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50.46c Implementation: Cladding Hydrogen Uptake Models

50.46c Testing Requirements and Guidance
Oak Ridge National Laboratory
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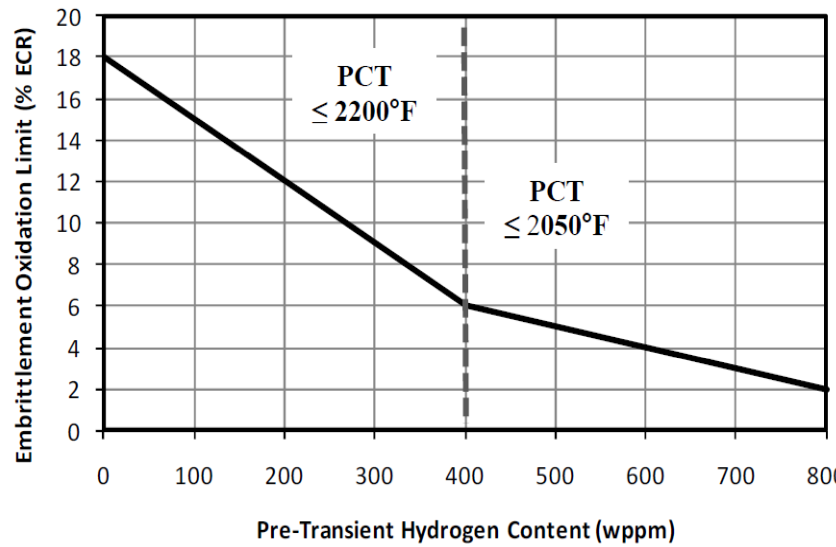
Paul M. Clifford
Division of Safety Systems
Nuclear Reactor Regulation

DG-1263 Figure 2

- Figure 2 of DG-1263 provides an acceptable analytical limit on peak cladding temperature and integral time-at-temperature (CP-ECR) as a function of pre-transient cladding hydrogen content



- Steady-state cladding waterside corrosion and hydrogen pickup models are needed to translate these analytical limits to fuel burnup
- Based upon public comments, NRC will provide acceptable hydrogen models to aid 50.46c implementation

Revised FRAPCON Models

- PNNL recently expanded FRAPCON's cladding corrosion and hydrogen uptake validation database.
- Based upon the expanded database, PNNL recommended changes to the FRAPCON-3.4 best-estimate hydrogen uptake models

Table 1 Hydrogen models in FRAPCON-3.4 and new model

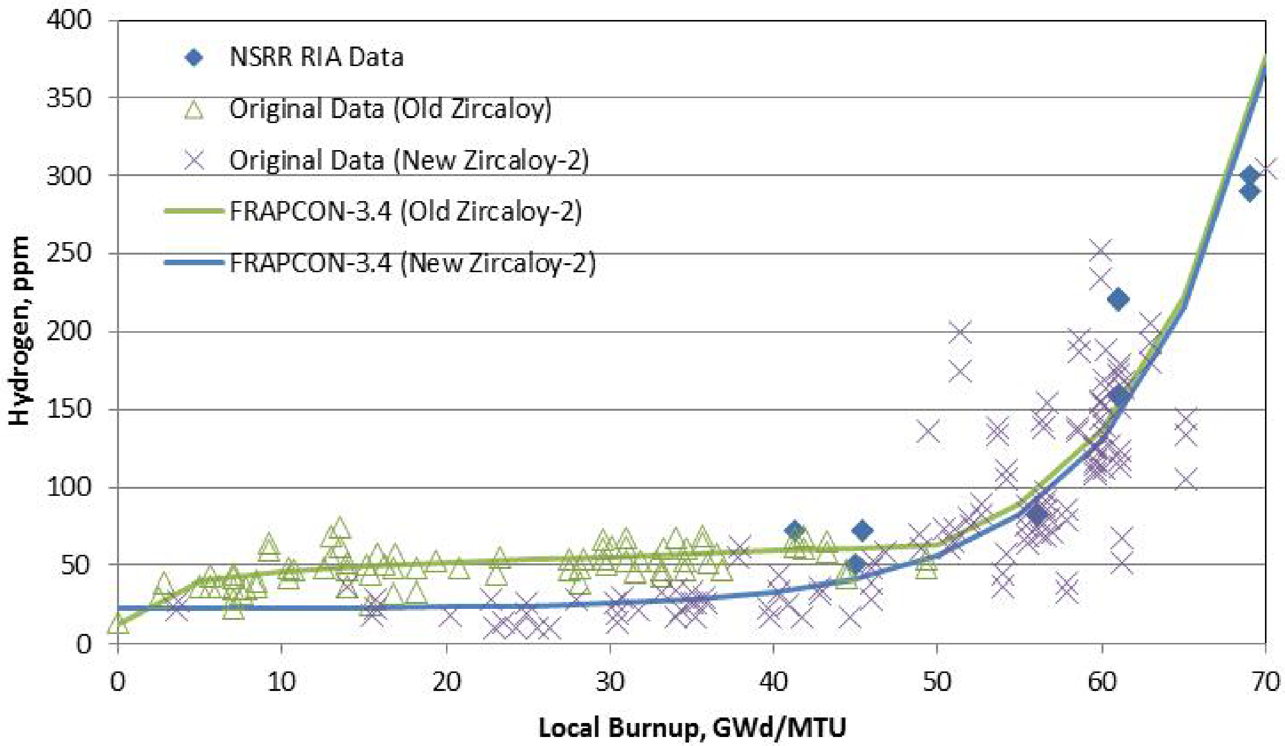
Alloy	FRAPCON-3.4		New Model	
	Model	Std. dev.	Model	Std. dev.
BWR				
Zry-2 pre 1998	Eq. 2	10 ppm[1] NA[2]	Eq. 2	10 ppm[1] 54 ppm[2]
Zry-2 post 1998	Eq. 3	11 ppm[1] 61 ppm[2]	Eq. 3	13 ppm[1] 60 ppm[2]
PWR				
Zry-4	15%[3]	40 ppm	15.3%[3]	94 ppm
ZIRLO™	12.5%[3]	162 ppm	17.3%[3]	110 ppm
M5™	10%[3]	20 ppm	10%[3]	23 ppm

