RPV Embrittlement Trends for Extended Lifetimes, and Related Database Efforts

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USA

U.S.NRC

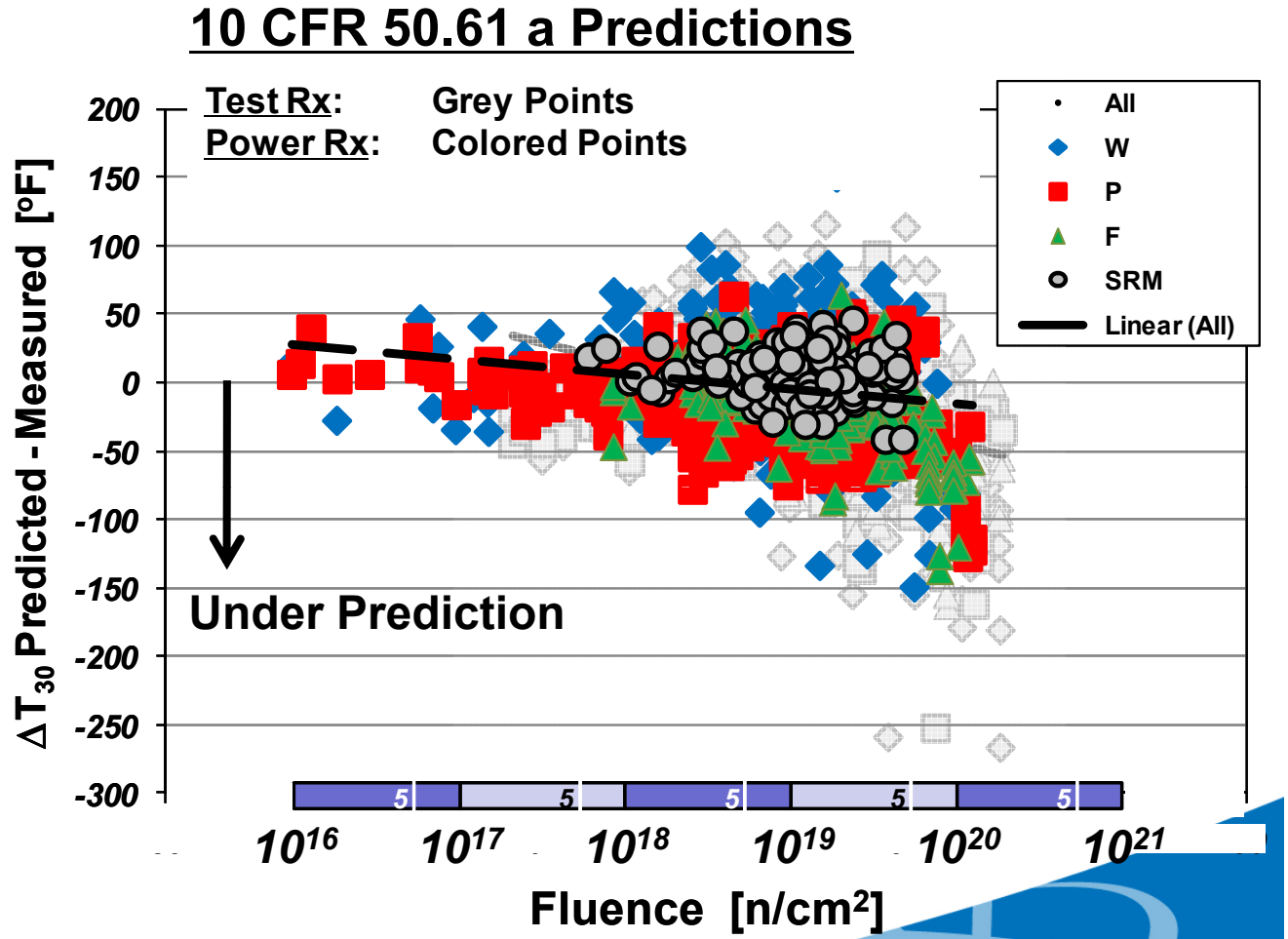
United States Nuclear Regulatory Commission

