RPV Embrittlement Trends for Extended Lifetimes, and Related Database Efforts

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USA

U.S.NRC

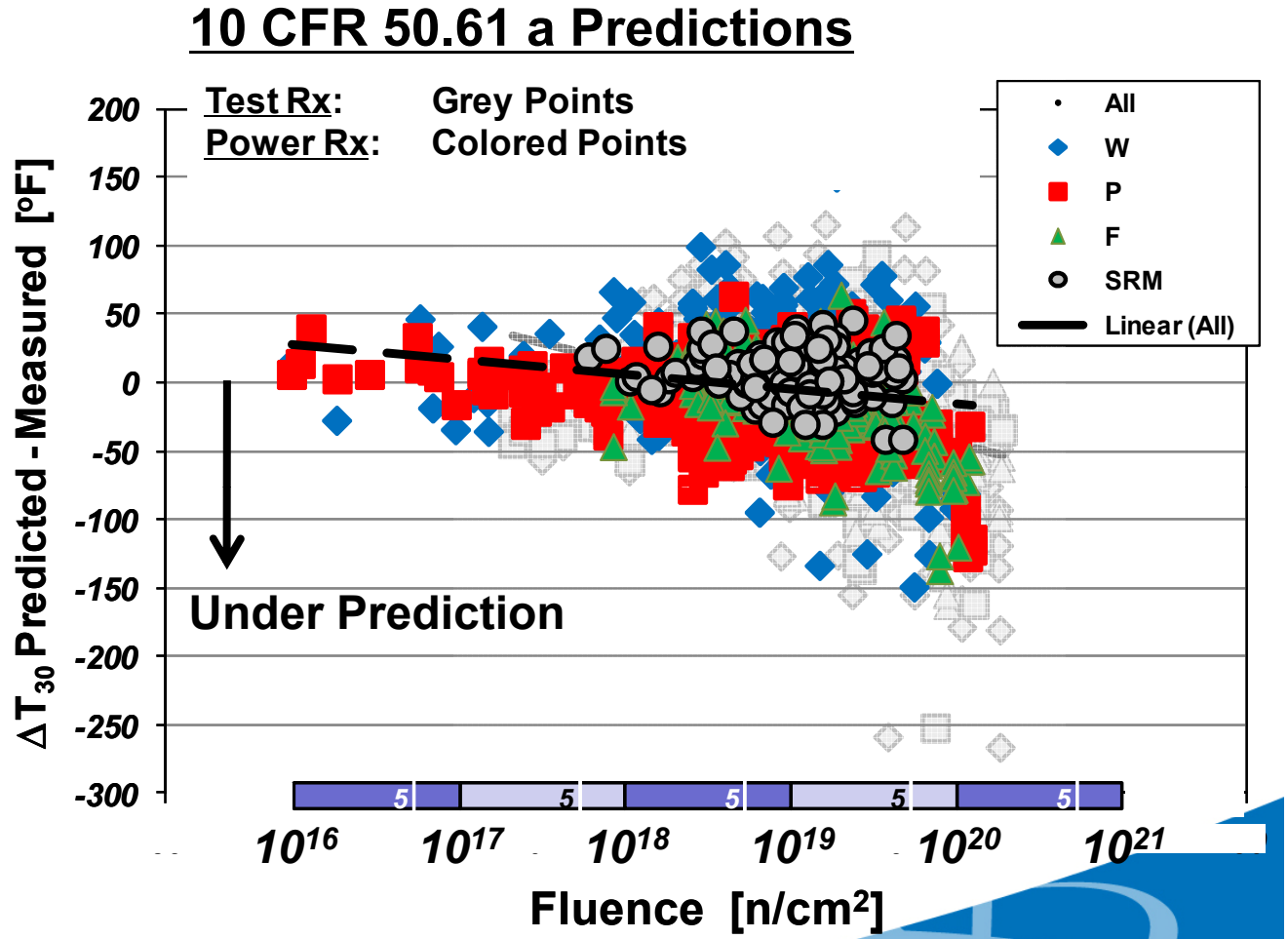
United States Nuclear Regulatory Commission

Protecting People and the Environment

Motivation

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

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



Presentation Overview

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- Assessment of the accuracy of existing trend curve predictions
  - Assembly of larger data set
  - Fit of the data
  - Comparison to new data
  - Comparison of different predictions for currently operating RPVs
- Database activity

Assembly of Larger Data Set

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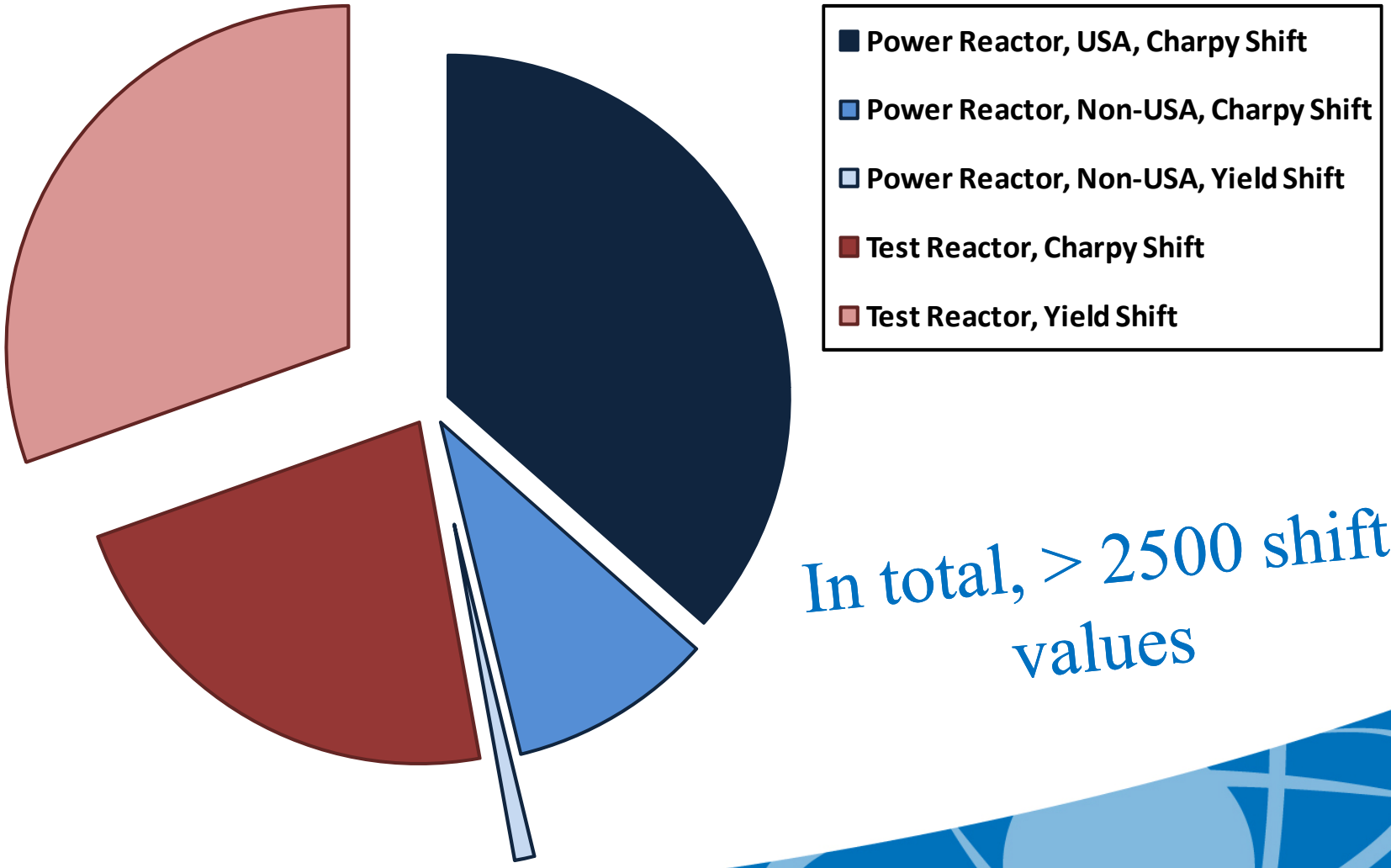
- Considerable data currently exists from non-traditional sources
  - Test reactors (not just surveillance)
  - Reactors overseas (not just domestic)
  - Measurements of ΔYS (not just ΔT_{30})
- Currently there is no consensus on how these data are appropriately used together, however
  - We examine them together here to estimate embrittlement trends in advance of any new testing program

