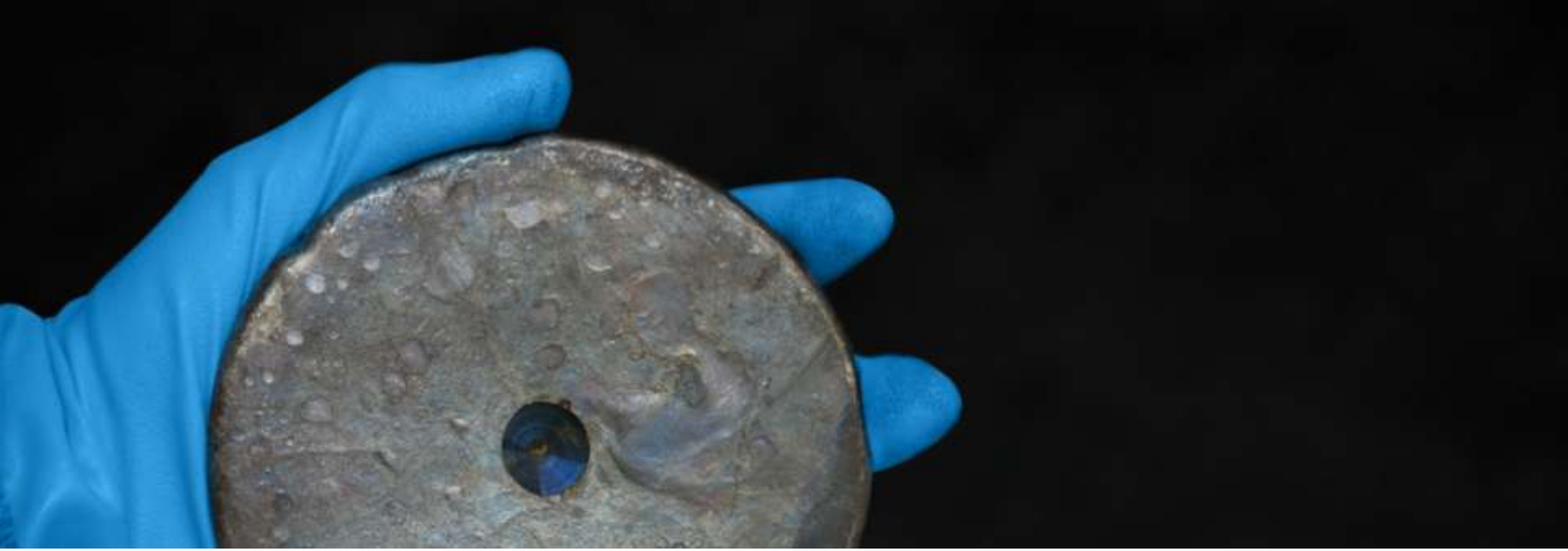

Artificial Neural Network Representation of Criticality Excursion Experiment Data

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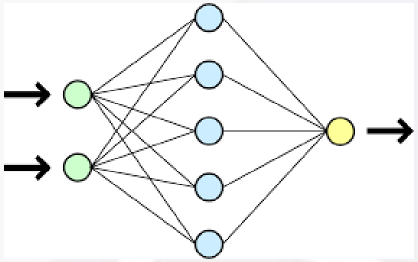
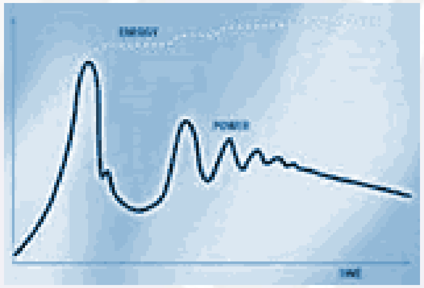
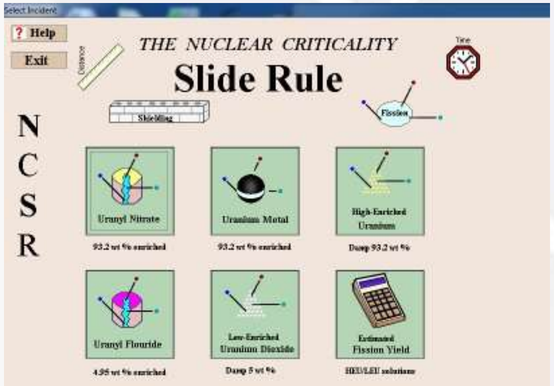
Brief Talk