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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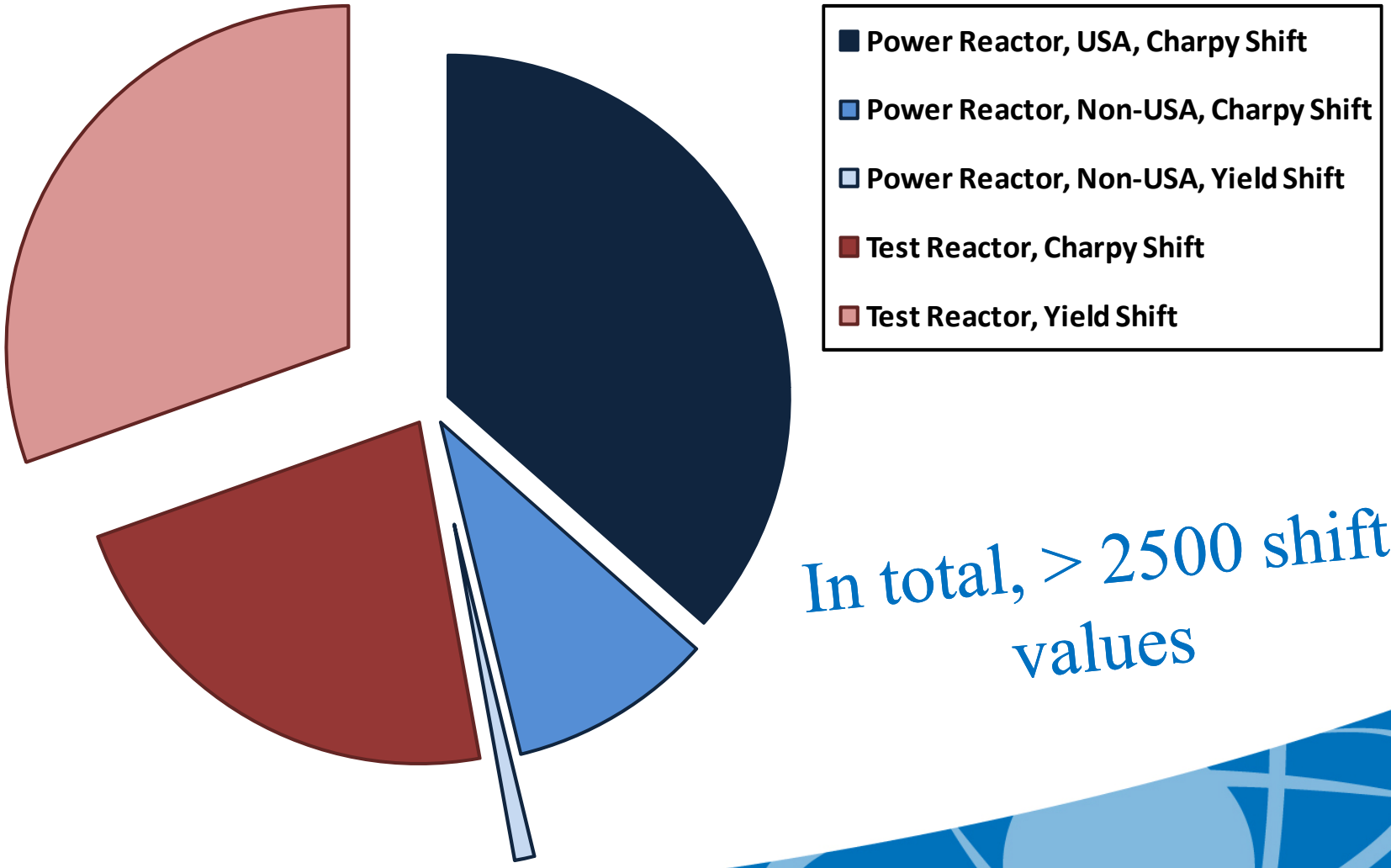
- Considerable data currently exists from non-traditional sources
  - Test reactors (not just surveillance)
  - Reactors overseas (not just domestic)
  - Measurements of ΔYS (not just ΔT_{30})
- Currently there is no consensus on how these data are appropriately used together, however
  - We examine 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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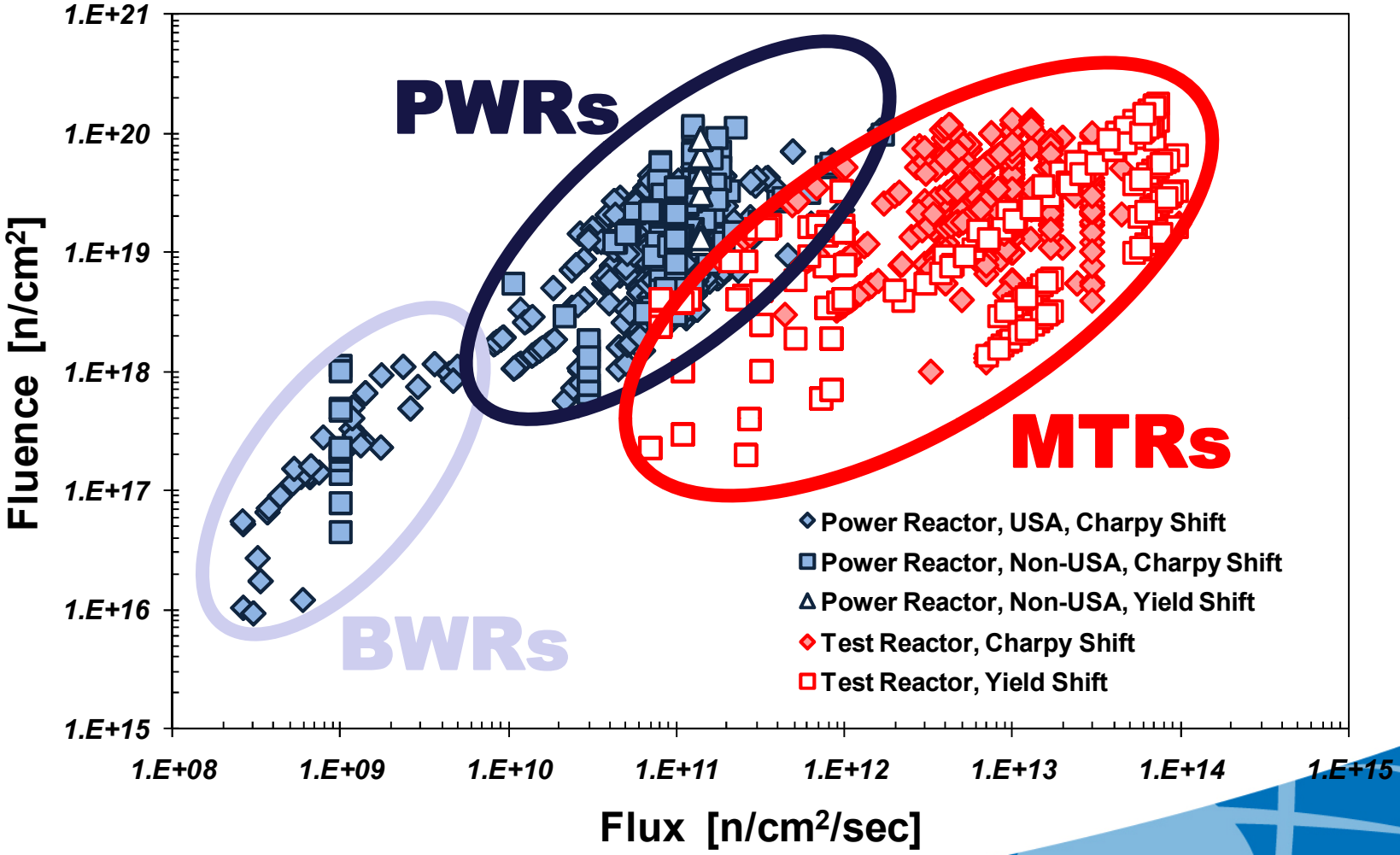
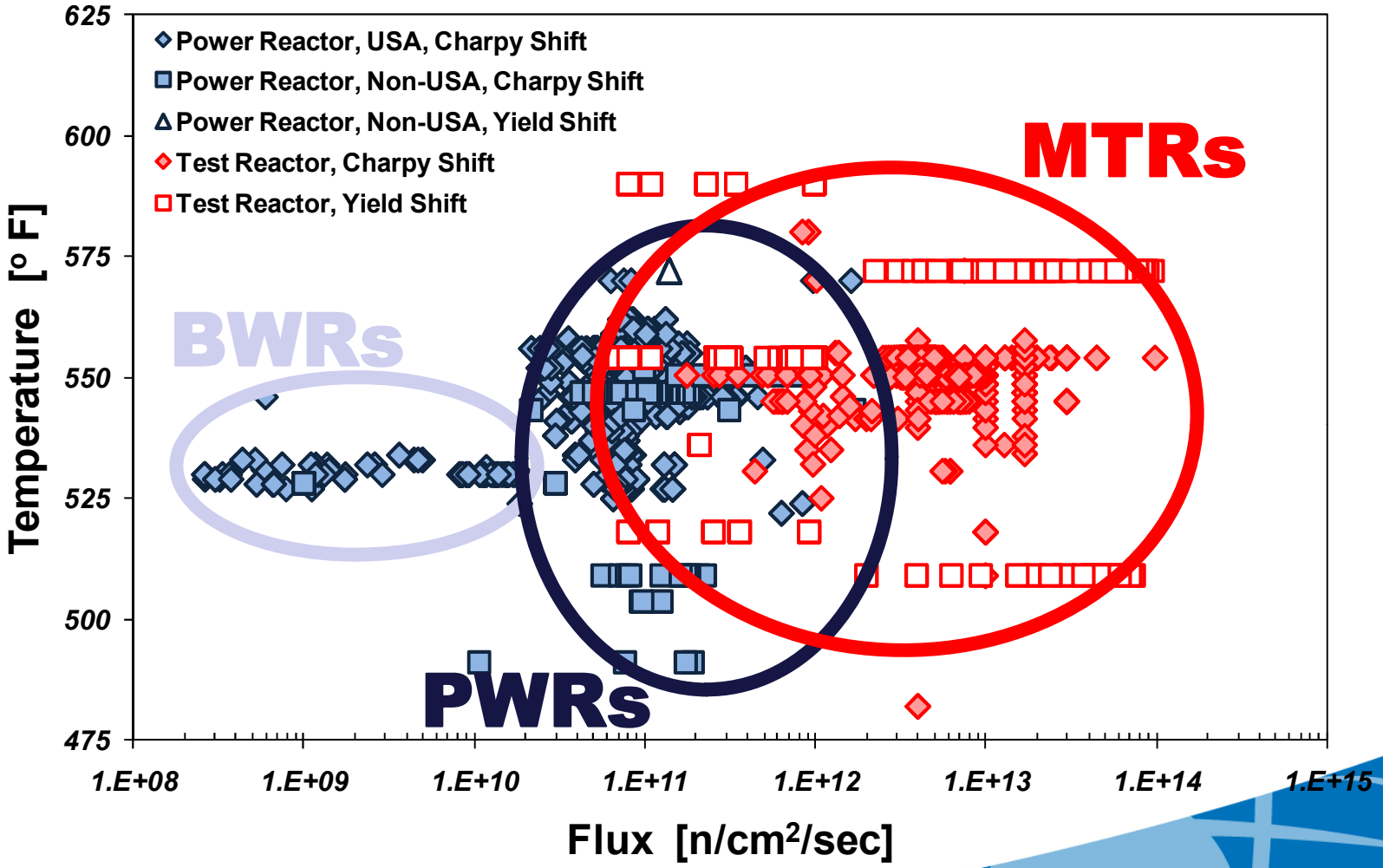


