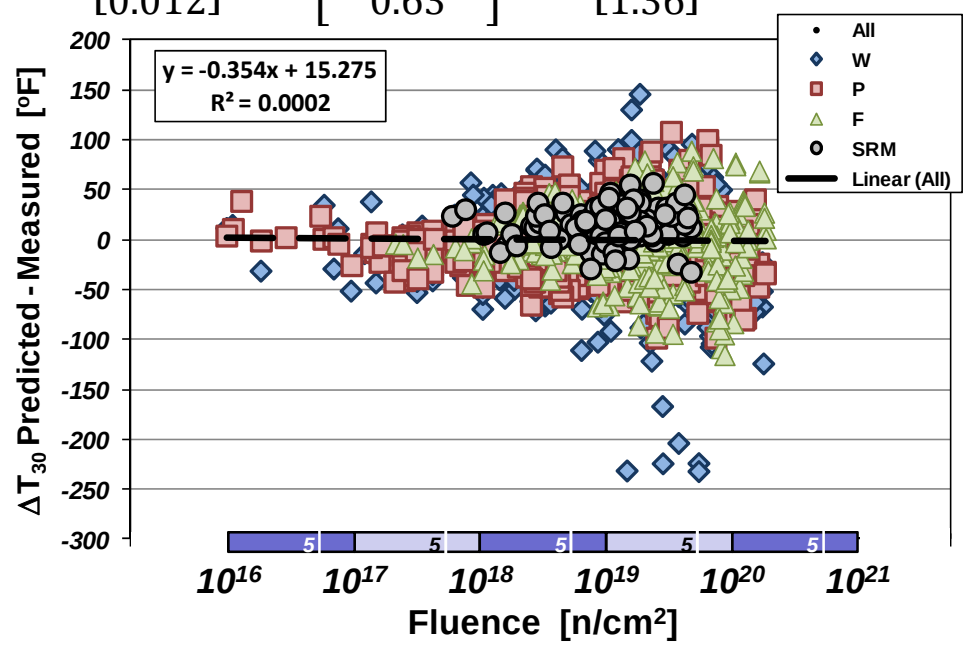
$$\boxed{\sigma = 0.073\Phi^{0.138}}$$

Uncertainty / scatter

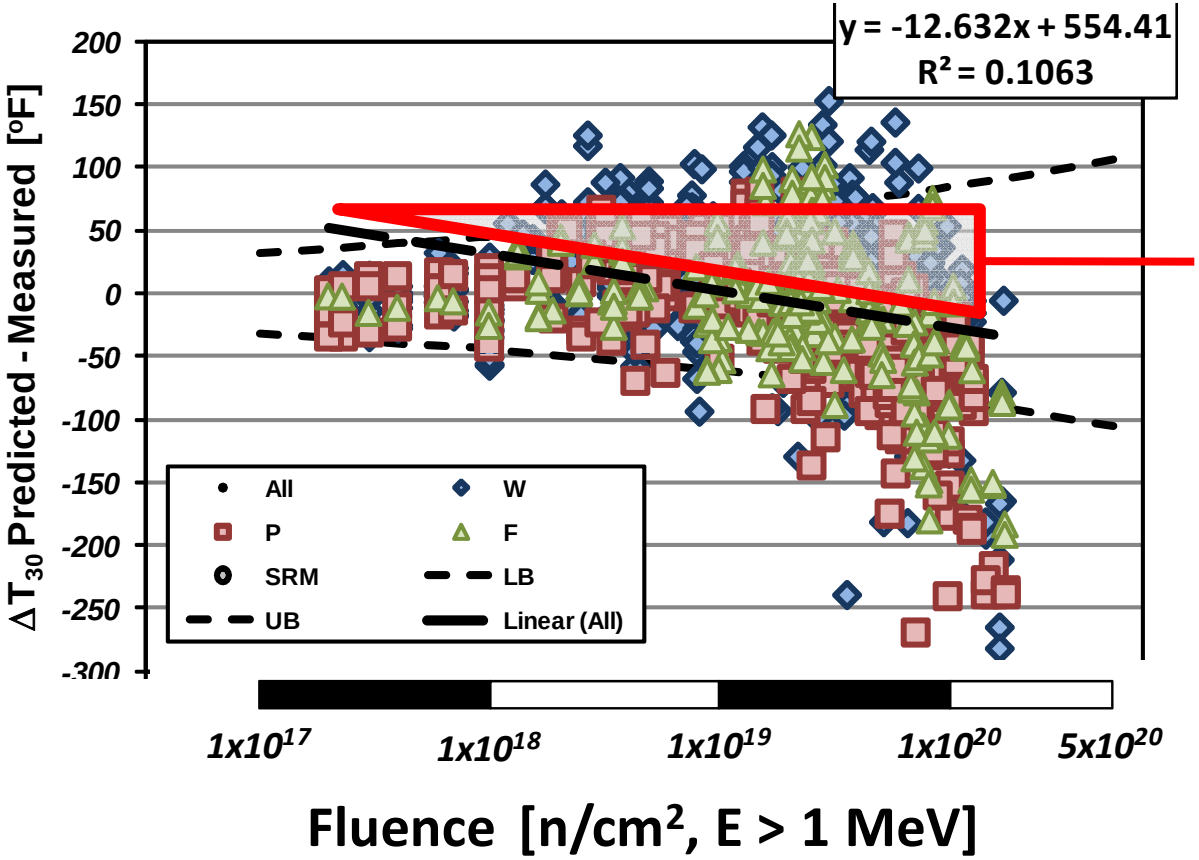
✓ **Increases with fluence**



Data for Blind Assessment of ETC Accuracy

- for WR-C(5)
  - 367 shift values recently reported in literature
    - 240 power reactor, 27 test reactor
- for Reg Guide 1.99 Rev 2 & 10 CFR 50.61a
  - The WR-C(5) assessment set … plus
  - The WR-C(5) fitting data that ***did not*** come from US power reactor surveillance
    - 1992 total
    - 794 power reactor
    - 1198 test reactor