- Working with data – the old fashioned way
- Why an Artificial Neural Net (ANN)?
- ANN “Lite” - A gentle introduction
- Solution criticality excursion characteristics
- ANN Mechanics – Essential steps
  - Designing the ANN architecture
  - Selecting input and output variables
  - Training/Testing/Validating ANN input/targets
  - Checking the ANN with additional KEWB and CRAC
  - Using the ANN – Slide Rule Test Set
- Comparing/verifying results
- Conclusions - Applications, Enhancements





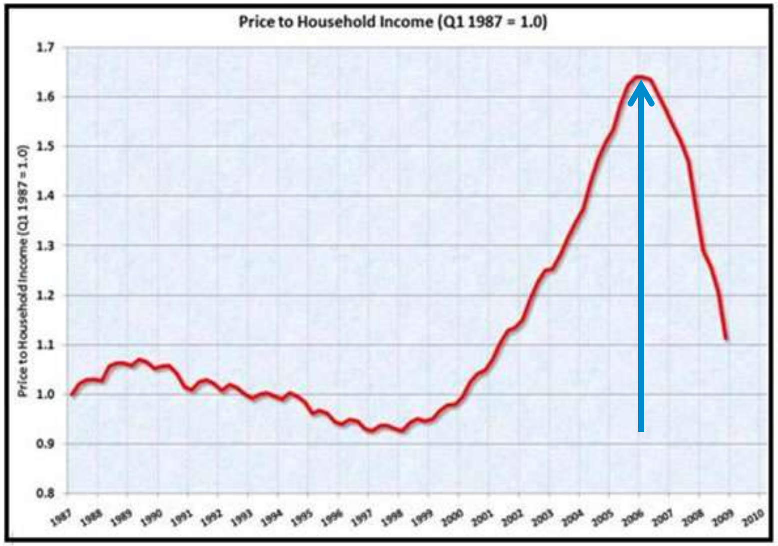
SILENE from LA-13638



From Hopper, Broadhead

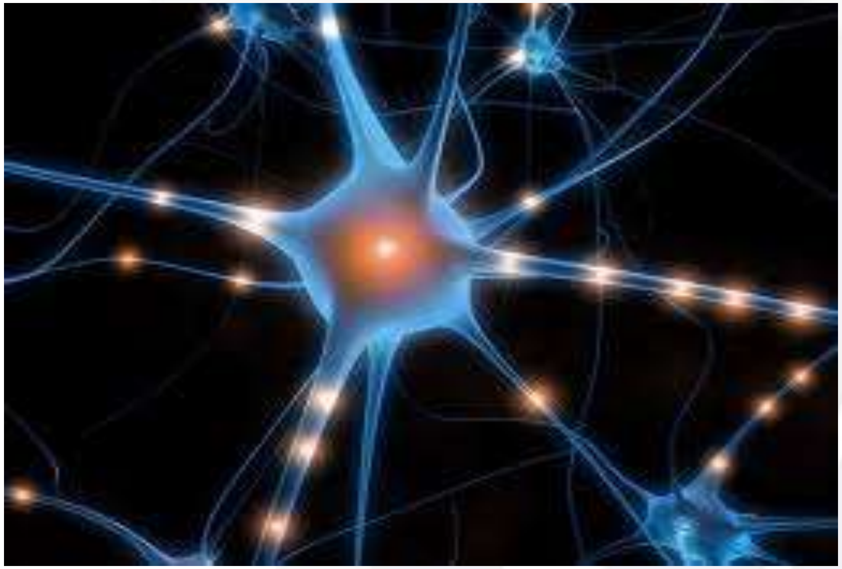
Working With Data – The Old Fashioned Way

- Example – Buying a house
- Objective – Optimal decision
- "Heuristic" or holistic analysis process:
    - **Collect** multivariate data
    - **Classify**, categorize, sort
    - **Prioritize**, rank, give "***weight***"
    - **Identify** relationships
    - **Seek** patterns
    - **Develop** ad hoc "functions"
    - **Detect** trends, outliers, anomalies
    - **Predict** outcomes
- Pitfalls – Data, - too little weight, data, too homogenous, local min/max, uncertainty
- **LEARN FROM DATA, EXPERIENCE**