Empirical Database

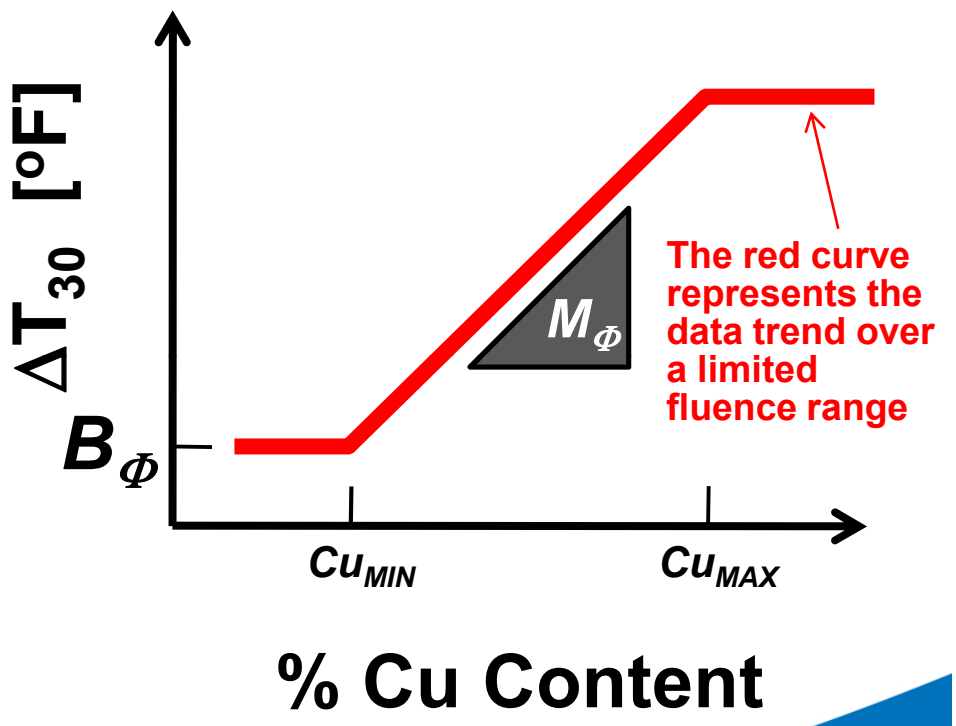


Fit to Data

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)

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

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

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

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

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)

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

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

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

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)

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

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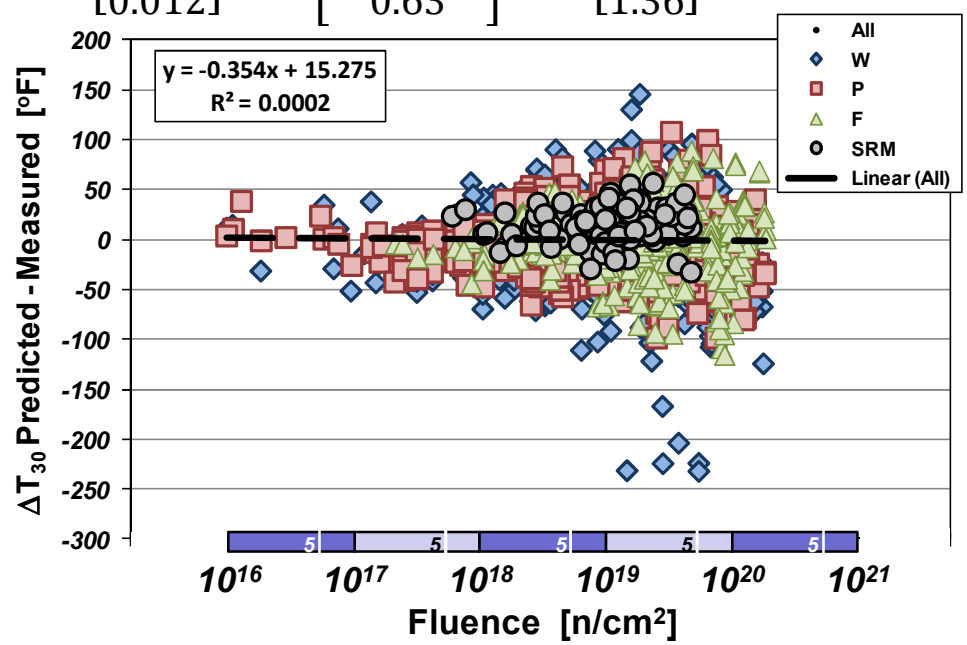
$$\boxed{\text{[illegible]} = 0.073\Phi^{0.138}}$$

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
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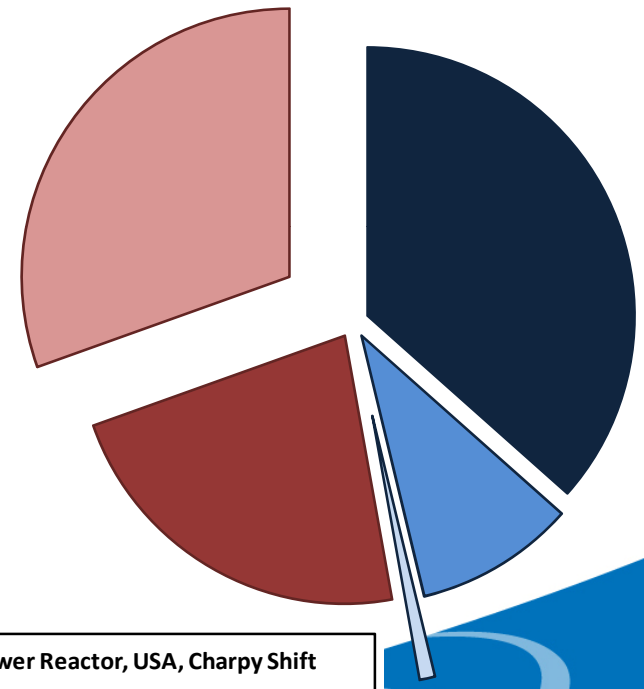

- Power Reactor, USA, Charpy Shift
- Power Reactor, Non-USA, Charpy Shift
- Power Reactor, Non-USA, Yield Shift
- Test Reactor, Charpy Shift
- Test Reactor, Yield Shift