Empirical Database



In total, > 2500 shift values

Empirical Database

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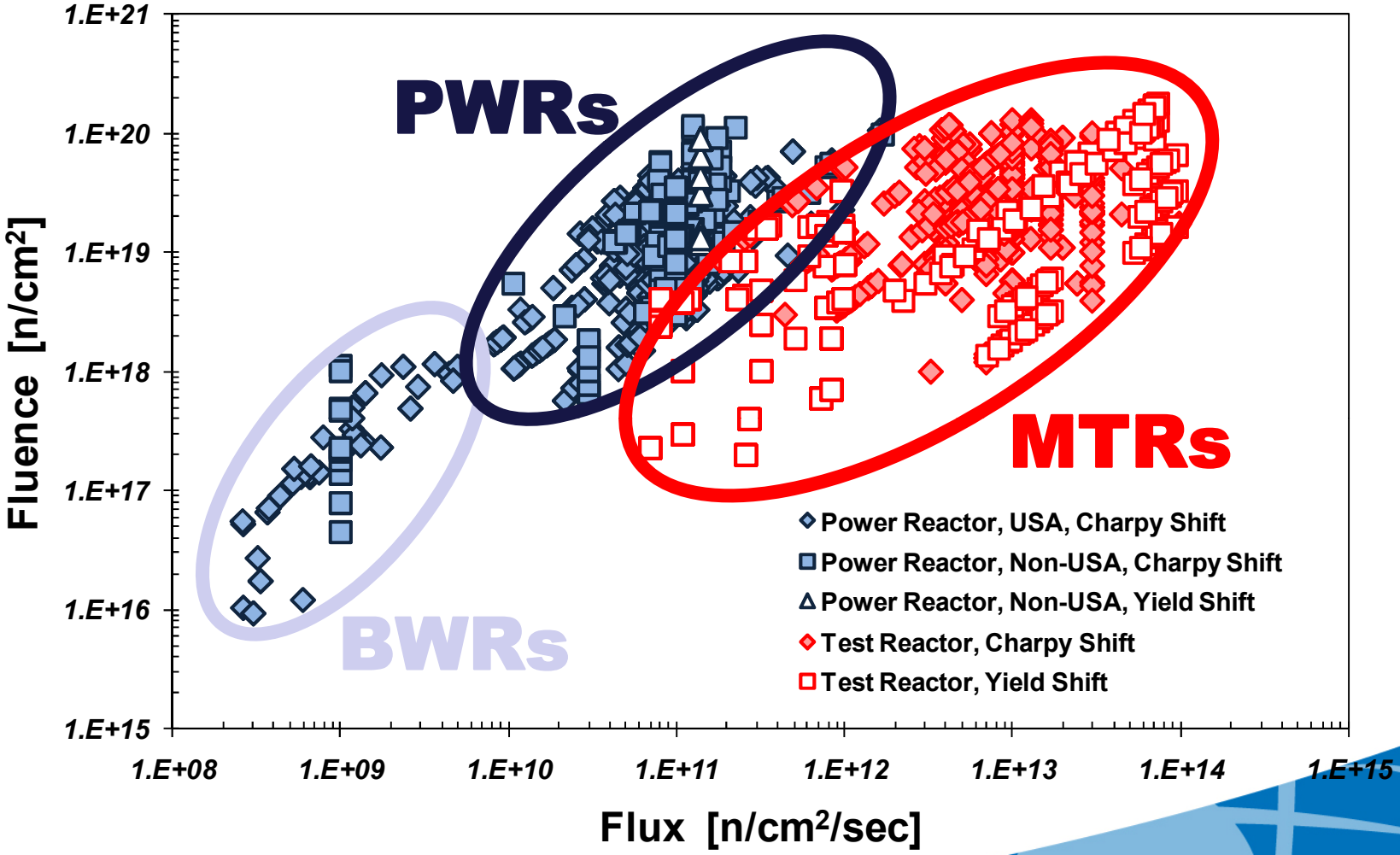
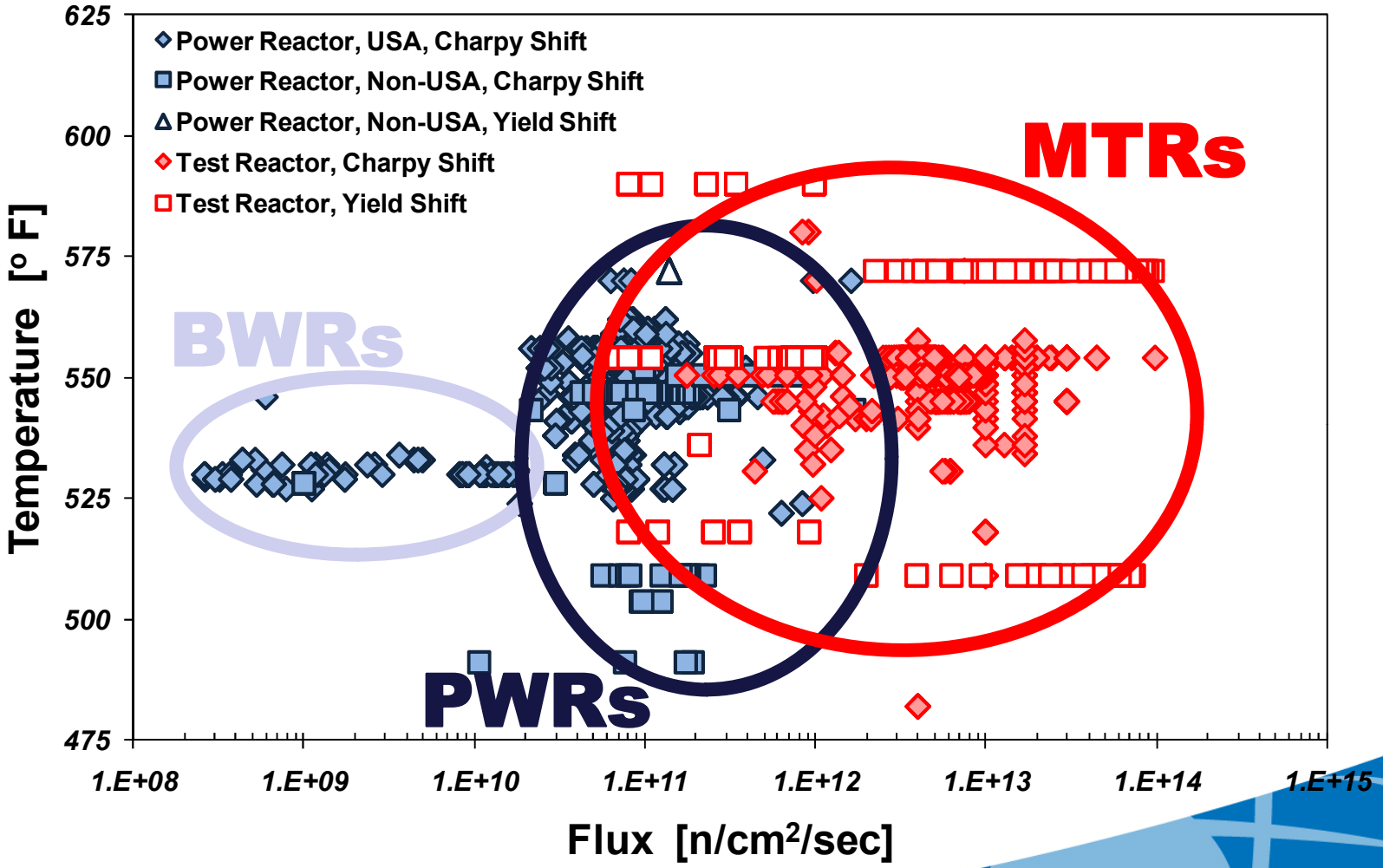


Empirical Database

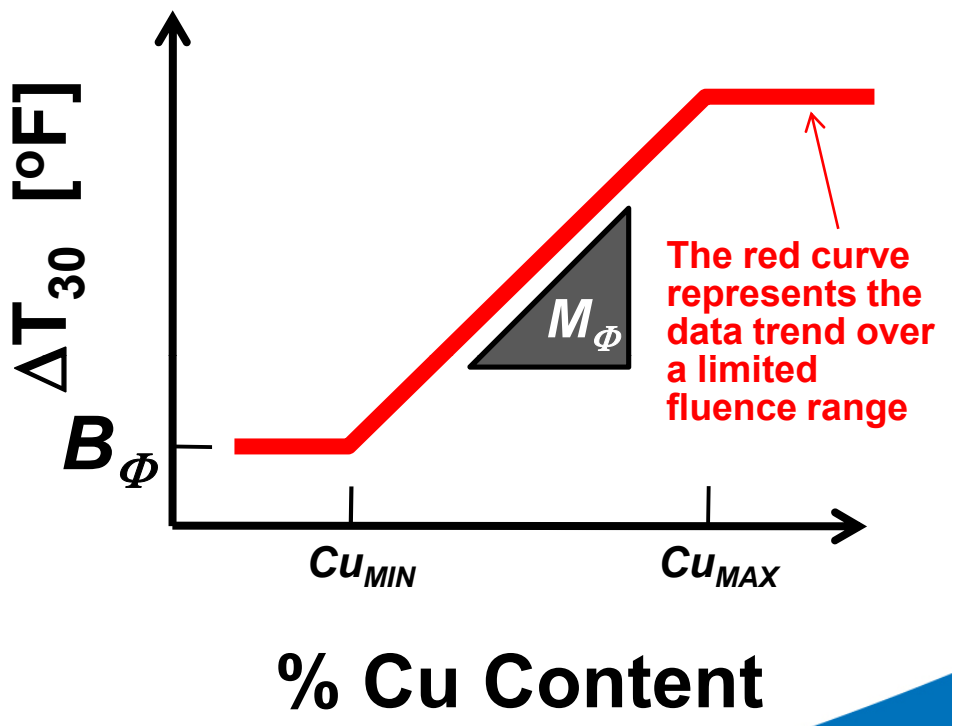


Fit to Data

Empirically Motivated

- The trends noted here 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



Fit to Data: WR-C(5)