2006 Housing Bubble

Why an Artificial Neural Net? – Consider the Brain

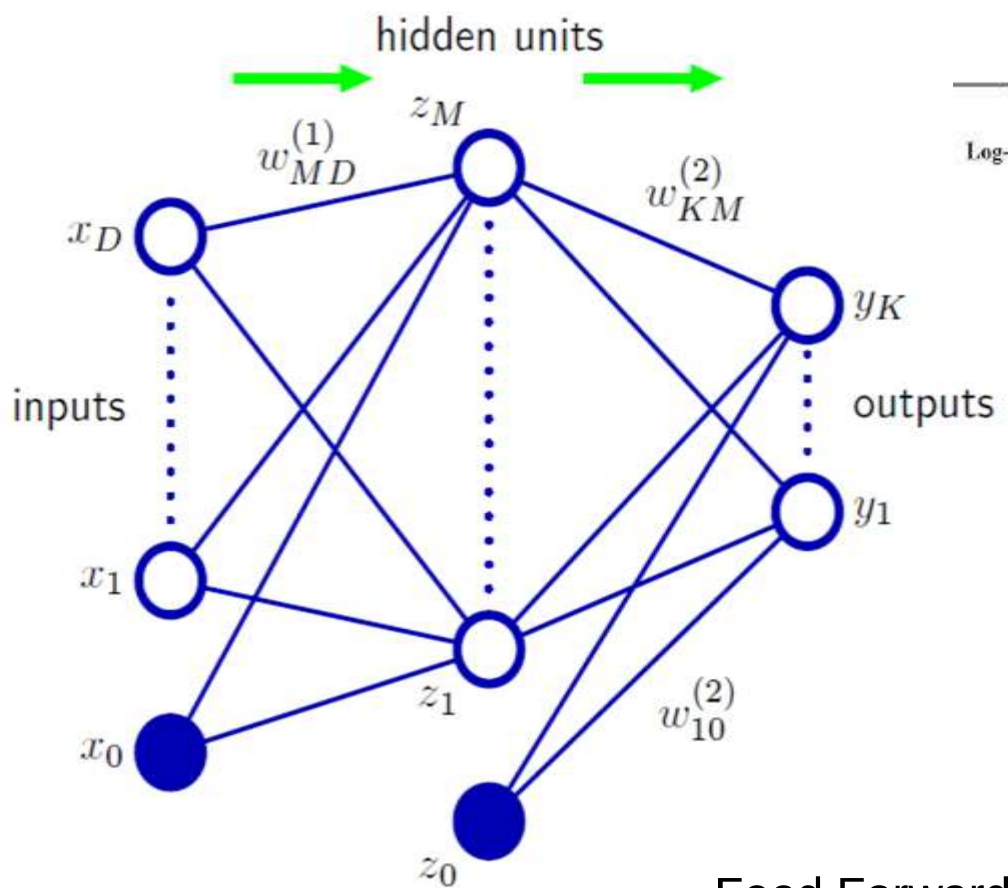


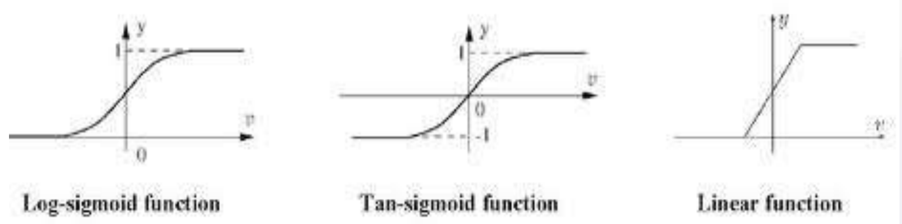
The brain calculates in parallel, considering multiple inputs, multiple outputs, and complex patterns and relationships between them.

Signals propagate through a "network" of interconnected neurons where "learning" takes place

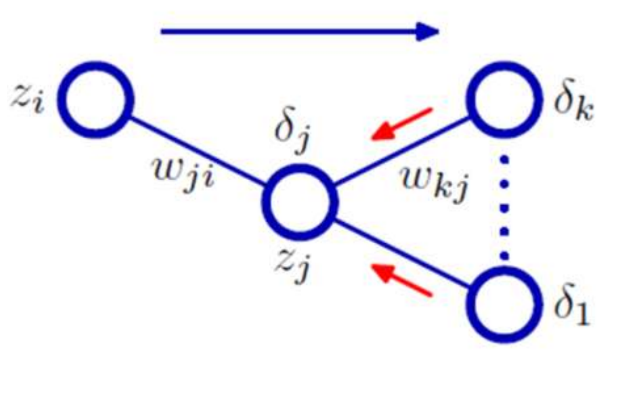
The brain model for computation accommodates sparse data, nonlinearity