Accuracy Assessment

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

Set ID	Product Form	Reactor Type	Highest Fluence [n/cm^2]	Flux [n/cm^2/s]	Temperature [^{o}F]	Cu	Ni	Mn	P
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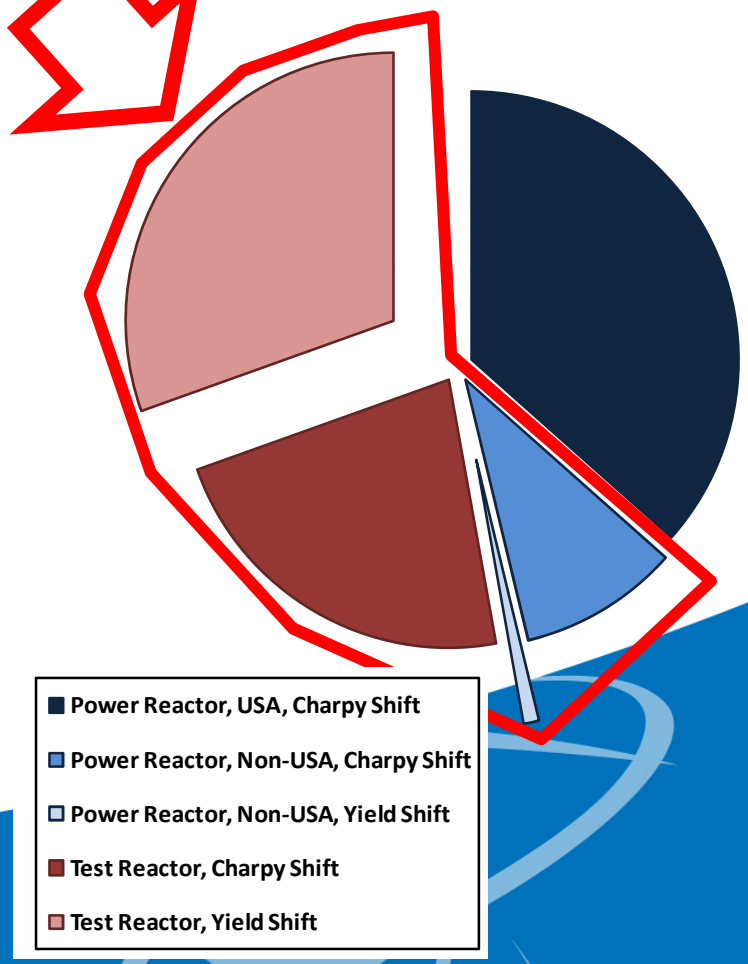
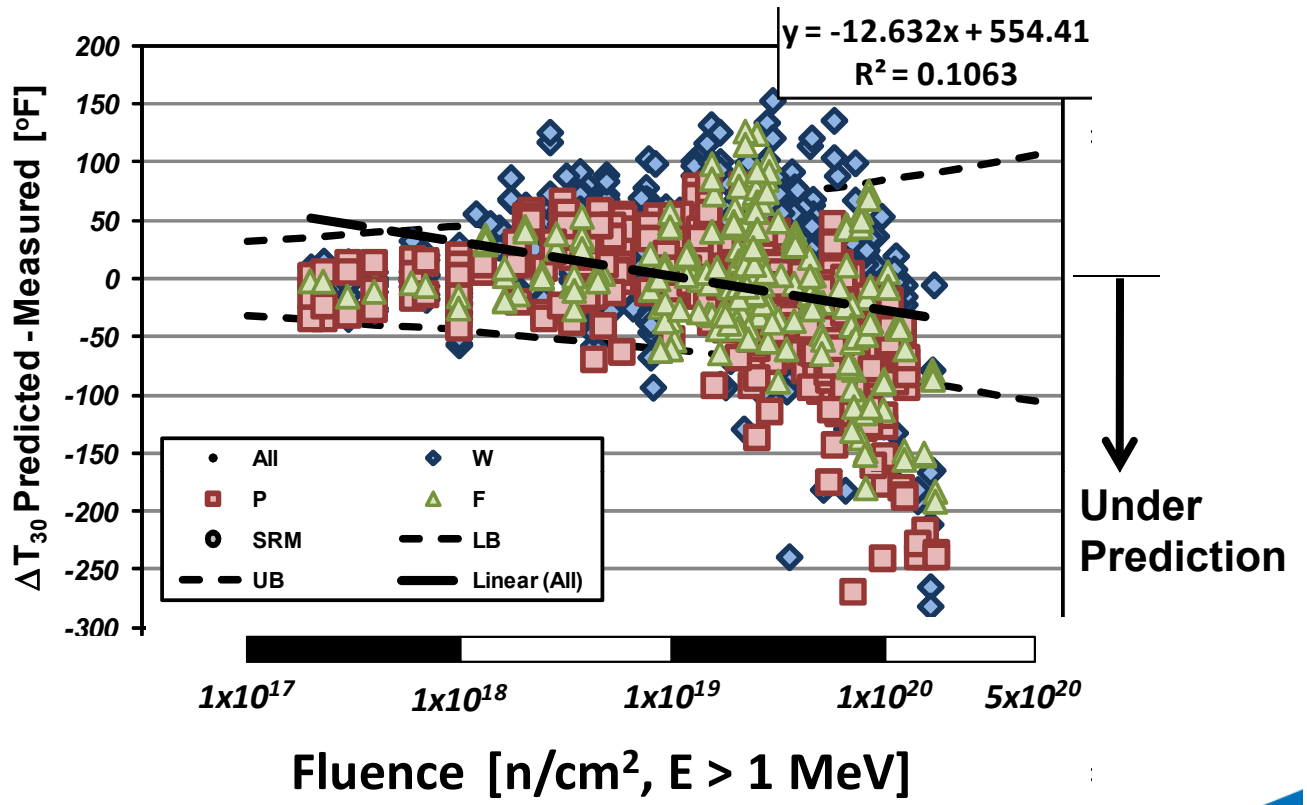


Assessment Methods

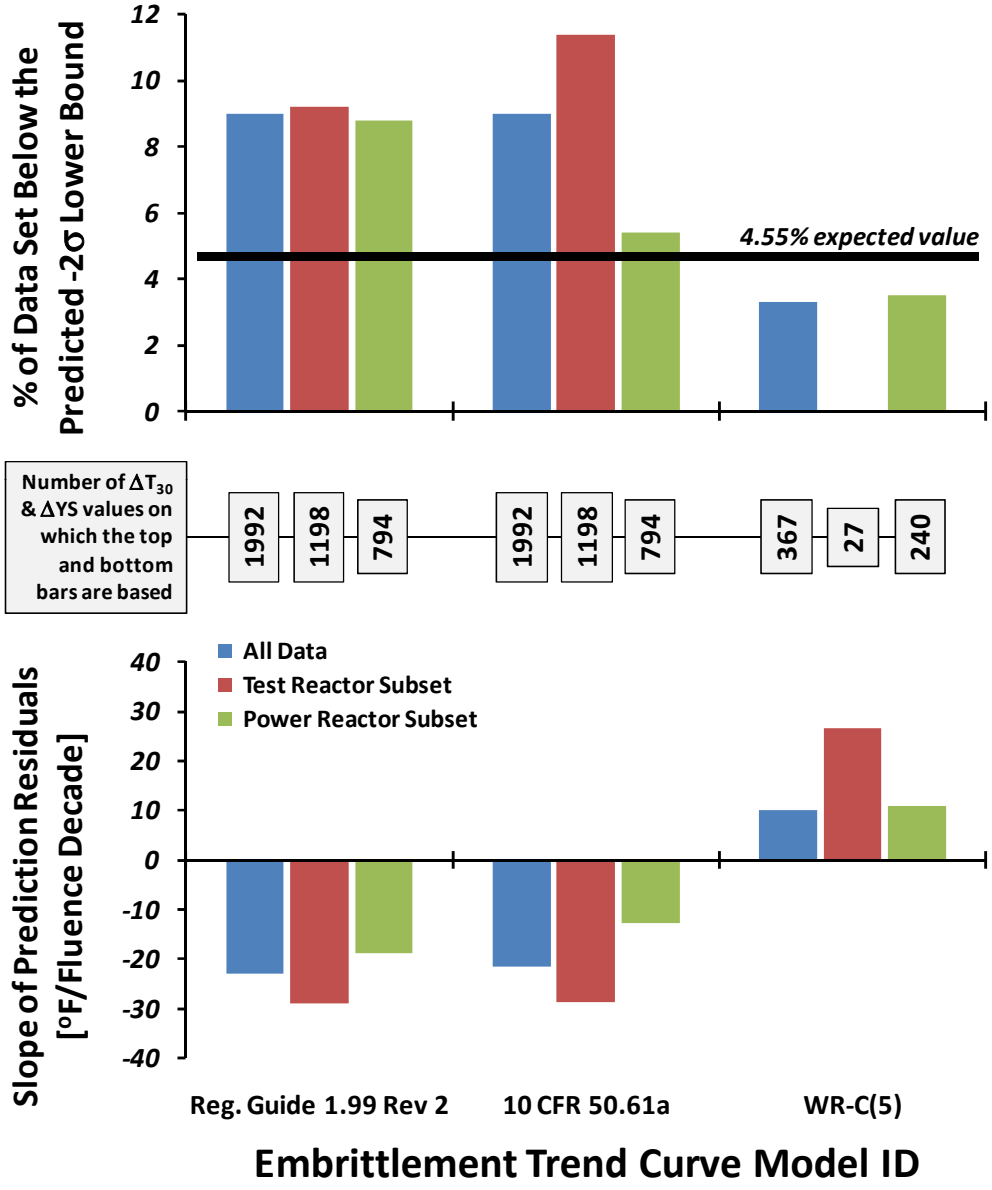
- Examine % of data set below the 2σ lower bound
- Examine trend of prediction residuals *vs.* fluence