[1] standard deviation below 50 GWd/MTU
[2] standard deviation above 50 GWd/MTU
[3] pickup fraction

- Standard deviation in hydrogen model quantified.
- Results 1st published at 2011 WRFP Meeting.
- NUREG/CR-7022 Vol.1 Rev.1 documents new models.

FRAPCON-3.5 Zry-2 Model

- For boiling water reactor (BWR) conditions, a constant hydrogen pickup fraction does not fit the observed cladding hydrogen data.
  - FRAPCON-3.5 uses a burnup-dependent hydrogen concentration model.



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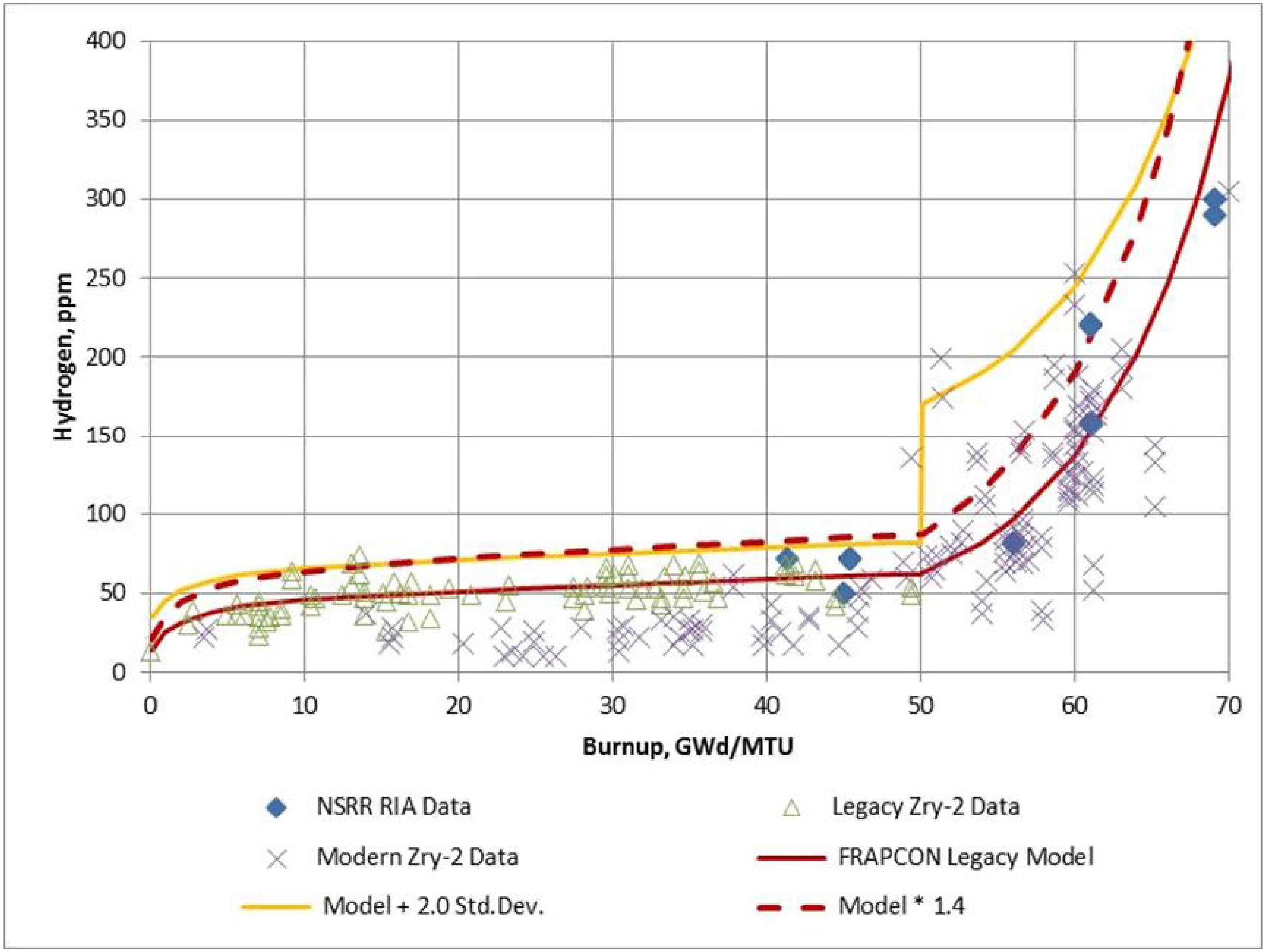
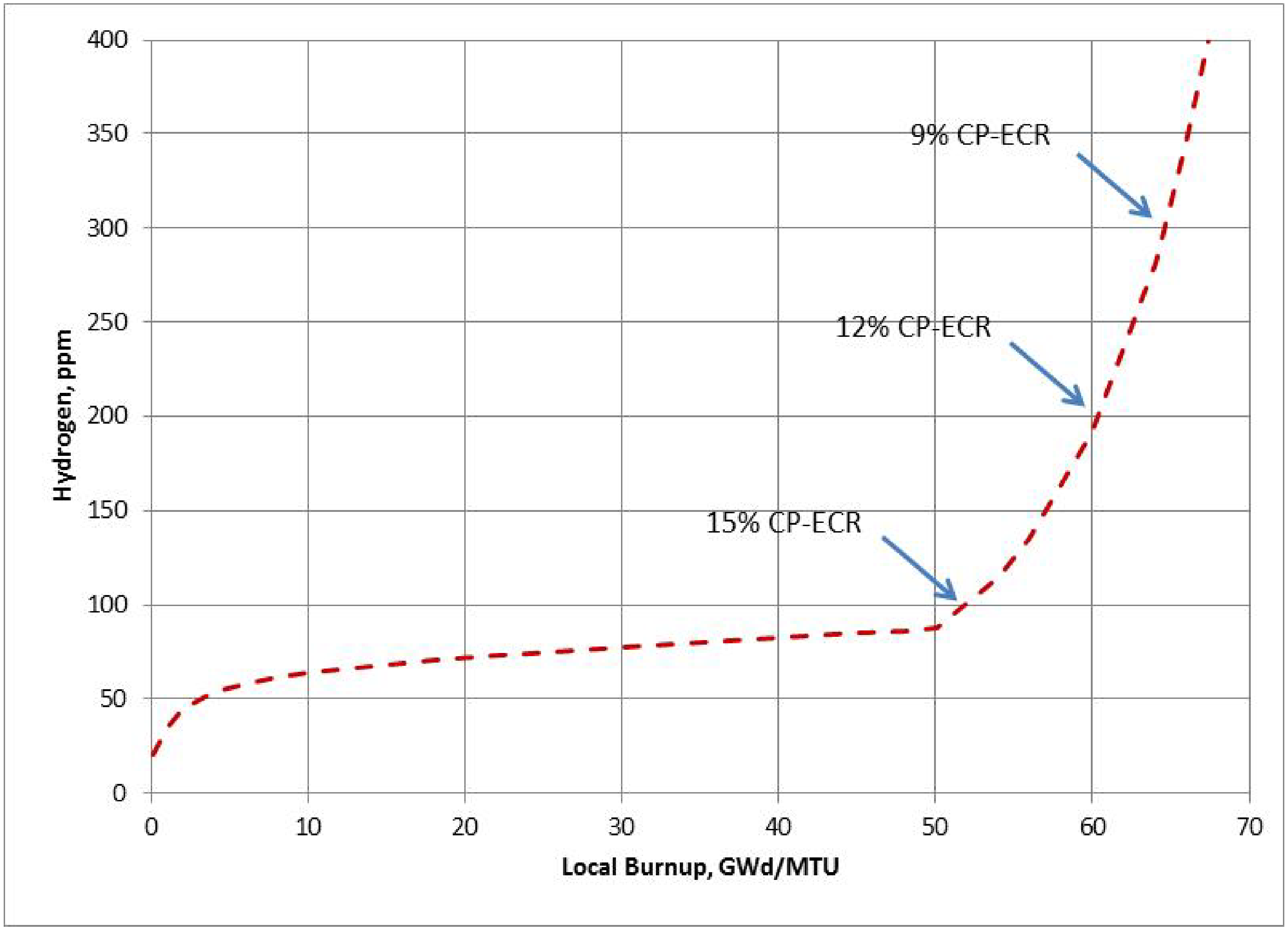
Variability and Uncertainty