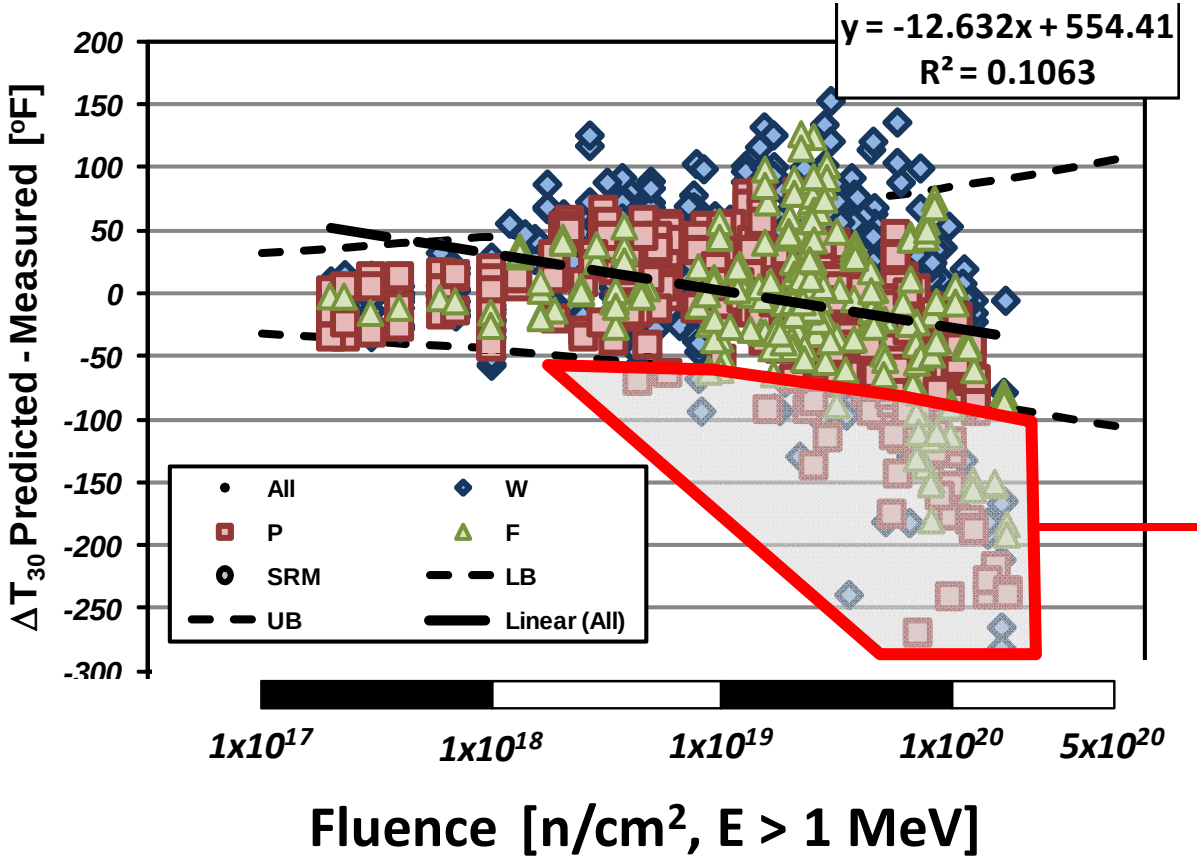
Accuracy Assessment Metrics



Slope of prediction residual vs. fluence

→ Negative slope indicates trend toward under-prediction at high fluences

Accuracy Assessment Metrics



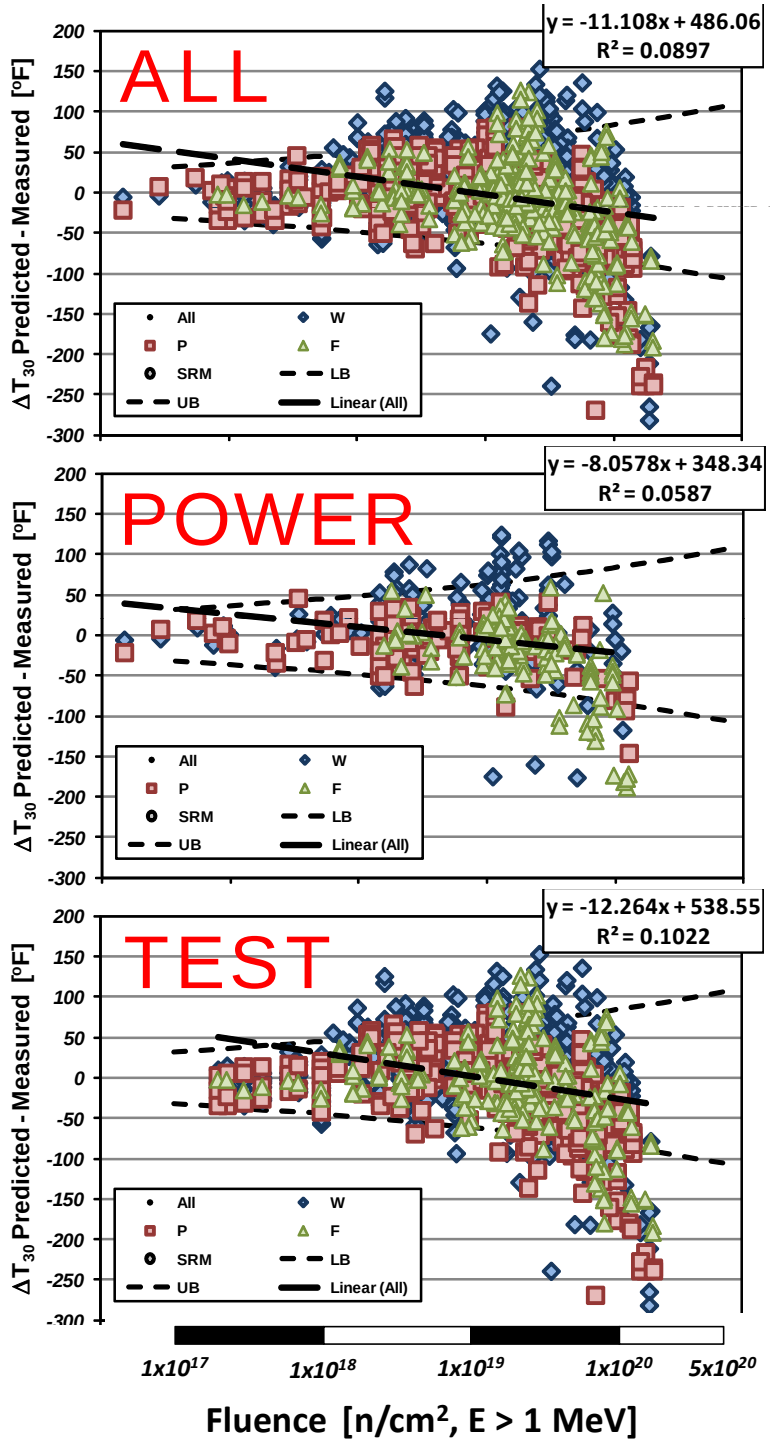
# of Datum below -2σ bound

→ Should be less than 4.6%

Reg Guide 1.99 Rev. 2

Accuracy Assessment

- Tendency to under-predict more as fluence increases
- More than the expected # of values are under-predicted
- Same outcome for both power & test reactor irradiations



ΔT30 Prediction: RG1.99R2

Reactor Type:	Power & Test
Data Plotted:	1625
Count below -2σ:	135
% below -2σ:	8.3%
Expected % below -2σ:	4.6%
Acutal / Expected:	1.8

ΔT30 Prediction: RG1.99R2

Reactor Type:	Power
Data Plotted:	454
Count below -2σ:	31
% below -2σ:	6.8%
Expected % below -2σ:	4.6%
Acutal / Expected:	1.5