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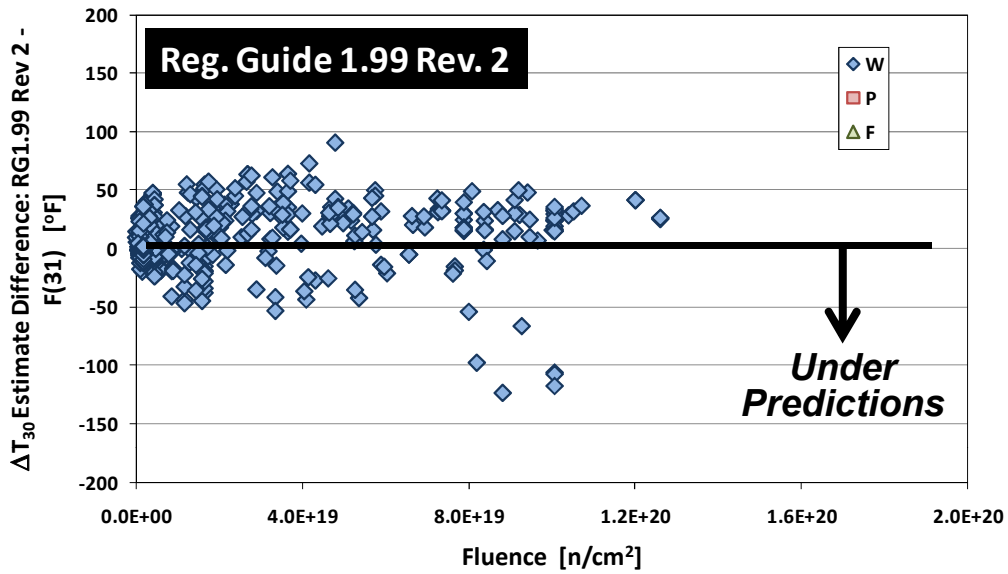
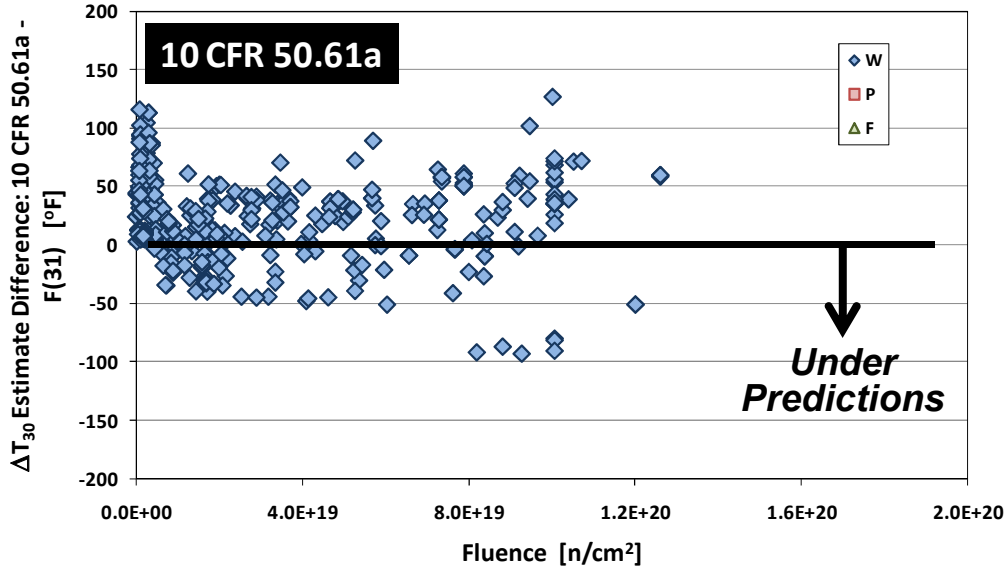
- Based on RVID-2 projected to 80 operating years
- Both
  - RG1.99R2, and
  - 10CFR50.61a

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





Plates

After 80 Years of Operation

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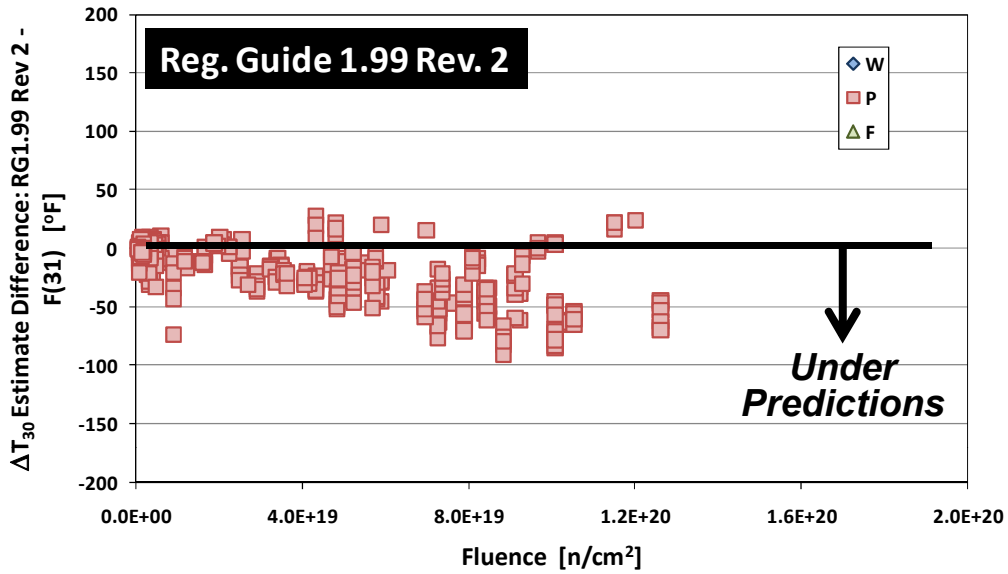
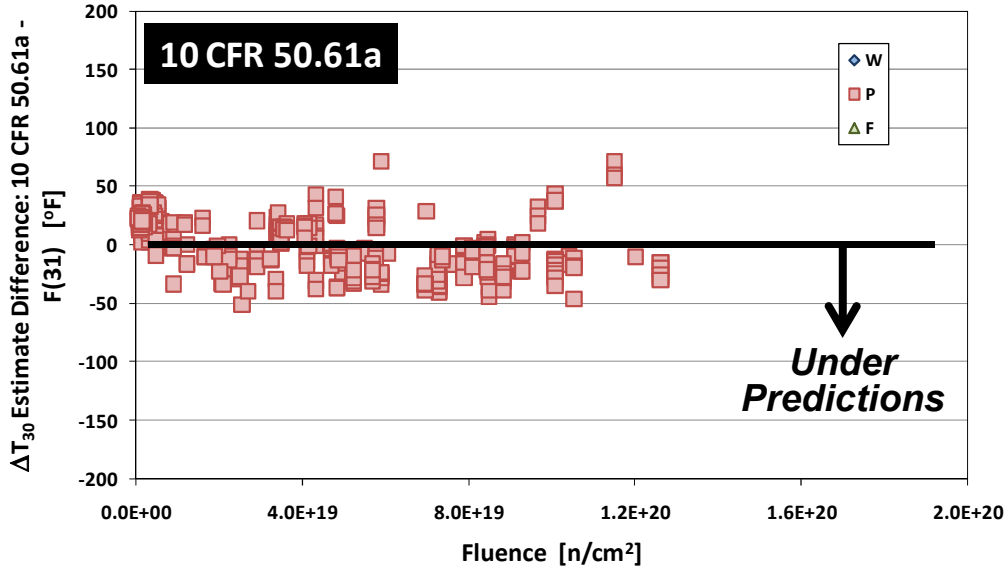
- Based on RVID-2 projected to 80 operating years
- Both
  - RG1.99R2, and
  - 10CFR50.61a