- Given the (1) lack of data from each vendor, (2) lack of sensitivity studies on operating conditions and plant chemistry, (3) allowable range in composition within the Zircaloy-2 ASTM specification, and (4) degree of flexibility and variability in manufacturing procedures among and between fuel vendors, the staff has elected to adopt a hydrogen model with the following attributes:
  - Encompass both modern and legacy alloys
  - Apply +2-sigma on the model prediction

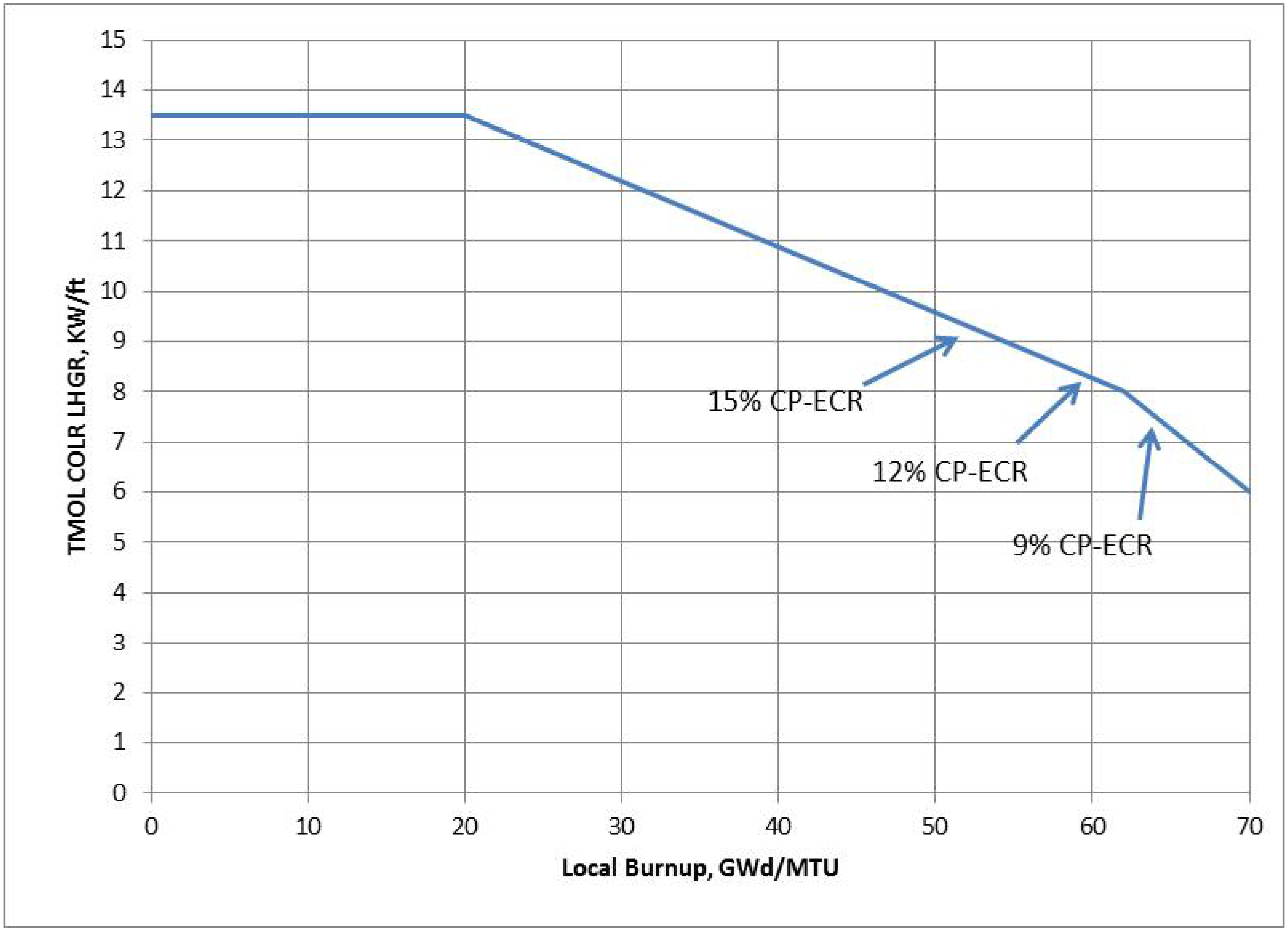
Acceptable Zry-2 Model