ΔT30 Prediction: RG1.99R2

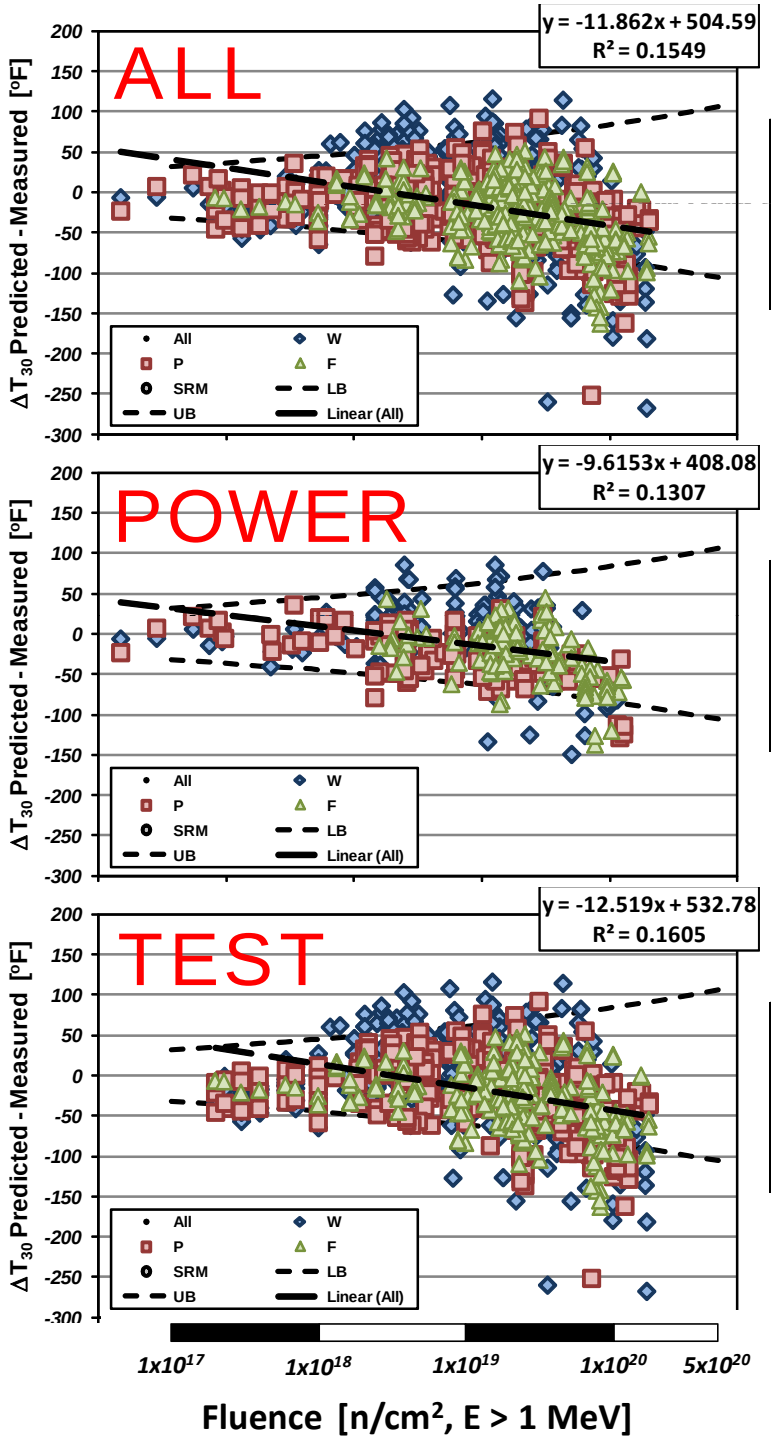
Reactor Type:	Test
Data Plotted:	1171
Count below -2σ:	104
% below -2σ:	8.9%
Expected % below -2σ:	4.6%
Acutal / Expected:	2.0

Dataset: WR-F(31) Calibration data with USLWR surveillance data removed 1625 datum)

10 CFR 50.61a

Accuracy Assessment

- Tendency to under-predict more as fluence increases
- More than the expected # of values are under-predicted
- Same outcome for both power & test reactor irradiations



ΔT30 Prediction: 10CFR50.61a

Reactor Type:	Power&Test
Data Plotted:	1625
Count below -2σ:	163
% below -2σ:	10.0%
Expected % below -2σ:	4.6%
Acutal / Expected:	2.2

ΔT30 Prediction: 10CFR50.61a

Reactor Type:	Power
Data Plotted:	454
Count below -2σ:	29
% below -2σ:	6.4%
Expected % below -2σ:	4.6%
Acutal / Expected:	1.4