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





Forgings

After 80 Years of Operation

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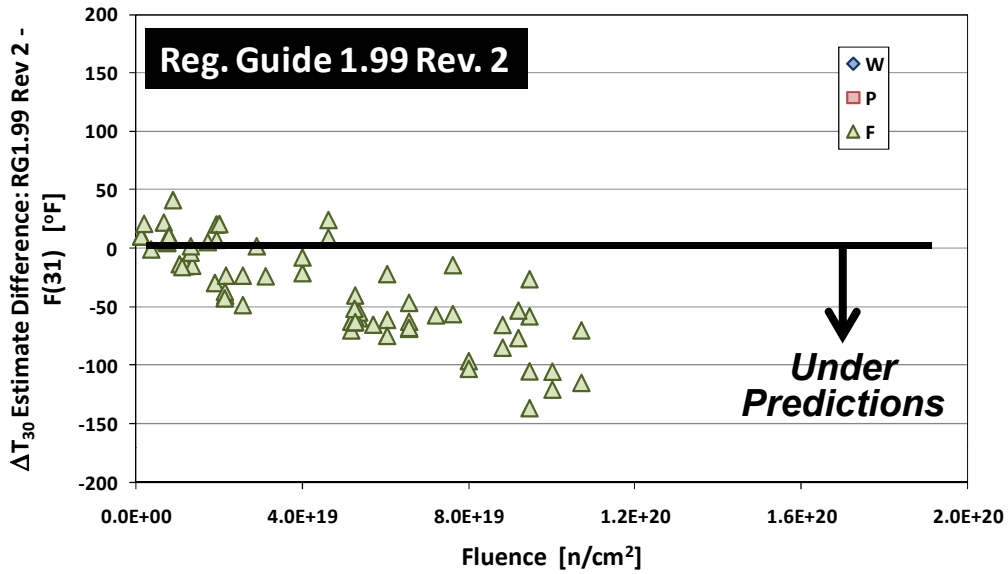
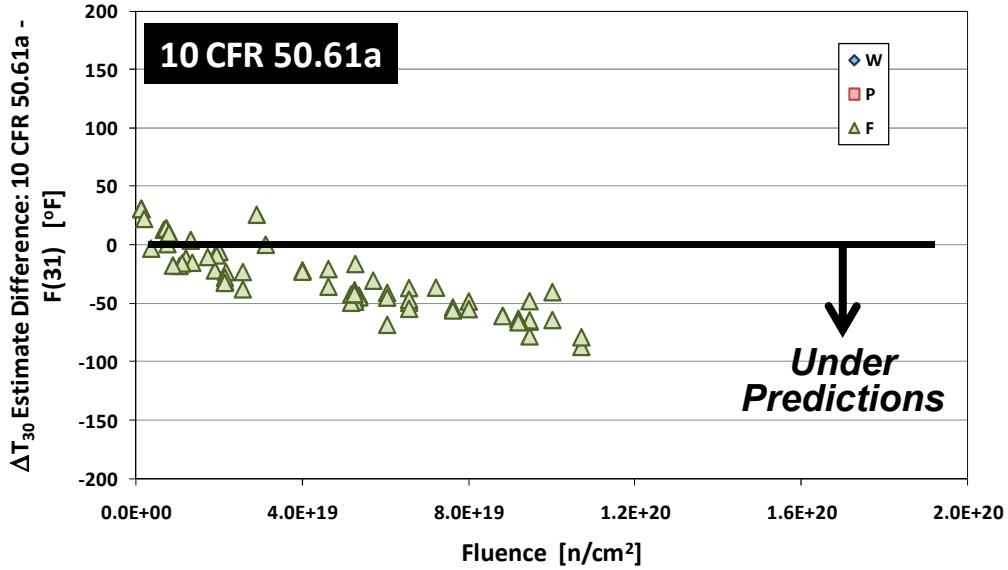
- Based on RVID-2 projected to 80 operating years
- Both
  - RG1.99R2, and
  - 10CFR50.61a

under-predict more as fluence increases





Why are only Forgings Under-Predicted?