Allowable CP-ECR vs BU



Allowable CP-ECR vs TMOL



PWR Cladding Alloys

- Corrosion rates and the amount of corrosion at discharge vary widely across the PWR fleet due to alloy composition, operating conditions, and residence time.

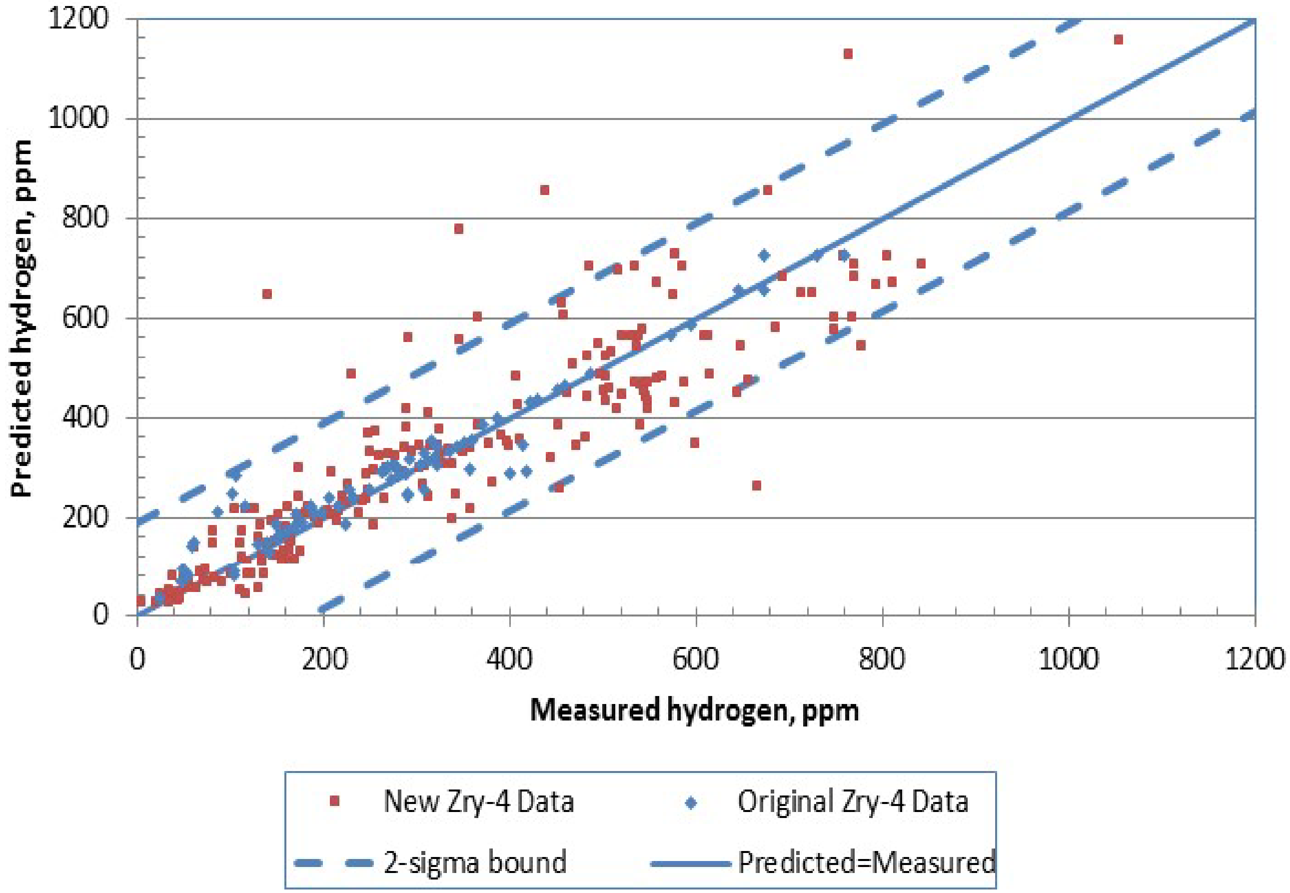
- Fuel vendors have approved fuel performance analytical tools along with corrosion models. In general, these corrosion models are capable of predicting a best-estimate corrosion thickness as a function of residence time (EFPD) and local operating conditions (fuel duty).