ΔT30 Prediction: 10CFR50.61a

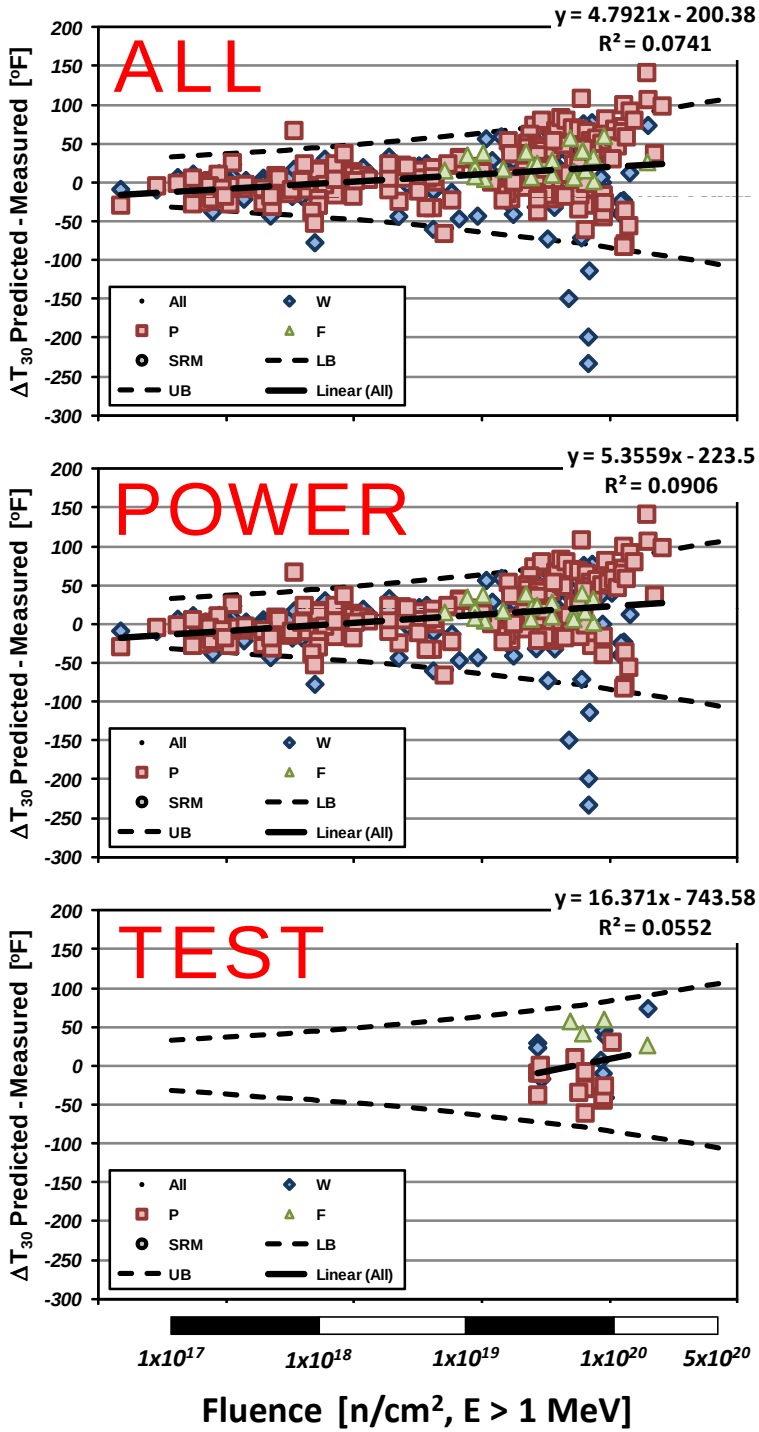
Reactor Type:	Test
Data Plotted:	1171
Count below -2σ:	134
% below -2σ:	11.4%
Expected % below -2σ:	4.6%
Acutal / Expected:	2.5

Dataset: WR-F(31) Calibration data with USLWR surveillance data removed (1625 datum)

WR-C(5)

Accuracy Assessment

- Slight tendency to over-predict as fluence increases
- No more than the expected # of values are under-predicted
- Same outcome for both power & test reactor irradiations



ΔT30 Prediction: WR-F(31)

Reactor Type:	Power&Test
Data Plotted:	367
Count below -2σ:	12
% below -2σ:	3.3%
Expected % below -2σ:	4.6%
Acutal / Expected:	0.7

ΔT30 Prediction: WR-F(31)