$$\Delta\square_{30} = \square\square\square\square\square\left\{\begin{matrix}\square\square\square\square(\square\square\square, 0.35) - 0.05) \\ - \\ 0\end{matrix}\right\} \times \square + \square$$

$$\square = \begin{bmatrix}\square\square_{\square\square} = 0.93 \\ \square\square_{\square\square} = 0.96 \\ \square\square_{\square\square} = 0.68\end{bmatrix} \square\square\square\square\square\langle\square\square\square\square\{[\square\square\square(\Phi) - \square\square\square(1.67 \times 10^{17})] \cdot 171.3 \cdot 733.5\}, 0\rangle \left[\frac{\square\square}{550}\right]^{\square\square_{\square\square}(\square\square)^{-3.84}} \cdot \left[\frac{(\square\square\square)^{1.155}}{0.63}\right]^{0.28}$$

$$\square = \begin{bmatrix}\square\square_{\square\square} = 1.12 \\ \square\square_{\square\square} = 1.056 \\ \square\square_{\square\square} = 0.925\end{bmatrix} \cdot \{9.78 \times 10^{-10} \cdot \Phi^{0.5564}\} \cdot \left[\frac{\square\square}{550}\right]^{-4.74} \cdot \left[\frac{\square\square}{0.012}\right]^{0.24} \cdot \left[\frac{(\square\square\square)^{0.865}}{0.63}\right]^{0.48} \cdot \left[\frac{\square\square\square\square}{1.36}\right]^{0.15}$$

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

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

Fit to Data: WR-C(5)

$$\Delta\square_{30} = \square\square\square\square\square\left\{\begin{matrix}\square\square\square\square(\square\square\square, 0.35) - 0.05 \\ - \\ 0\end{matrix}\right\} \times \square - \square$$

$$\square = \begin{bmatrix}\square\square_{\square\square} = 0.93 \\ \square\square_{\square\square} = 0.96 \\ \square\square_{\square\square} = 0.68\end{bmatrix} \square\square\square\square\square\langle\square\square\square\square\{[\square\square\square(\Phi) - \square\square\square(1.67 \times 10^{17})] \cdot 171.3{,}733.5\}, 0\rangle \cdot \left[\frac{\square\square}{550}\right]^{\square\square_{\square\square}(\square\square)^{-3.84}} \cdot \left[\frac{(\square\square\square)^{1.155}}{0.63}\right]^{0.28}$$

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

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

Fit to Data: WR-C(5)

$$\Delta T_{30} = \begin{Bmatrix} \text{[illegible]}(\text{[illegible]}, 0.35) - 0.05 \\ - \\ 0 \end{Bmatrix} \times \text{[illegible]} + \text{[illegible]}$$

$$\text{[illegible]} = \begin{bmatrix} \text{[illegible]}_{\text{[illegible]}} = 0.93 \\ \text{[illegible]}_{\text{[illegible]}} = 0.96 \\ \text{[illegible]}_{\text{[illegible]}} = 0.68 \end{bmatrix} \text{[illegible]}\langle \text{[illegible]}\{[\text{[illegible]}(\Phi) - \text{[illegible]}(1.67 \times 10^{17})] \cdot 171.3, 733.5\}, 0\rangle \cdot \left[\frac{\text{[illegible]}}{550}\right]^{\text{[illegible]}(\text{[illegible]})^{-3.84}} \cdot \left[\frac{(\text{[illegible]})^{1.155}}{0.63}\right]^{0.28}$$

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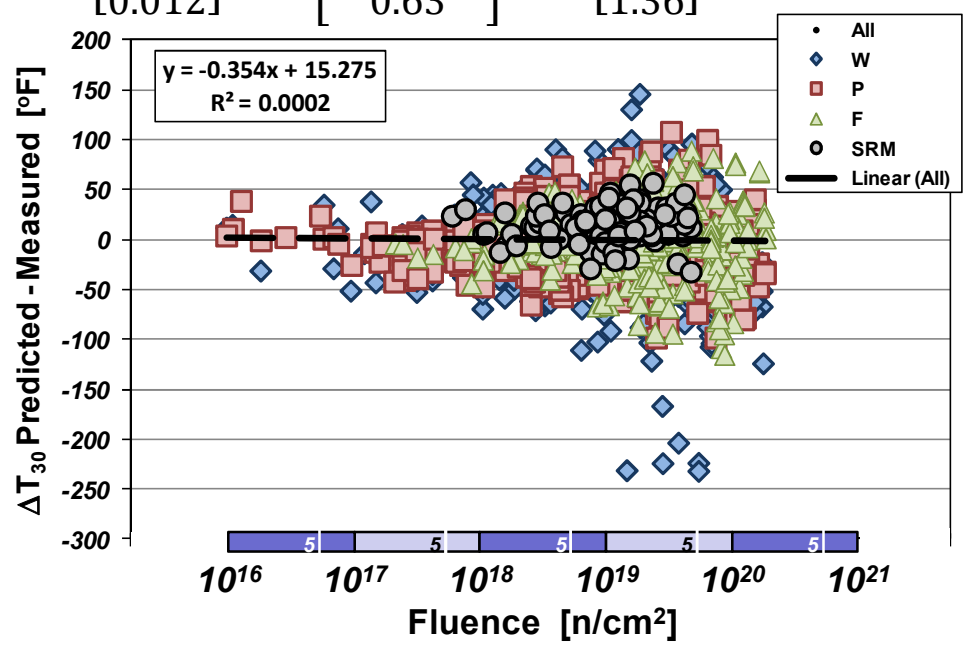
$$\text{[illegible]} = 0.073\Phi^{0.138}$$

Uncertainty / scatter

✓ **Increases with fluence**



Accuracy Assessment

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For WR-C(5), use 367 new datum

Set ID	Product Form	Reactor Type	Highest Fluence [n/cm^2]	Flux [n/cm^2/s]	Temperature [^{o}F]	Cu	Ni	Mn	P
Soneda - S1s	*Plate*	*Power*	*6E+19*	*1E+11*	*554*	*0.09*	*0.62*	*1.36*	*0.007*
Belgian, Base 2	Forging	Power	7E+19	1E+11	545	0.05	0.745	1.31	0.0115
Belgian, Base 1	Forging	Power	7E+19	1E+11	563	0.045	0.755	1.425	0.0065
Belgian, Weld 2	Weld	Power	8E+19	1E+11	545	0.05	0.96	1.15	0.016
Farley	Weld	Power	9E+19	1E+11	544	0.14	0.19	***1.36***	0.016
Farley	Plate	Power	9E+19	1E+11	544	0.1	0.555	***1.36***	0.015
Belgian, Weld 1	Weld	Power	1E+20	1E+11	545	0.08	0.84	1.11	0.015
Viehrig - JFL	Forging	Power	9E+19	1E+11	491	0.01	0.75	***1.36***	0.004
Viehrig - JRQ	Plate	Power	1E+20	1E+11	491	0.14	0.84	***1.36***	0.017
Brumovski - JRQ	Plate	Power	2E+20	7E+11	518	0.14	0.84	1.420	0.019
Soneda - Base 6	Plate	Test	9E+19	5E+12	554	0.1	0.92	1.47	0.008
Soneda - Base 7	Plate	Test	9E+19	5E+12	554	0.1	0.63	1.53	0.017
Soneda - Base 8	Plate	Test	9E+19	5E+12	554	0.1	0.63	1.53	0.009
Soneda - W2	Weld	Test	1E+20	5E+12	554	0.13	0.86	1.21	0.016
Soneda - W3	Weld	Test	1E+20	5E+12	554	0.1	0.88	1.19	0.016
Soneda - Base 1	Plate	Test	1E+20	5E+12	554	0.21	0.63	1.55	0.009
Soneda - Base 5	Plate	Test	1E+20	5E+12	554	0.1	0.59	1.52	0.009
Soneda - Base 9	Plate	Test	1E+20	5E+12	554	0.04	0.62	1.5	0.003
Soneda - S1	Plate	Test	1E+20	5E+12	554	0.09	0.62	1.36	0.007
Soneda - W1	Weld	Test	1E+20	5E+12	554	0.2	0.88	1.19	0.016
Soneda - Base 4	Plate	Test	1E+20	5E+12	554	0.17	0.62	1.51	0.009
Soneda - W4	Weld	Test	1E+20	5E+12	554	0.02	0.84	1.23	0.008
Belgian, Base 1	Forging	Test	2E+20	7E+13	563	0.045	0.755	1.425	0.0065
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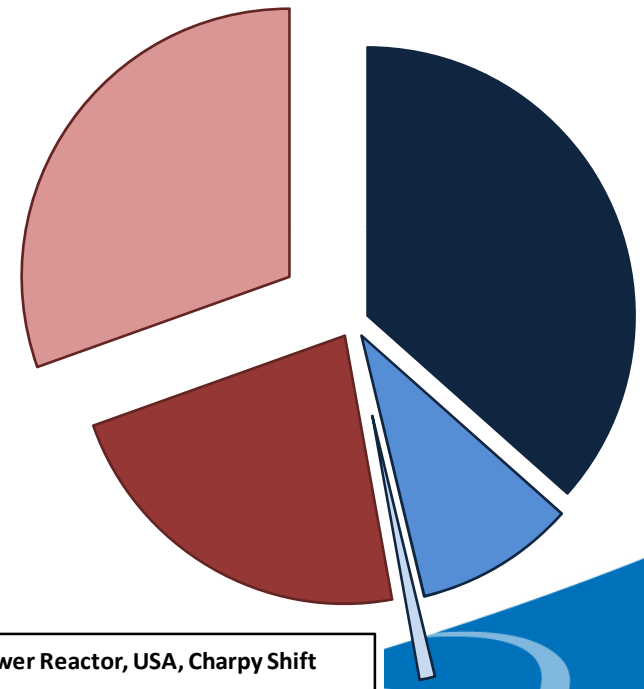