PWR Cladding Alloys

- An examination of available PWR cladding hydrogen data suggests the following trends:
  - PWR cladding alloys do not exhibit the same breakaway hydrogen uptake at higher fluence levels as observed in the Zircaloy-2 data.
  - Hydrogen pickup fraction does appear to be alloy-specific.
- As a result, a constant hydrogen pickup fraction will be proposed for each zirconium alloy.
- These hydrogen pickup fractions should be used, along with a best-estimate prediction of the peak oxide thickness using an approved fuel rod thermal-mechanical model, to estimate the cladding hydrogen content.

FRAPCON-3.5 Zry-4 Model

- Based upon 280 data points, PNNL recommended a pickup fraction of 15.3% with a standard deviation of 94 wppm.

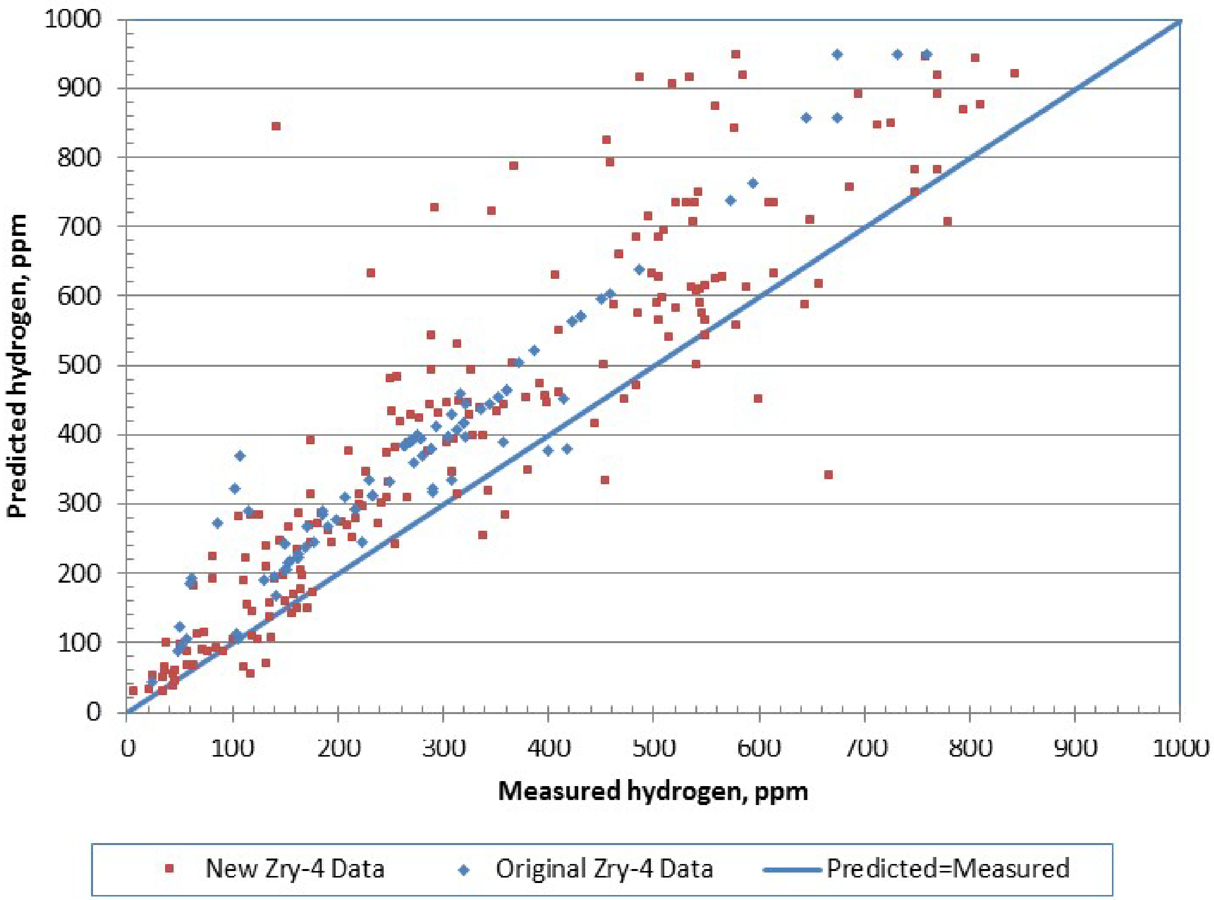


Variability and Uncertainty

- Similar to the above BWR model, the staff initially decided to apply a +2-sigma on the model prediction to account for variability and uncertainty in the database.
- With over 280 data points, a 95/95 non-parametric statistical upper bound could be derived. However, given all of the variables (e.g., alloy content, operating conditions) and uncertainties, there is no guarantee that the data is actually poolable.
- Furthermore, the application of a constant, additive standard deviation has negative attributes:
  (1) Overly conservative when applied to low burnup, low corrosion fuel rods
  (2) no recognition for larger scatter in highly corroded fuel rods