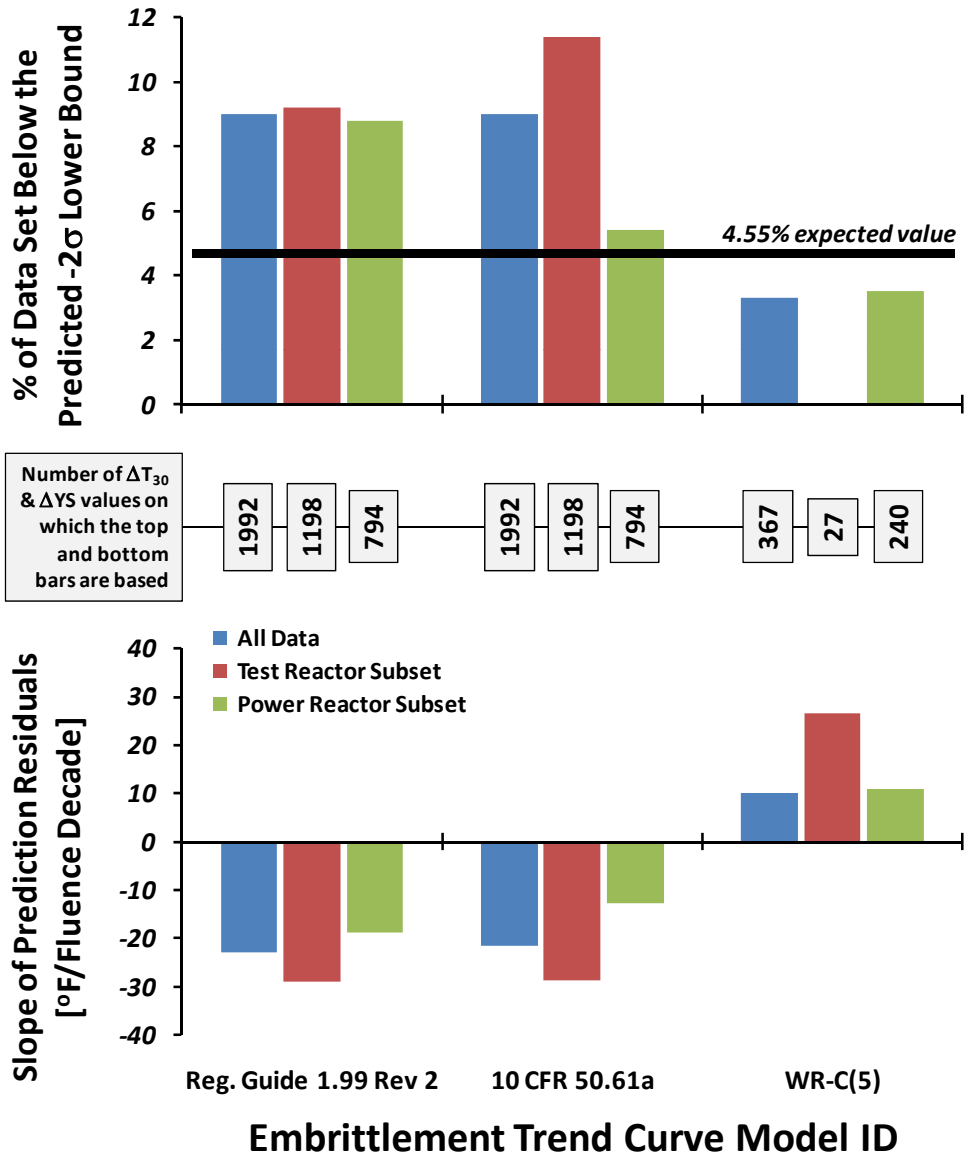
Reactor Type:	Power
Data Plotted:	340
Count below -2σ:	12
% below -2σ:	3.5%
Expected % below -2σ:	4.6%
Acutal / Expected:	0.8

ΔT30 Prediction: WR-F(31)

Reactor Type:	Test
Data Plotted:	27
Count below -2σ:	0
% below -2σ:	0.0%
Expected % below -2σ:	4.6%
Acutal / Expected:	0.0

Dataset: Checking data independent of WR-F(31) calibration data set (367 datum)

Summary
Accuracy Assessment



- Relative to data ***not used*** in their calibration:
  - Reg Guide 1.99 Rev 2 and 10 CFR 50.61a under-predict high fluence trends (non-conservative)
  - WR-C(5) predicts high fluence trends with reasonable accuracy