- Power Reactor, USA, Charpy Shift
- Power Reactor, Non-USA, Charpy Shift
- Power Reactor, Non-USA, Yield Shift
- Test Reactor, Charpy Shift
- Test Reactor, Yield Shift

Accuracy Assessment

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For RG1.99R2 and 10CFR50.61a, use 367 new datum and 1625 datum from WR-C(5) calibration

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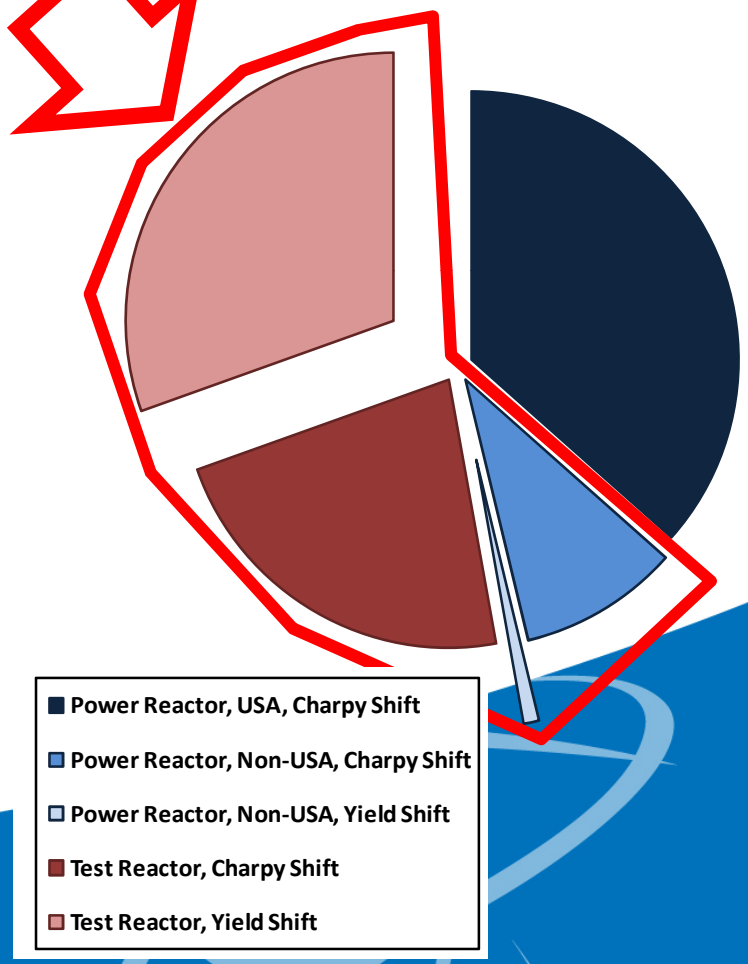
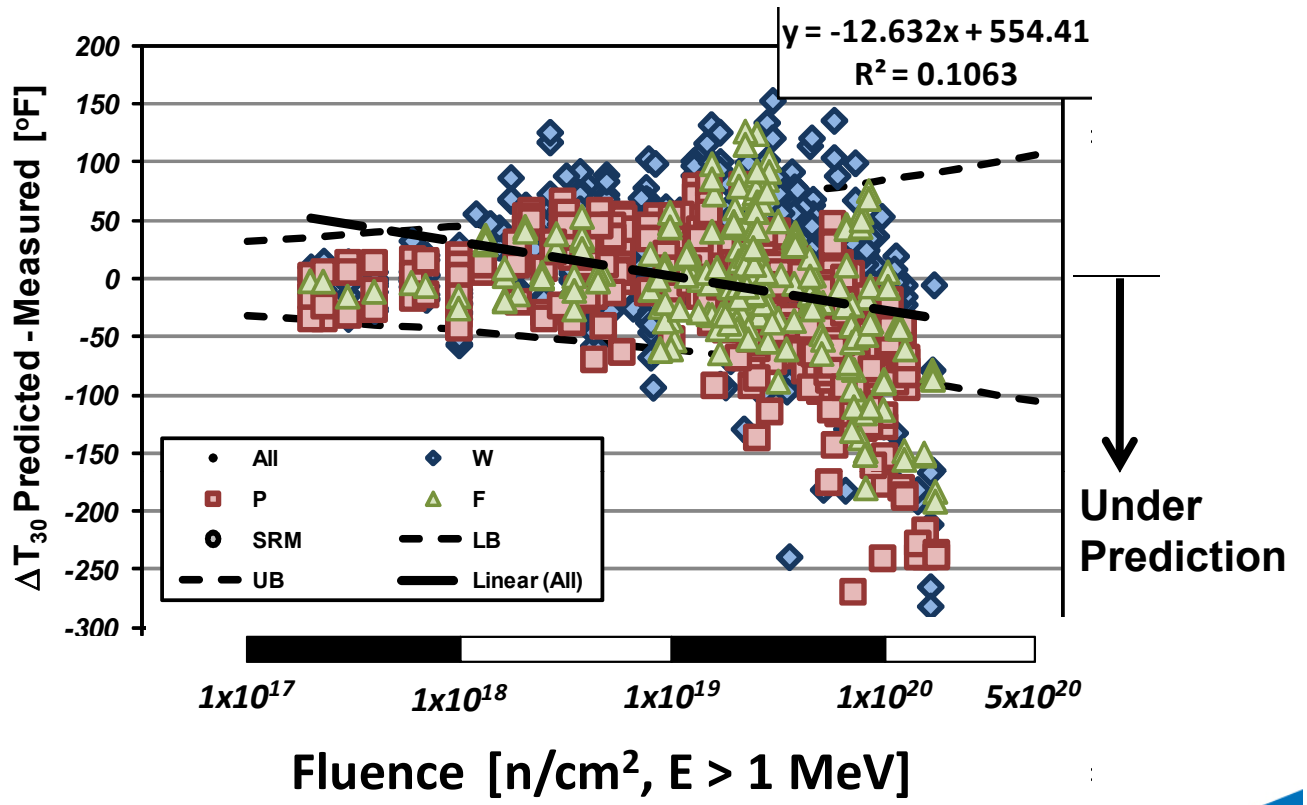