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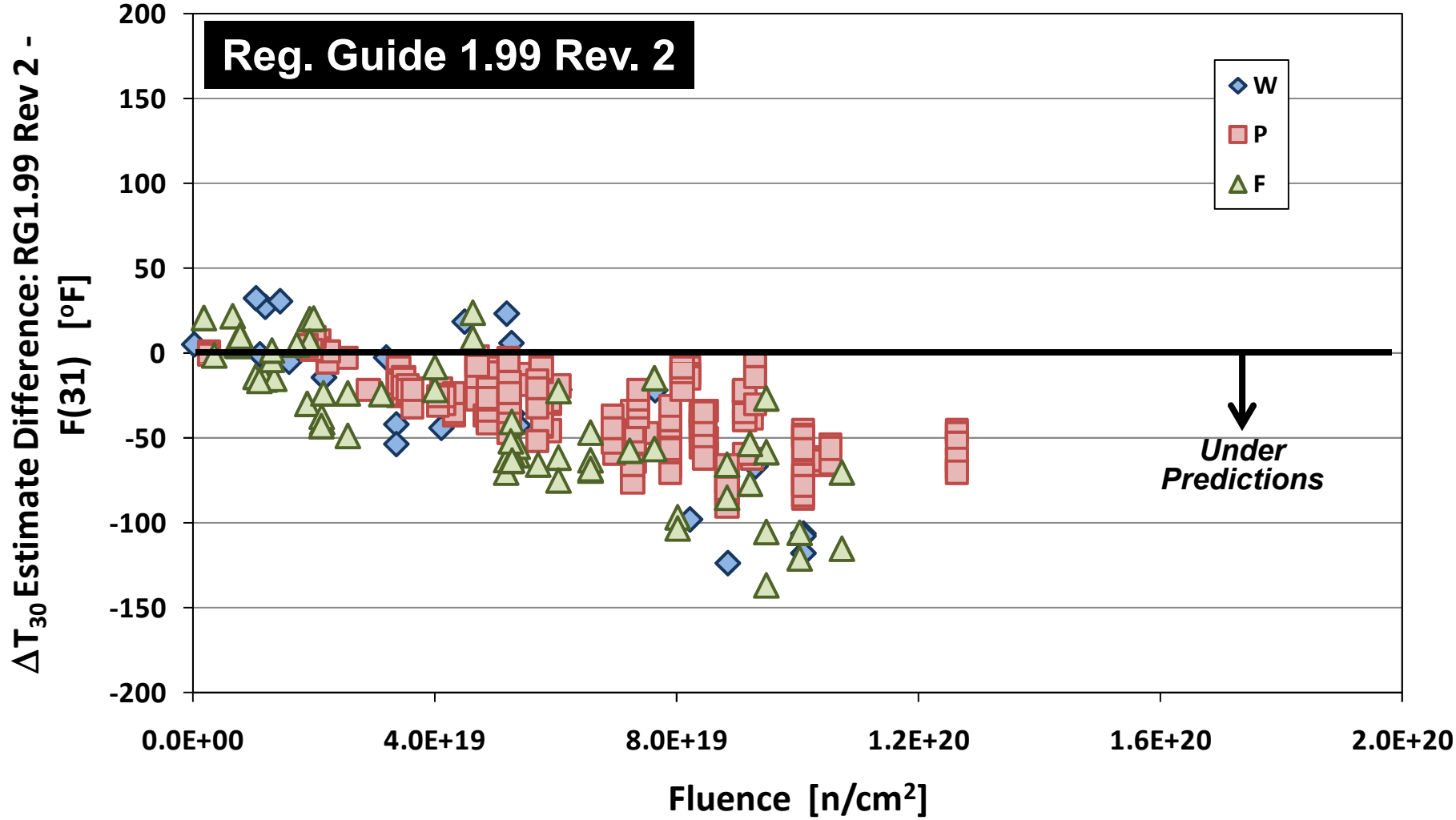
- It turns out it is not just the forgings, but rather ***all materials of similar chemistry***
  - Cu < 0.17 weight percent
  - Ni > 0.4 weight percent
- All materials of this chemistry range tend toward under-prediction as fluence increases
- BWRs are excluded from further comparisons because they 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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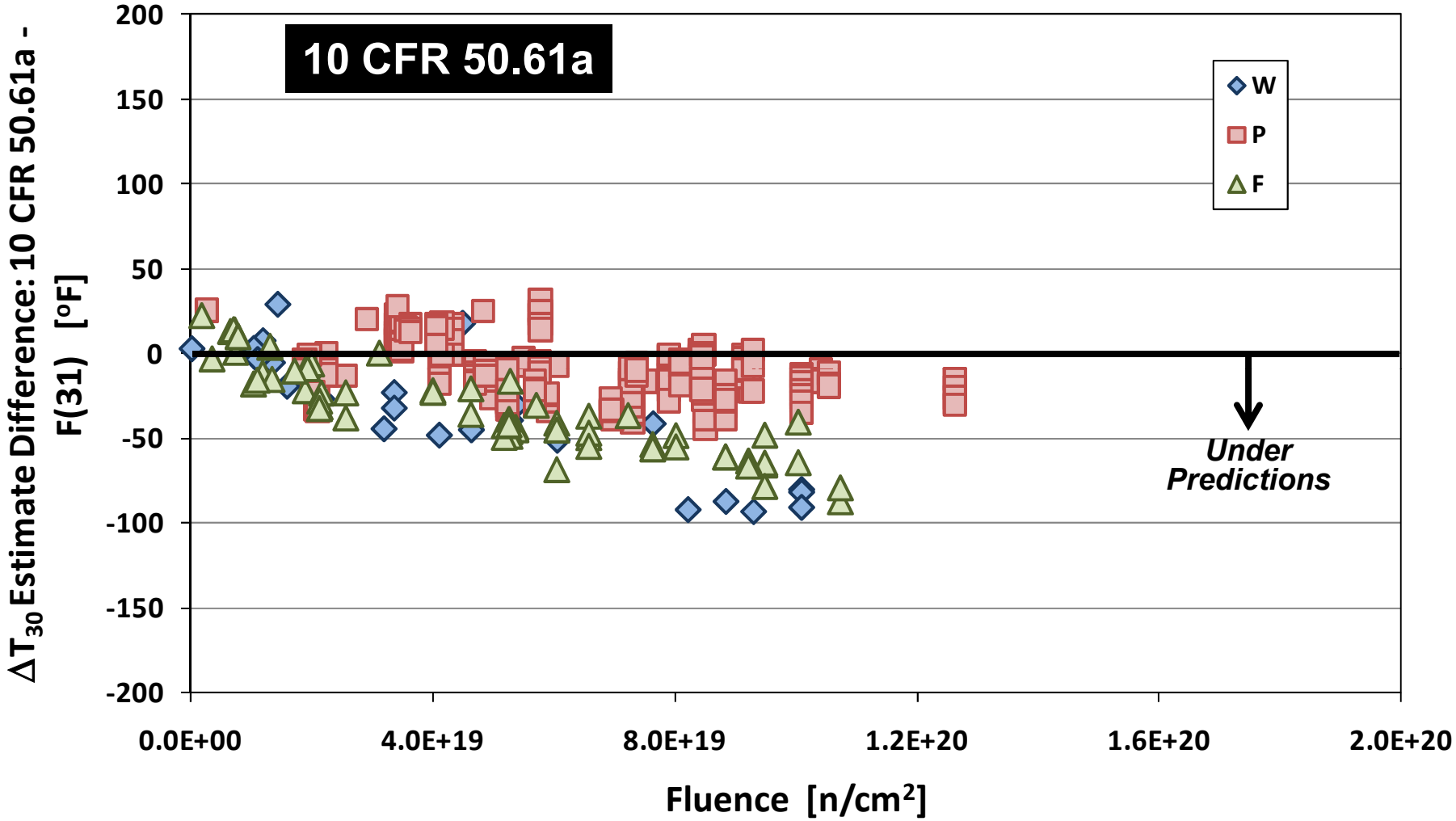

Summary

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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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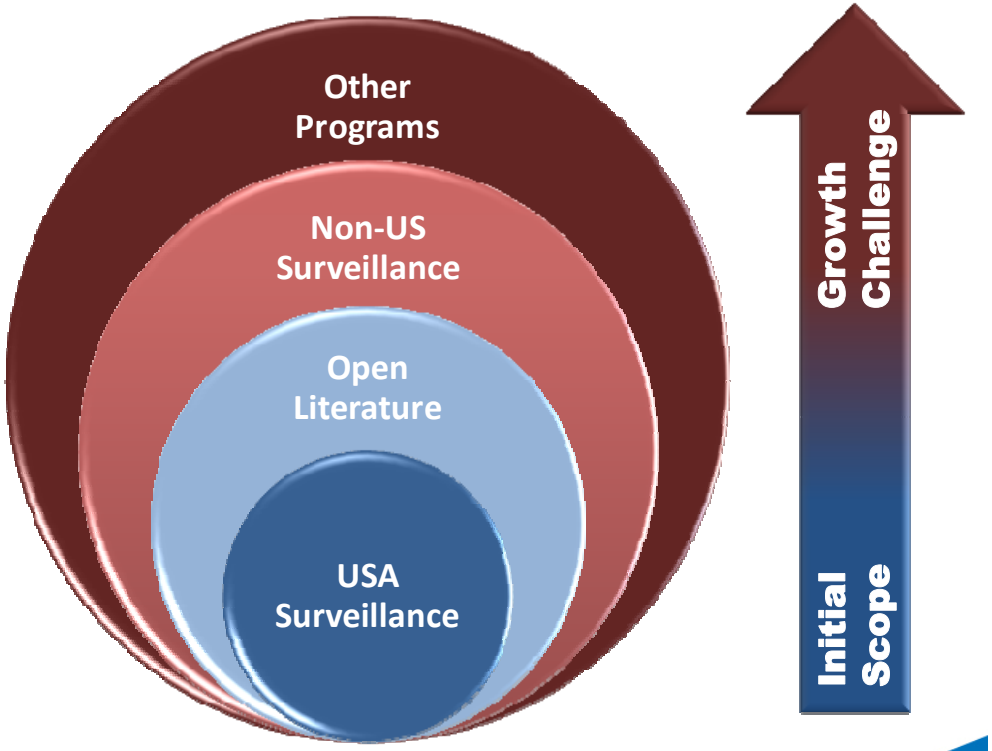
Database Characteristics