ANN “Lite” – A Gentle Introduction





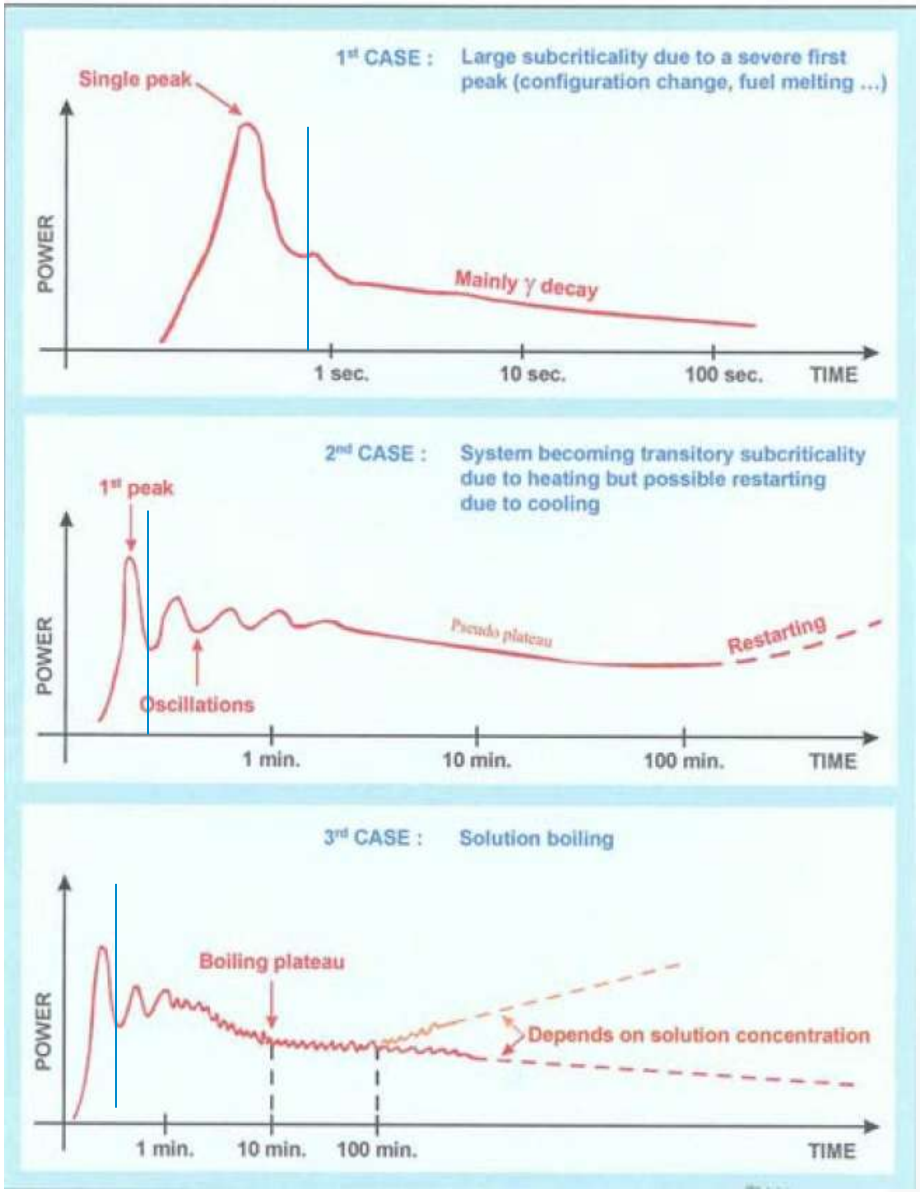
Transfer functions are used to calculate a layer's output from its network input.



Feed Forward with Error Back Propagation (FFBP)

The ANN mimics the natural brain computing function to predict outputs involving “learned weights” over a wide parameter space