Assessment Methods

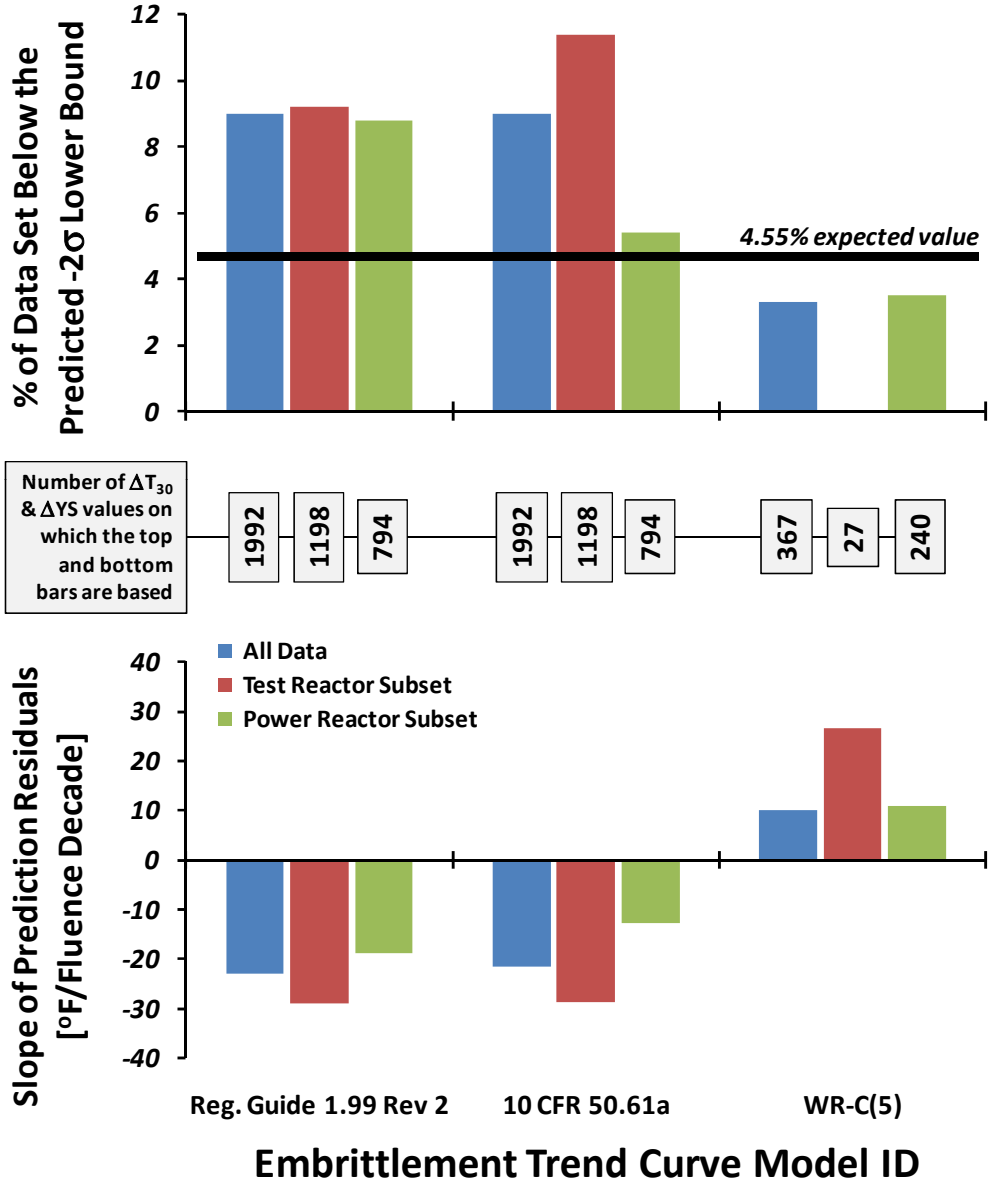
- Examine % of data set below the 2σ lower bound
- Examine trend of prediction residuals *vs.* fluence



Assessment Summary

- Both
  - RG1.99R2
  - 10CFR50.61a

  exhibit trends toward increasing under-prediction as fluence increases



Predictive Accuracy of Current ETCs for Future Embrittlement Trends

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- Comparisons with available data indicate that WR-C(5) fit provides the best overall representation of all available data
- We therefore compare the predictions of the current ETCs in regulatory use:
  - Reg Guide 1.99 Revision 2, and
  - 10 CFR 50.61a

  to the predictions of the WR-C(5) fit to assess their accuracy
- Predictions made for the conditions of the existing fleet as described in RVID-2

Welds

After 80 Years of Operation

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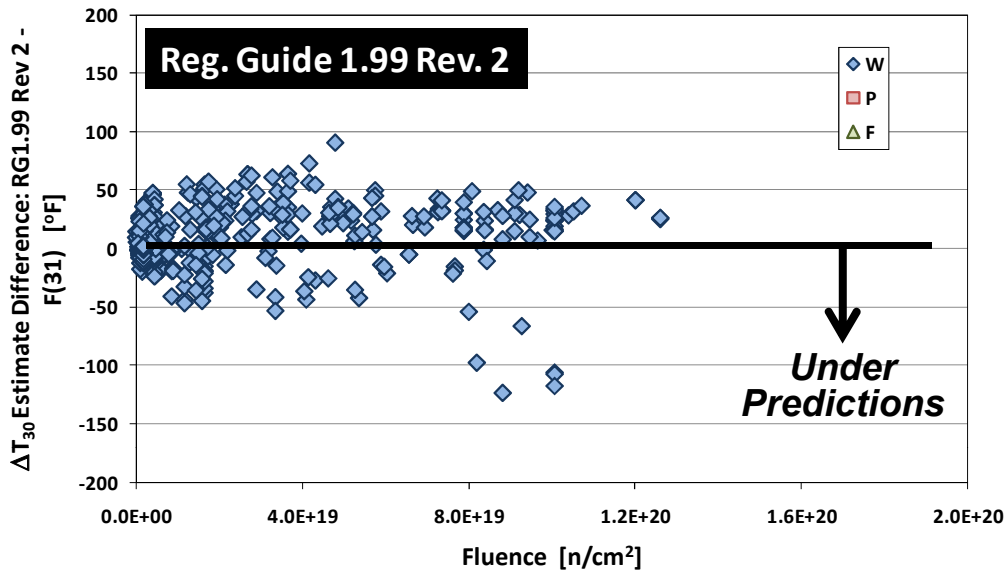
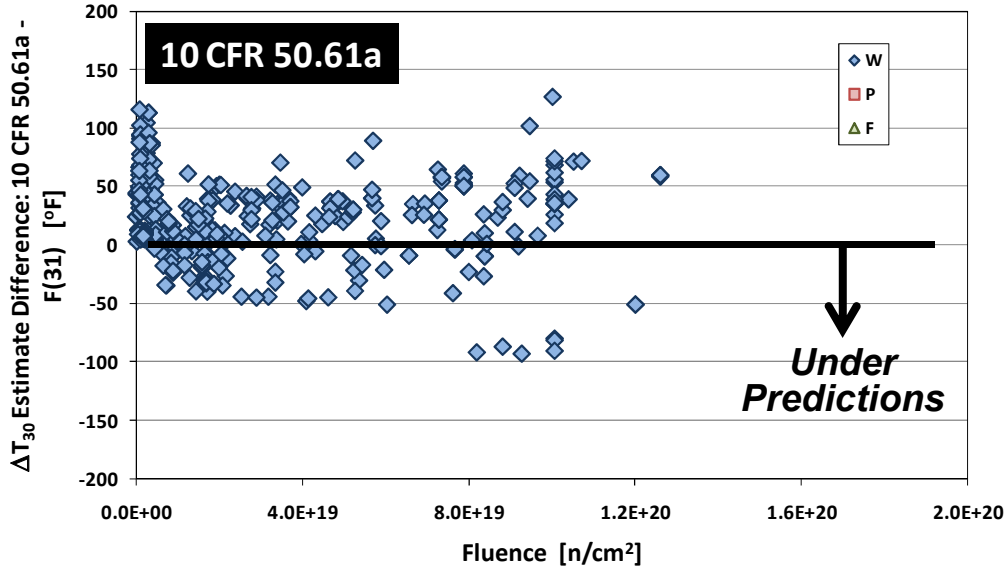
- Based on RVID-2 projected to 80 operating years
- Both
  - RG1.99R2, and
  - 10CFR50.61a