- 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

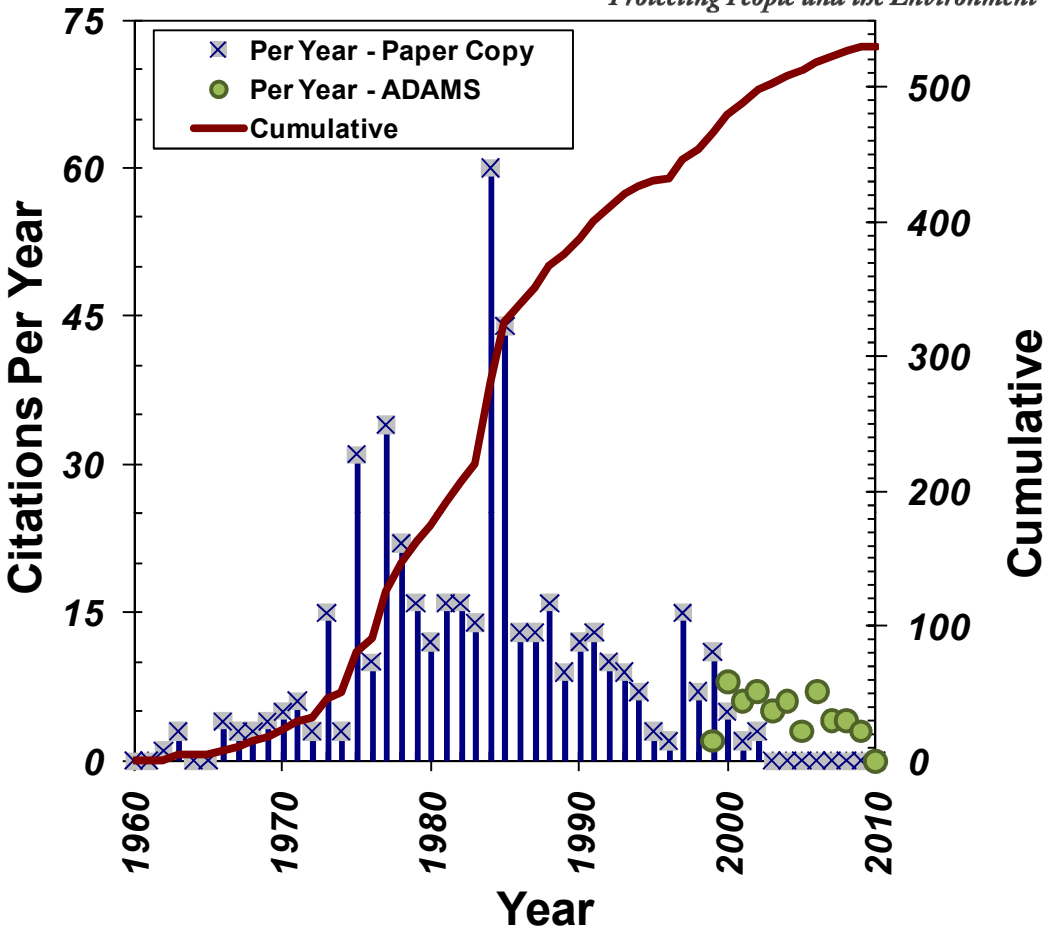


Initial Information Sources

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

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

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

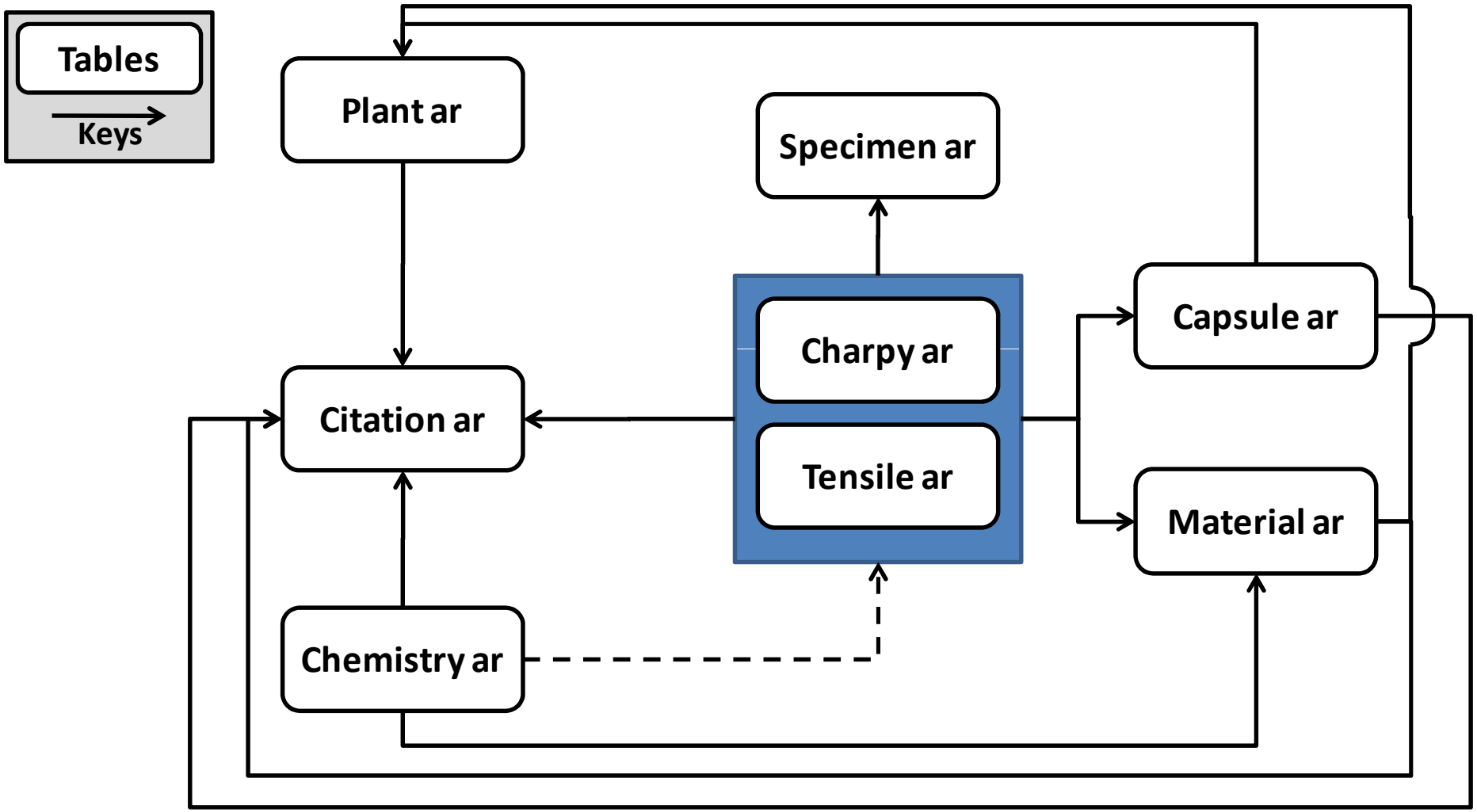
ar
- As-reported layer
- Verbatim echo of information in source documents
- No interpretation

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

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

- 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