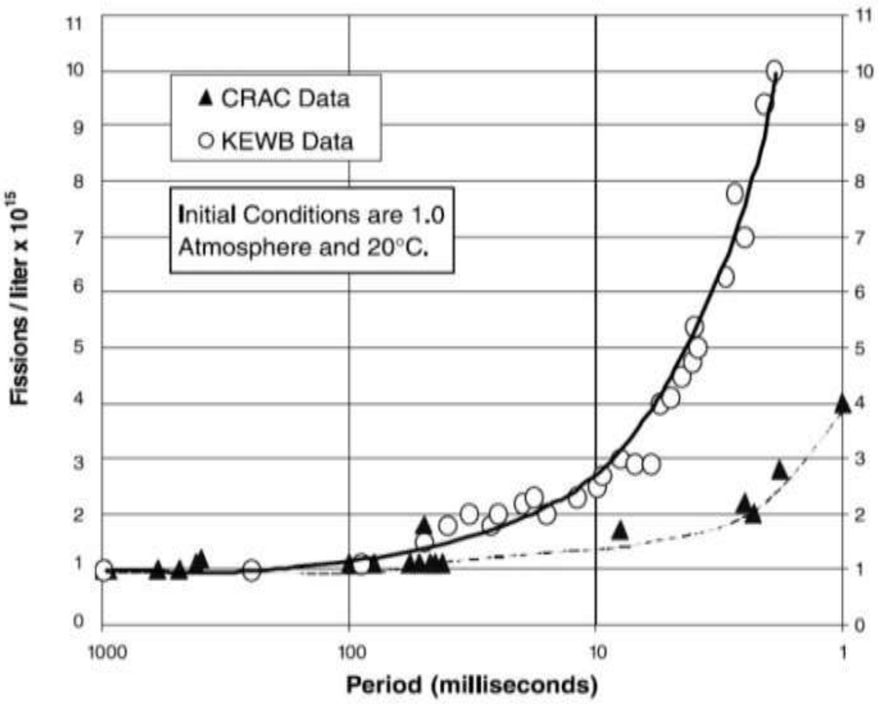
Critical Solution Excursion Physics



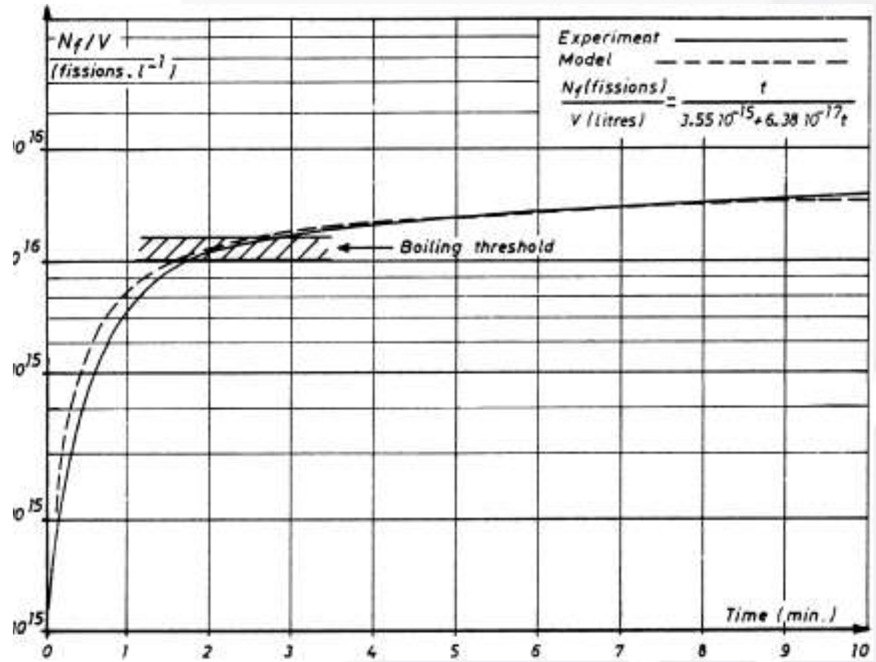
For this **initial work** with ANNs, we will focus on predicting/verifying **initial spike characteristics**