  are mostly within ±50 °F of the trends suggested by all of the data





Plates

After 80 Years of Operation

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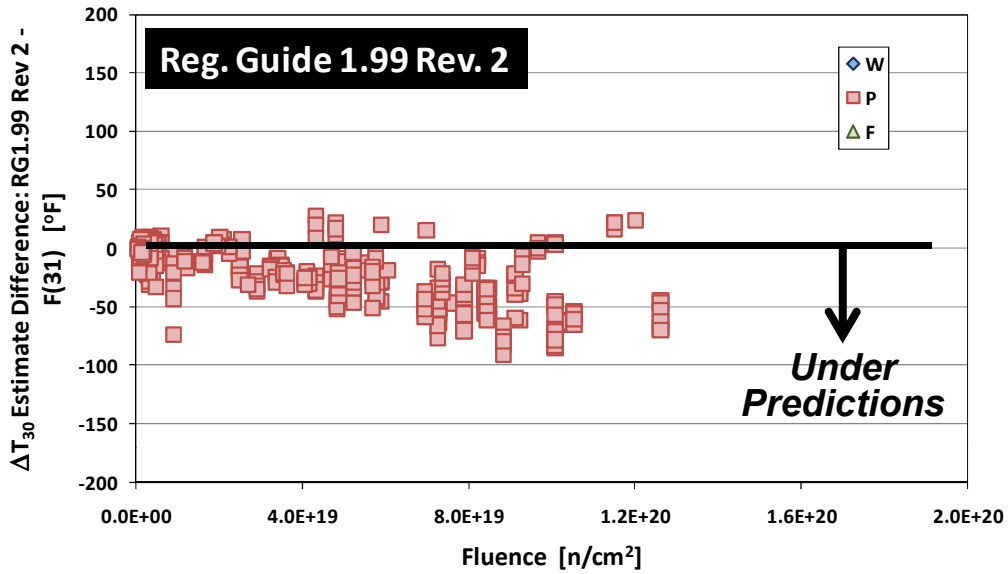
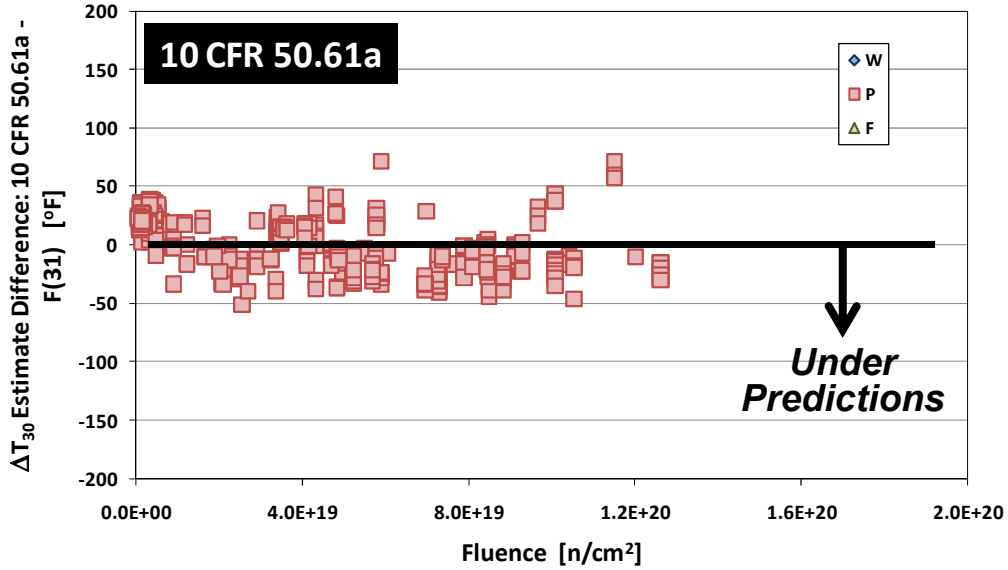
- Based on RVID-2 projected to 80 operating years
- Both
  - RG1.99R2, and
  - 10CFR50.61a

  are mostly within ±50 °F of the trends suggested by all of the data





Forgings

After 80 Years of Operation

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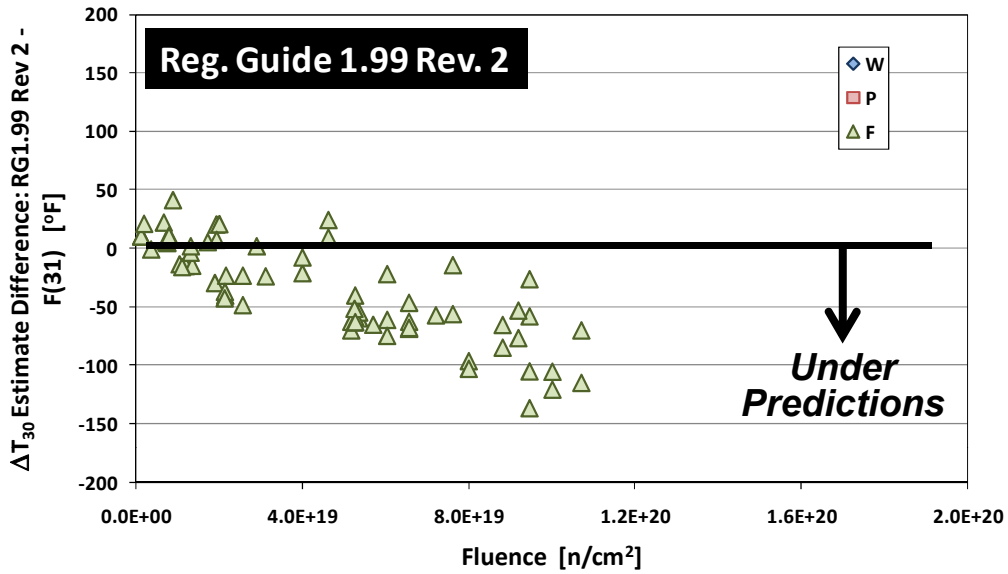
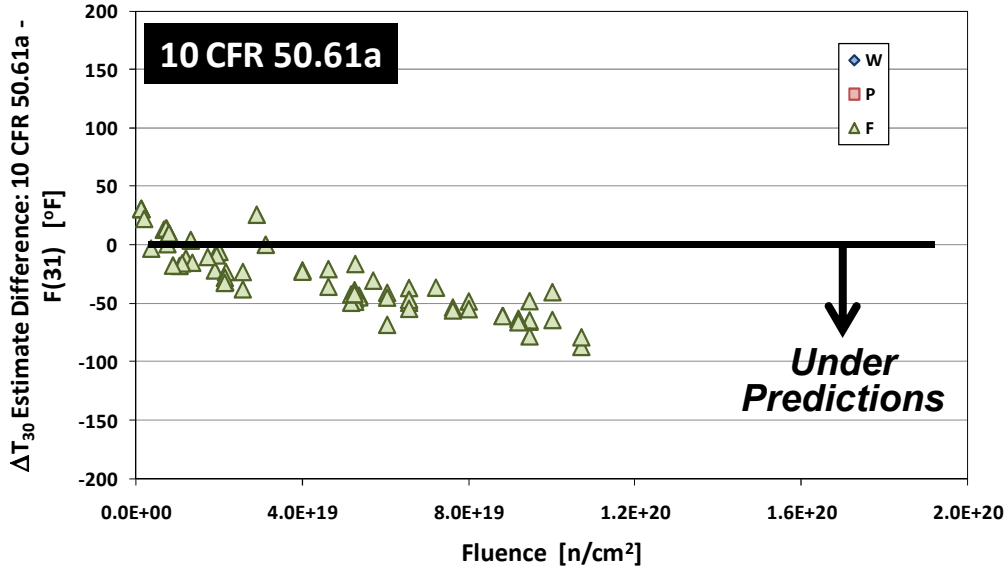
- Based on RVID-2 projected to 80 operating years
- Both
  - RG1.99R2, and
  - 10CFR50.61a

under-predict more as fluence increases





Why are only Forgings Under-Predicted?

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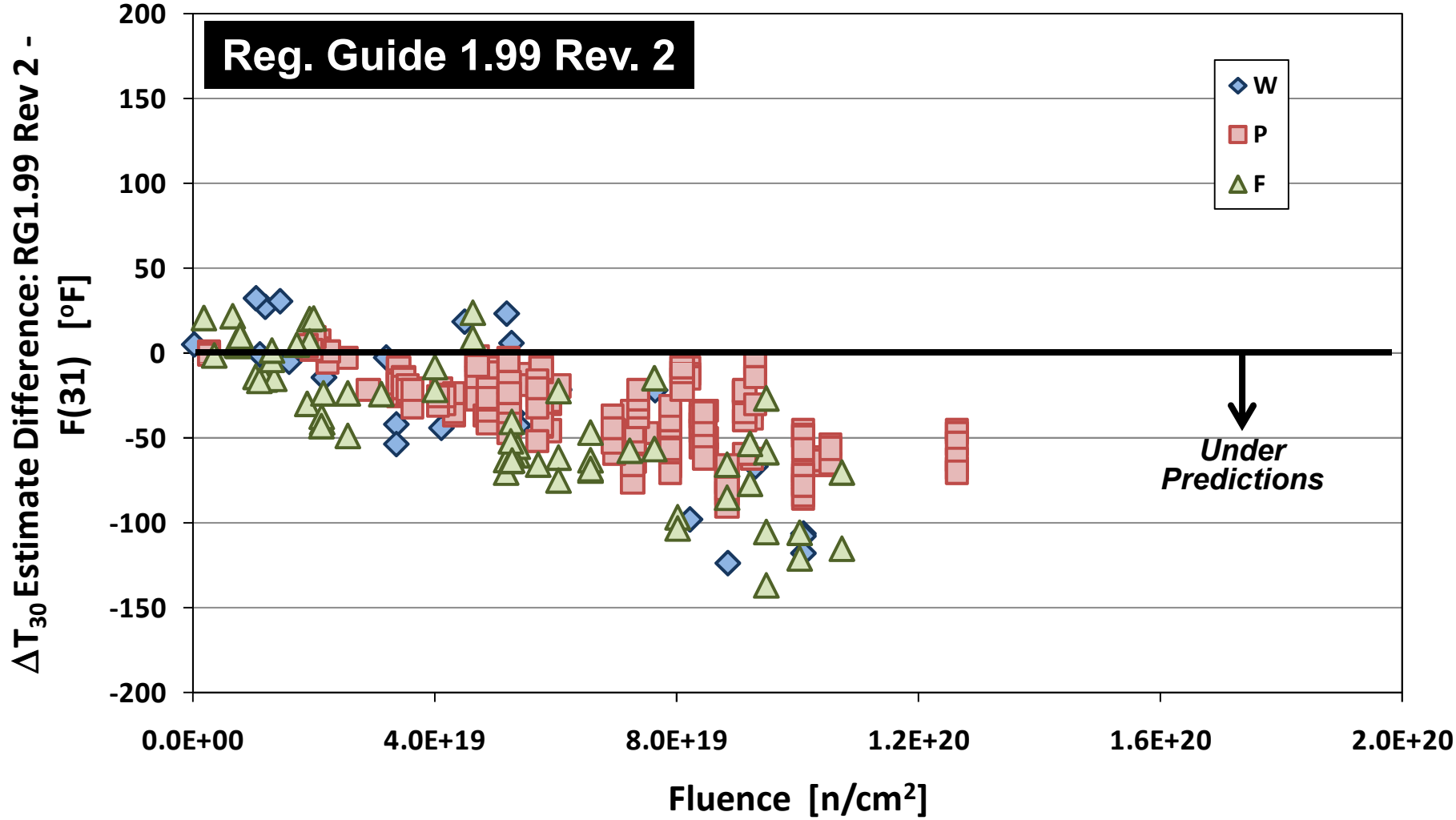
- It turns out it is not just the forgings, but rather ***all materials of similar chemistry***
  - Cu < 0.17 weight percent
  - Ni > 0.4 weight percent
- All materials of this chemistry range tend toward under-prediction as fluence increases
- BWRs are excluded from further comparisons because they never reach a high enough fluence to be significantly under predicted by any ETC, even out to 100 years of operation