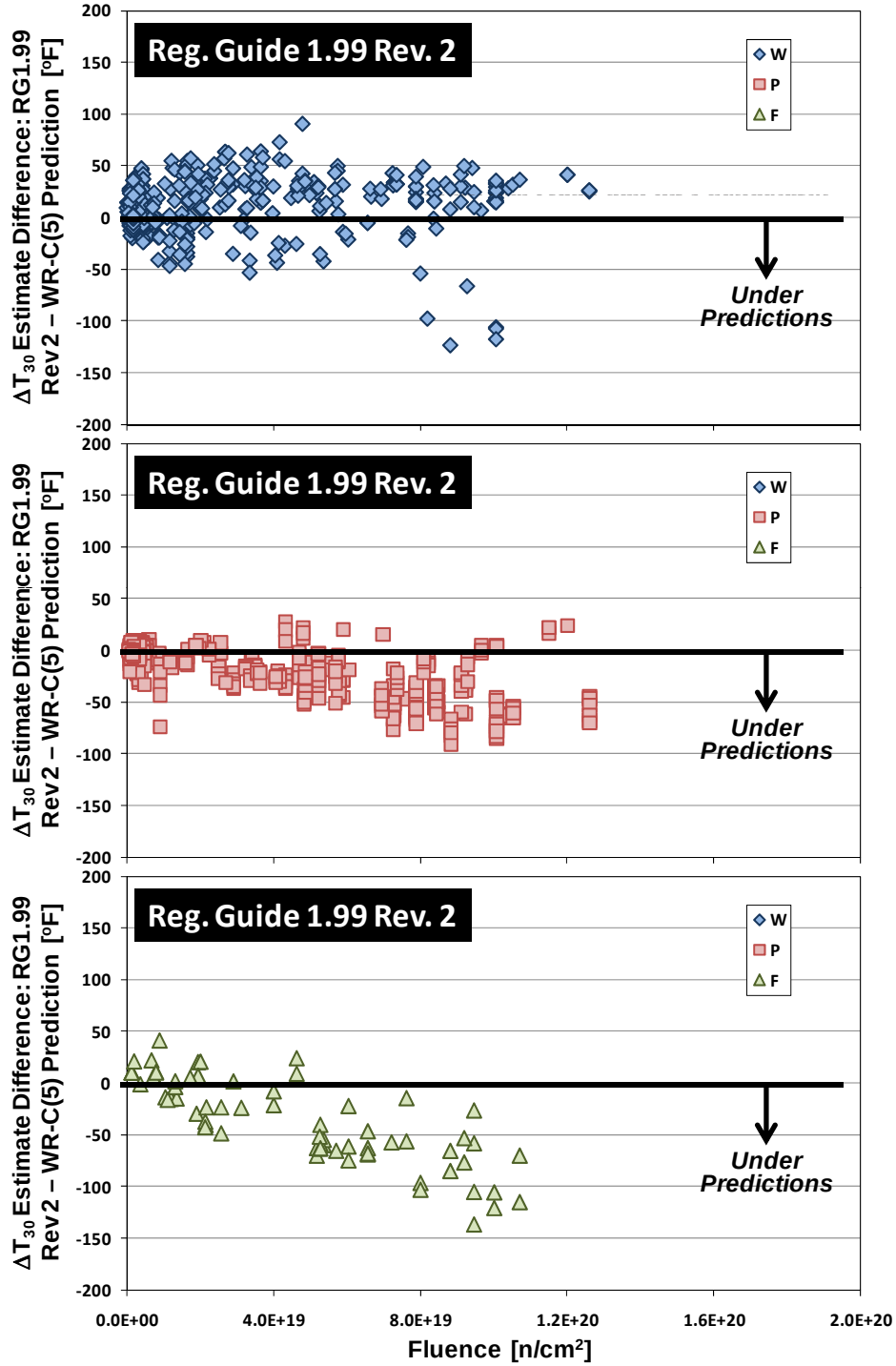
ETC ←→ ETC Comparison

- Assessment of blind predictive accuracy shows that WR-C(5) is a more accurate representation of all available data than either of the other trend curves
- Both Reg Guide 1.99 Rev 2 and 10 CFR 50.61a trend curves are therefore compared to WR-C(5) for the licensing basis