From F. Barbry, NS&E 161 2009

Critical Solution Excursion Characteristics



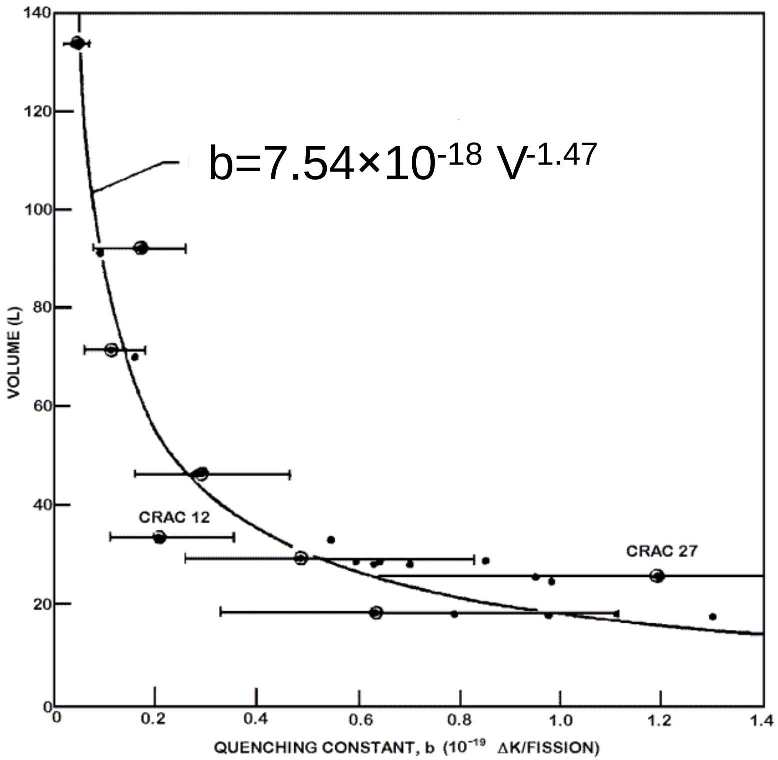
From T. McLaughlin ICNC 2003



From F. Barbry

Well characterized relationships are directly tied to experiment parameters

Application of Experiment Data – Hansen Weak Source



From Mee, Reed, Taylor 1988

$$E(t_1) = \frac{1}{b}\left[\alpha^2 t_1^2 + 2\alpha\tau \, \ln\left(\frac{2\alpha\tau \, W(t_1)}{b}\right)\right]^{\frac{1}{2}},$$

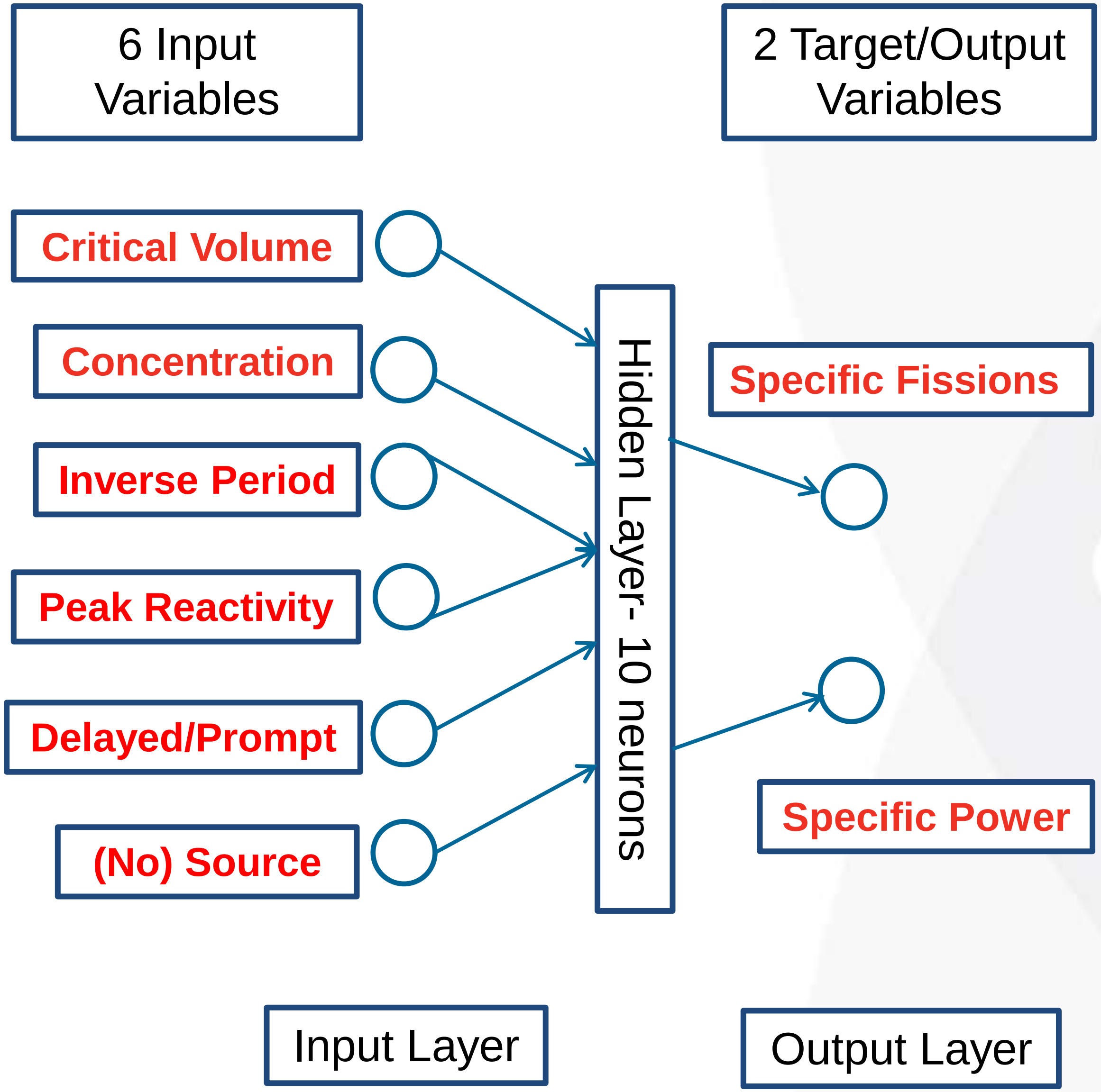
$$W(t_1) = \frac{\left(\frac{8\alpha\tau}{\pi \bar{\upsilon}^2 \Gamma_2^2}\right)^{\frac{1}{2}} \exp\left(-\frac{\alpha t_1^2}{2\tau}\right)}{1 - \mathrm{erf}\left[\left(\frac{\alpha}{2\tau}\right)^{\frac{1}{2}} t_1\right]}.$$