Acceptable Zry-4 Model

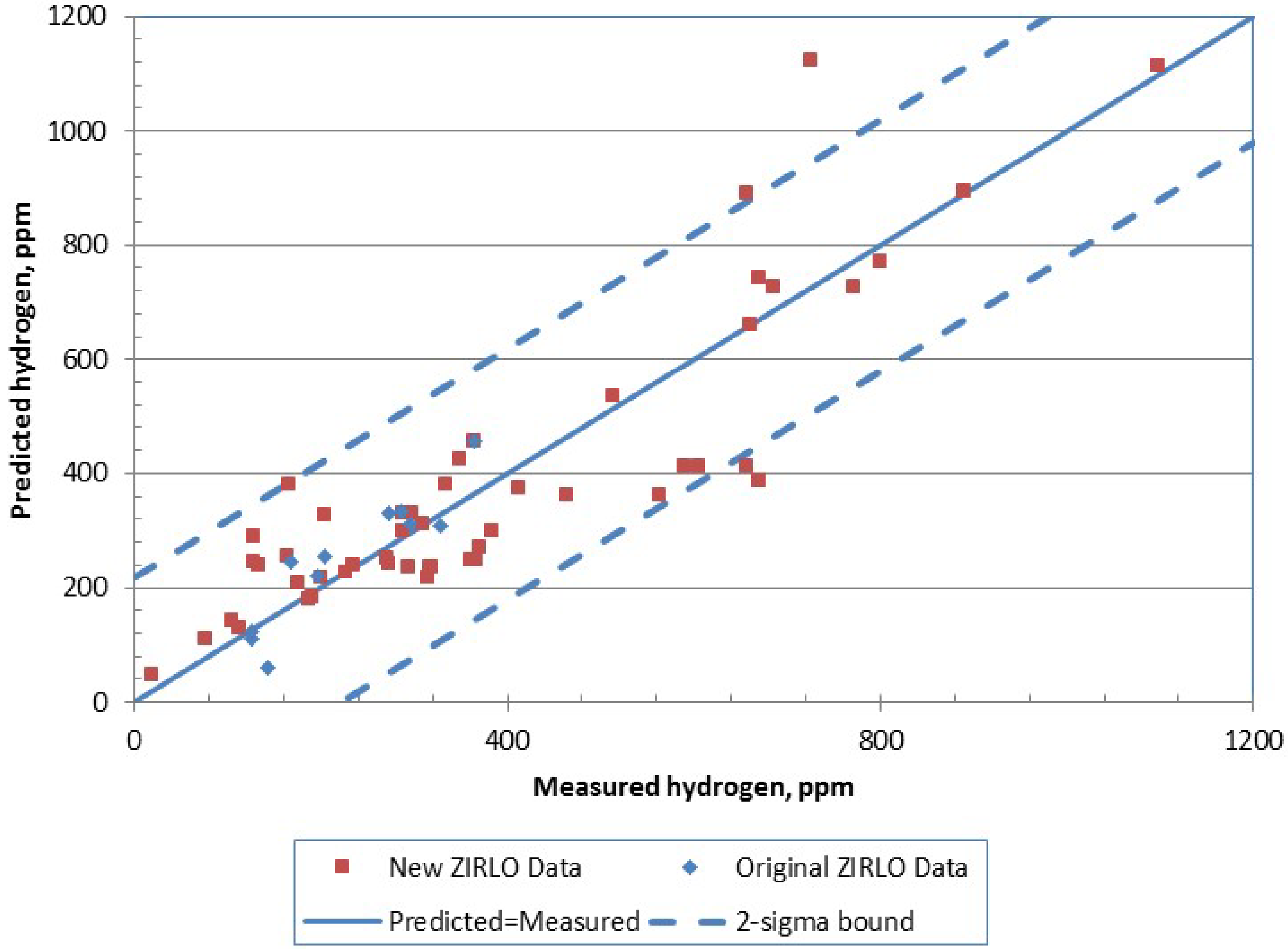
- Staff elected to iterate on pickup fraction until a reasonable upper bound prediction was obtained.