Reg Guide 1.99 Rev. 2

Cu < 0.17, Ni > 0.4, PWR Only, 80 Years



10 CFR 50.61a

Cu < 0.17, Ni > 0.4, PWR Only, 80 Years

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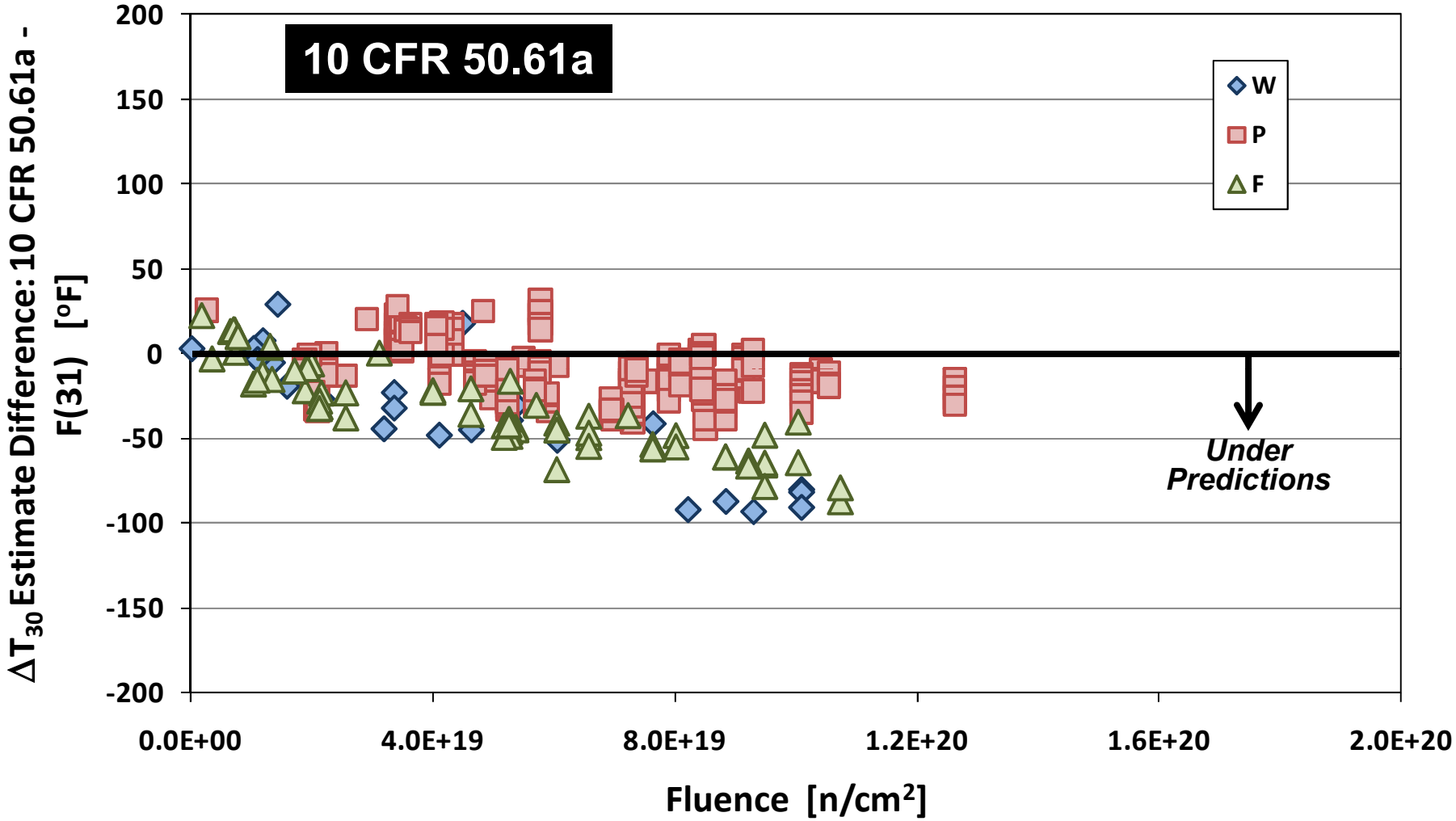

Summary

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- Both trend curves in current regulatory use have a tendency toward increased under-prediction as fluence increases for low copper materials
- Current plans are to adopt the 10CFR50.61a trend curve and surveillance check into RG1.99R3
  - Surveillance check provides some indication if under-prediction is occurring on a material-specific basis
- Parallel effort to update and build embrittlement database is a 1st step at building technical community consensus on appropriate treatment of non-conventional data

Database Motivation

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- The NRC requires licensees to submit considerable information on the materials and design of NPPs
- This information is not now stored and maintained in a way that facilitates easy assessment of the effects of regulatory changes
  - e.g., changes in embrittlement trend curves
- Previous NRC efforts (PR-EDB and RVID-2)
  - Were not continuous / kept up to date
  - Were not linked
  - Traceability to original source documents was difficult

Database Effort Initiated at ORNL

Objective

Develop a modern, web-based, database for US surveillance reports and other embrittlement-related data

Database Effort Initiated at ORNL

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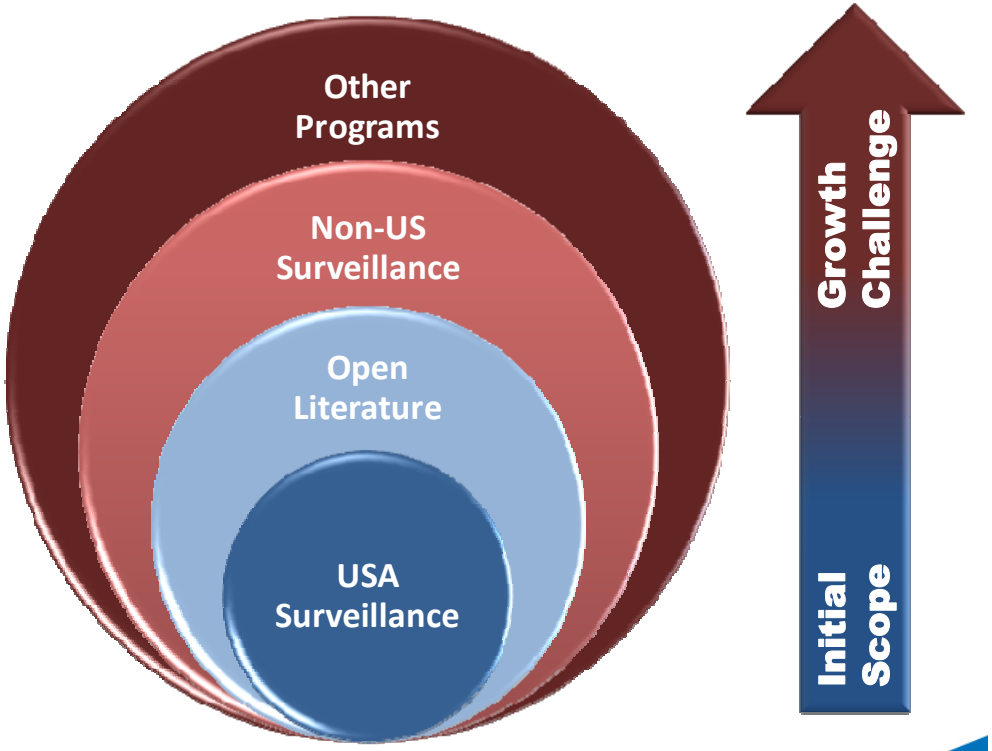
Database Characteristics