conditions of practical interest to the currently operating (US) fleet
  - As represented by RVID database
  - Comparisons made at 80 years of operation

RG1.99R2

Compare to WR-C(5) at 80 years

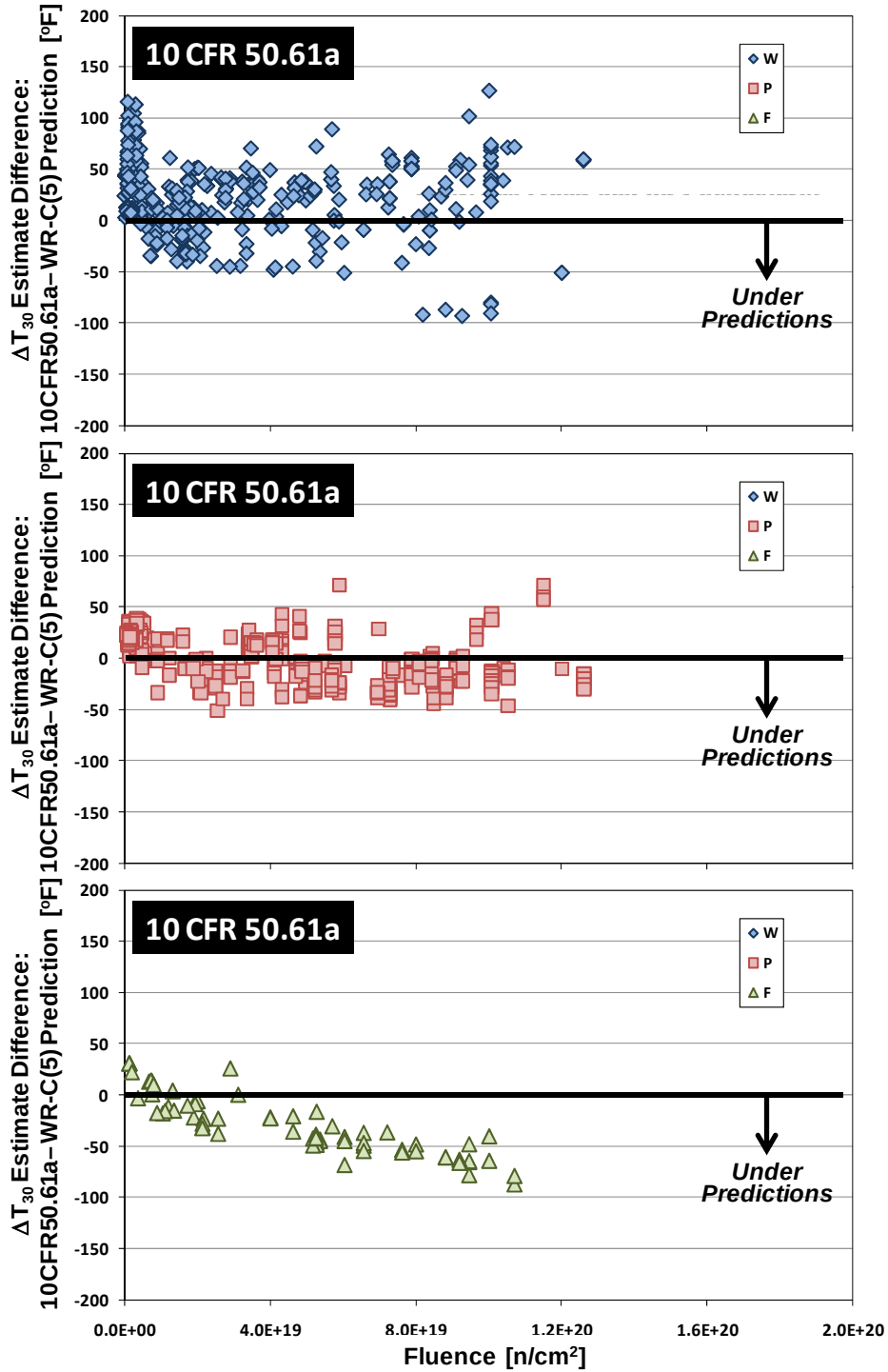
- Only forgings show a significant trend toward increasing under-prediction as fluence increases