From Hansen, Slide Rule

GOAL – Predict general initial spike/peak characteristics WITHOUT this step

ANN Mechanics - Architecture

Normalize Inputs [0 1]

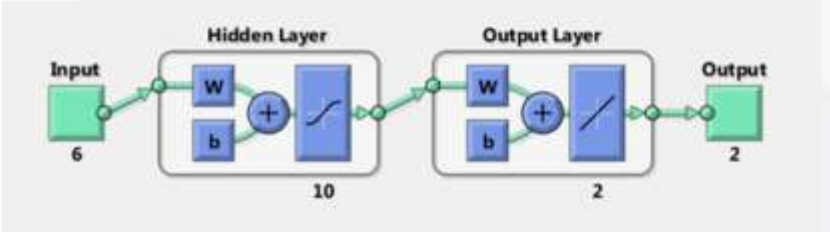


Normalize Targets [0 1]

Extract output values

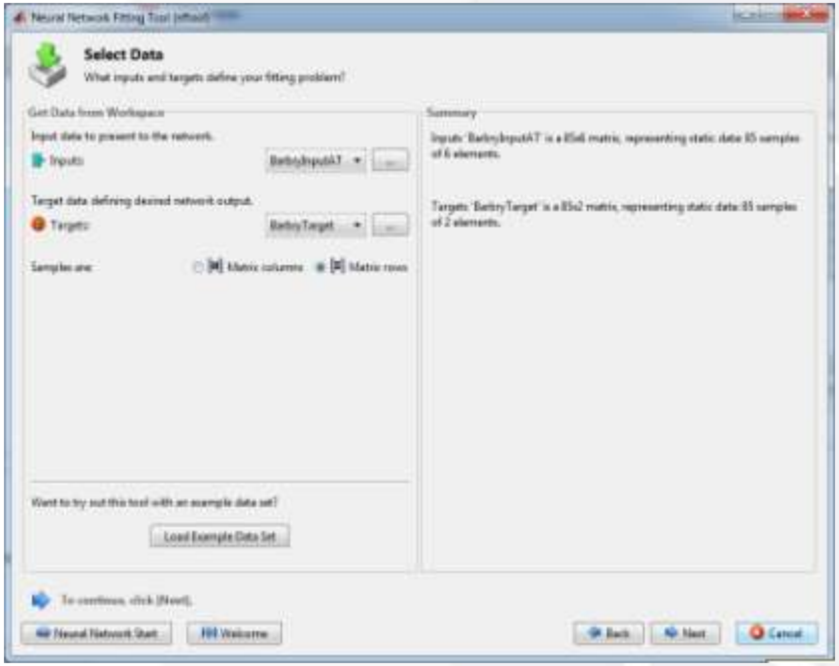
ANN Mechanics – Input Data

- All calculations from MATLAB Neural Network Toolbox (GUI and script based)
- **Select** experiment data sets complete inputs/targets
- Choose 85 HEU - CRAC (46) and SILENE (39)