- Web-based
- Continuously maintained and updated
- Includes
  - Searchable electronic database of information from surveillance reports
  - Scanned pdf copies of all US surveillance reports
- Read access in the public domain
- QA and data entry procedures available on website



Initial Information Sources

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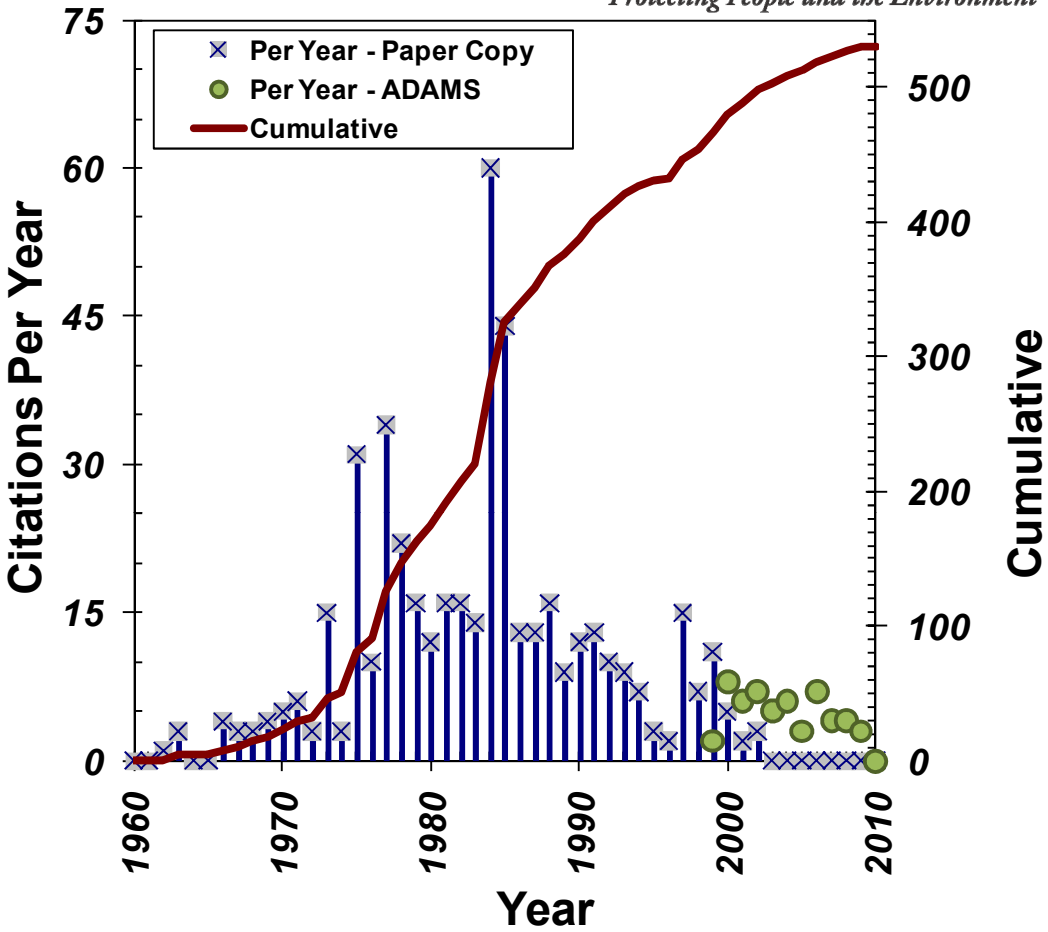
Pre-2000 Library of of Hard Copies at ORNL

Post-2000 Electronic ADAMS Library at NRC



Comprehensive list of all historic reports, and list of capsule reports expected in the future

Layered Database Structure

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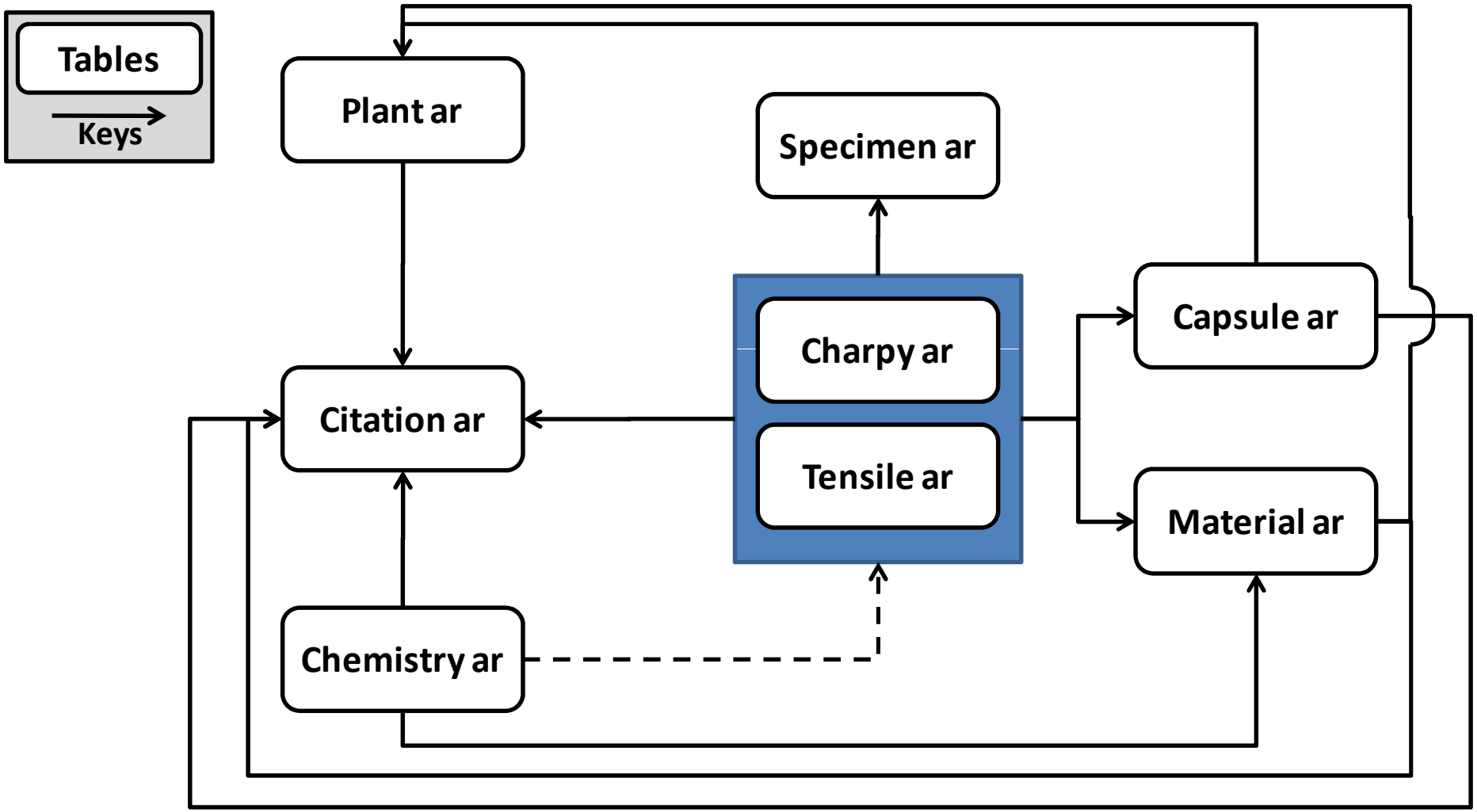
ar
- As-reported layer
- Verbatim echo of information in source documents
- No interpretation

p1
- Processed 1 layer
- Units made consistent
- Multiple values of fluence, chemistry, etc. reconciled into single values

p2
- Processed 2 layer
- Transition temperatures, athermal yield strengths, upper shelf energies calculated
- TT shifts, YS increases, and USE drops calculated

rg
- Regulatory layer
- Regulatory values

Initial Design for "ar" Layer



Status, Upcoming Events, Collaboration

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- Current status
  - Existing stock of 500+ surveillance reports all scanned into searchable PDF files
  - Comprehensive list of capsule reports developed
  - Initial database design established
  - Hardware in place at ORNL
- Upcoming events
  - 9/14-15/2010: Meeting to discuss 1st working version in Rockville, MD
  - Mid 2011: Some subset of information uploaded to data.gov
- Collaboration: Partners sought to further goals of
  - Efficient identification of source documents (past & future)
  - Data entry
  - Data QA
  - Data analysis protocols
  - Database expansion