10CFR50.61a

Compare to WR-C(5) at 80 years

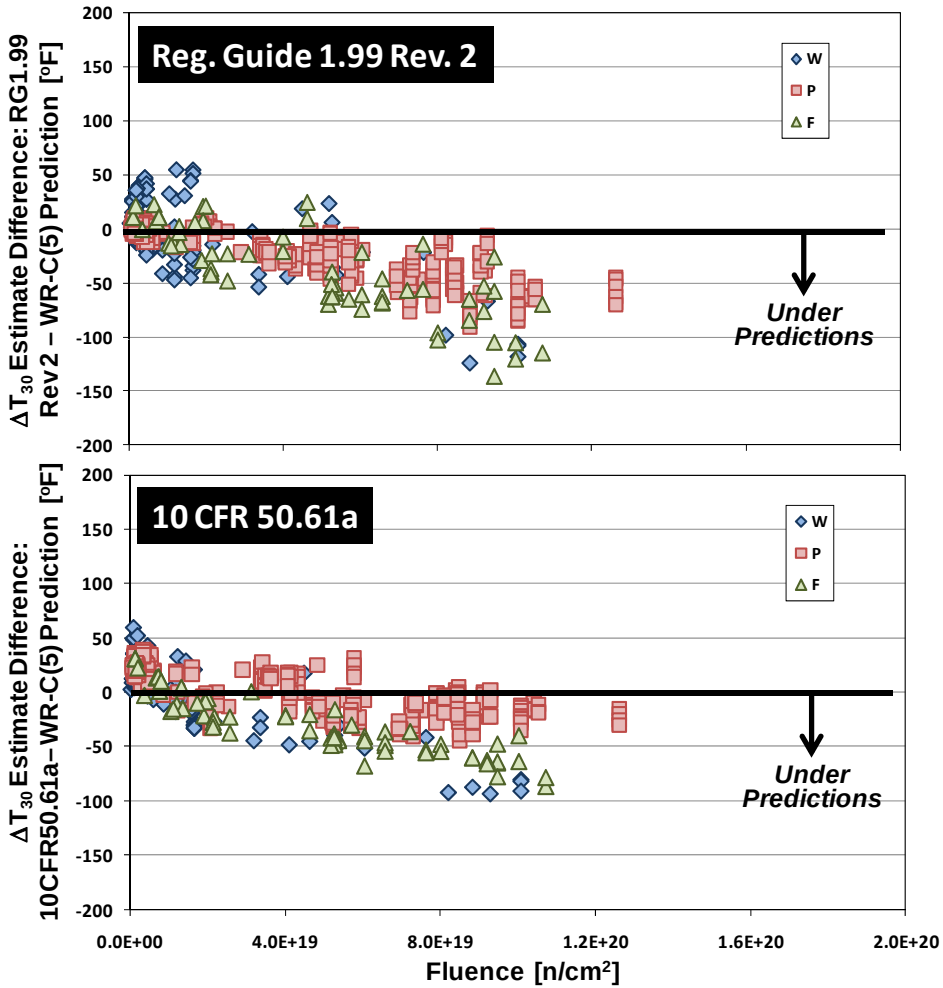
- Only forgings show a significant trend toward increasing under-prediction as fluence increases



Composition of Forgings

Compare to WR-C(5) at 80 Years

- Restricted to Cu<0.17, Ni>0.4
- Shows that region of under-prediction is restricted to low copper materials, but is not restricted to forgings



Conclusions

- Relative to a data set that includes world-wide surveillance data, and test reactor data on embrittlement shift caused by neutron irradiation, the WR-C(5) ETC provides better accuracy at high fluences than the ETCs found in either of the following:
  - Reg Guide 1.99 Revision 2
  - 10 CFR 50.61a
- Region of non-conservative predictions is limited to materials having copper contents below 0.17 weight percent