20% Pickup

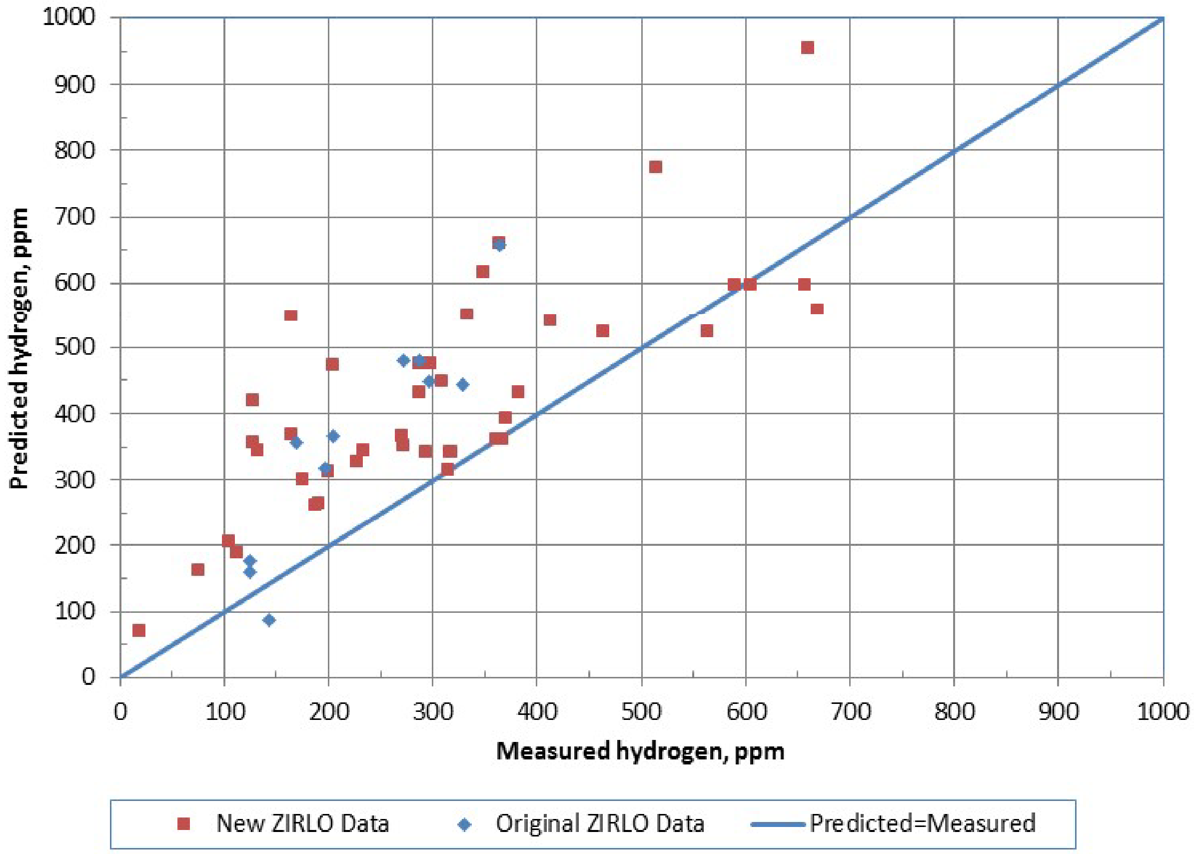
FRAPCON-3.5 ZIRLO™ Model

- Based upon 60 data points, PNNL recommended a pickup fraction of 17.3% with a standard deviation of 110 wppm.



Acceptable ZIRLO™ Model

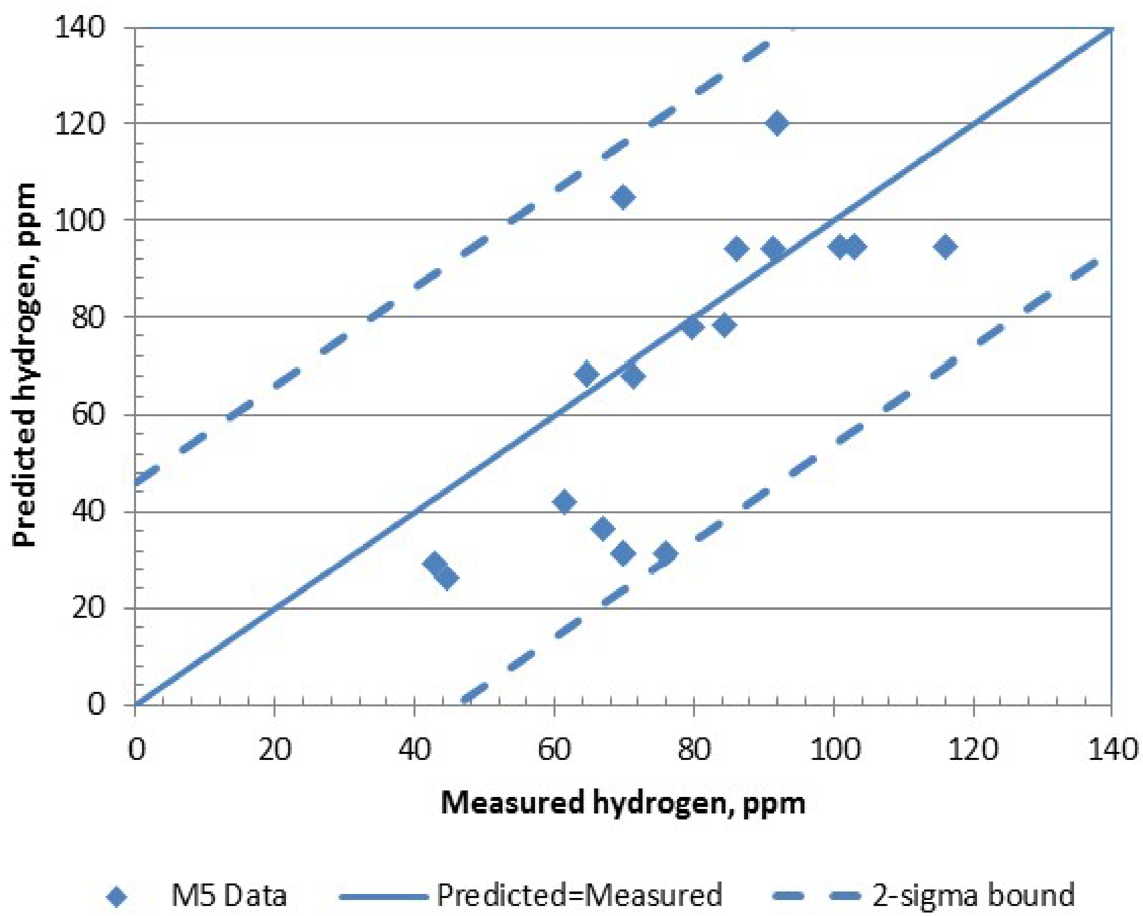
- Staff elected to iterate on pickup fraction until a reasonable upper bound prediction was obtained.



25% Pickup

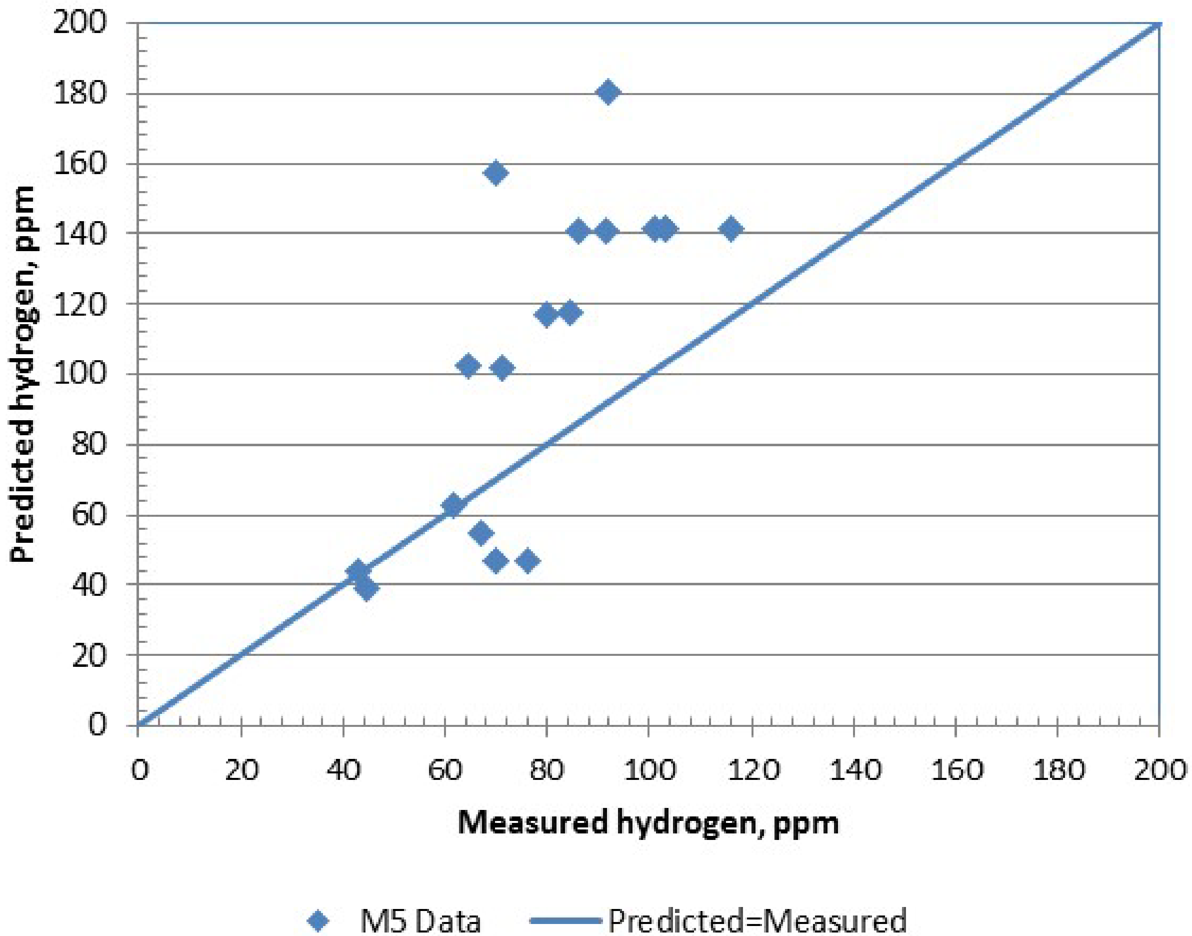
FRAPCON-3.5 M5™ Model

- Based upon 17 data points, PNNL recommended a pickup fraction of 10% with a standard deviation of 23 wppm.



Acceptable M5™ Model

- Staff elected to iterate on pickup fraction until a reasonable upper bound prediction was obtained.



15% Pickup

Acceptable PWR Models

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- Based on the above discussion, the staff finds the following bounding hydrogen pickup fractions acceptable.

Zircaloy-4	= 20% hydrogen absorption
ZIRLO^{TM}	= 25% hydrogen absorption
Optimized ZIRLO^{TM}	= 25% hydrogen absorption
M5^{TM}	= 15% hydrogen absorption

- These hydrogen pickup fractions should be used, along with a best-estimate prediction of the peak oxide thickness using an approved fuel rod thermal-mechanical model, to estimate the cladding hydrogen content.

Range of Applicability

- Applicability limited to current limits on fuel rod burnup and residence time.
- Applicability limited to currently approved commercial cladding alloys.
  - Not applicable to new alloys.
- Not applicable to fuel rods which experience oxide spallation.