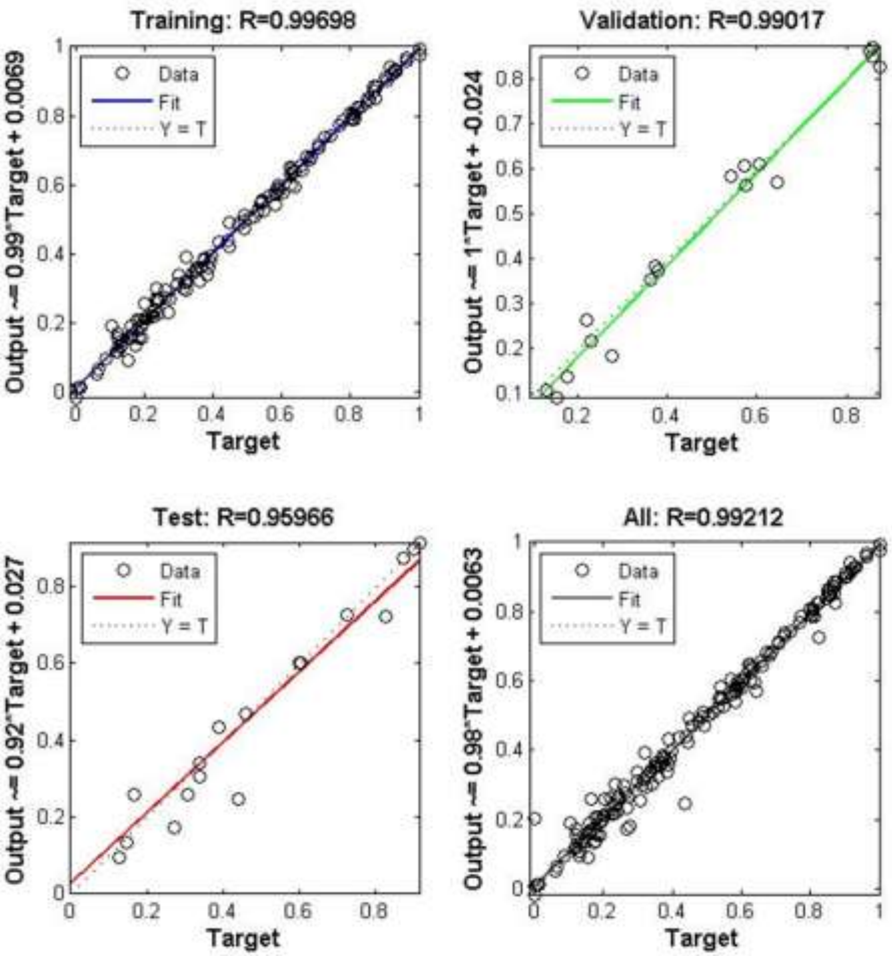
Barbry et al NS&E Vol. 161(2009)

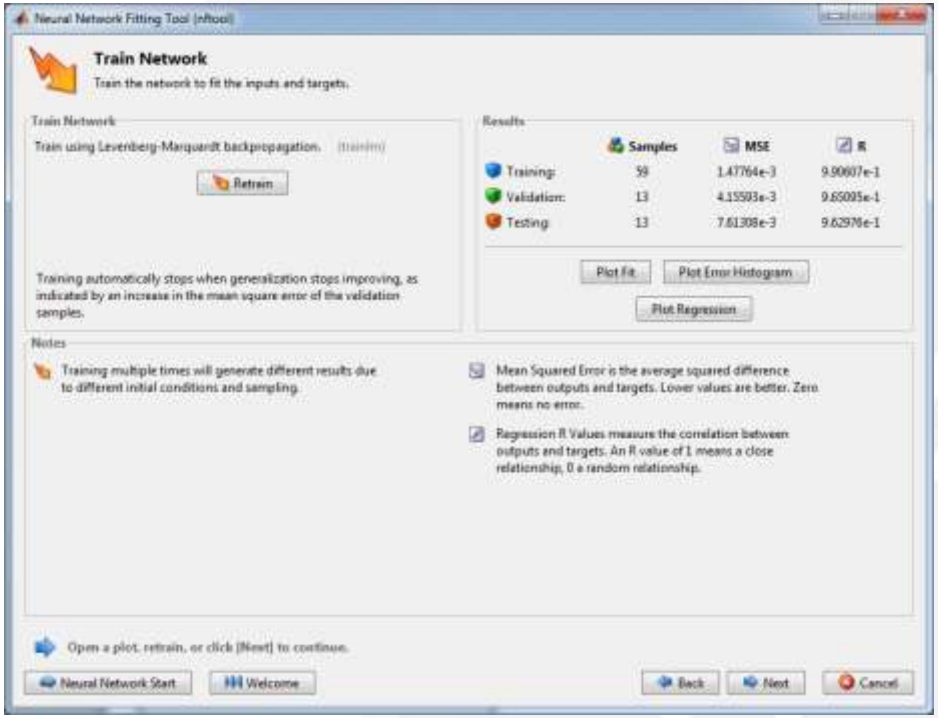
  - 34 CRAC prompt and delayed ramp experiments with 300 mm diameter tank
  - 12 CRAC prompt and delayed ramp experiments with 800 mm diameter tank
  - 10 SILENE pulse-type fast kinetics experiments
  - 7 SILENE slow kinetics with < 1$ insertion
  - 4 SILENE ramp reactivity with 3$ insertion
  - 5 SILENE experiments with constant concentration (71 g/L)
  - 6 SILENE boiling experiments
  - 7 SILENE pulse-type and reactivity ramp



- **Check** with KEWB (19) and **additional** CRAC (14)
- **Use** ANN on altogether new data set (**Slide Rule "Test Set"** – 80 additional cases)

ANN Mechanics - Training, Testing, Validation



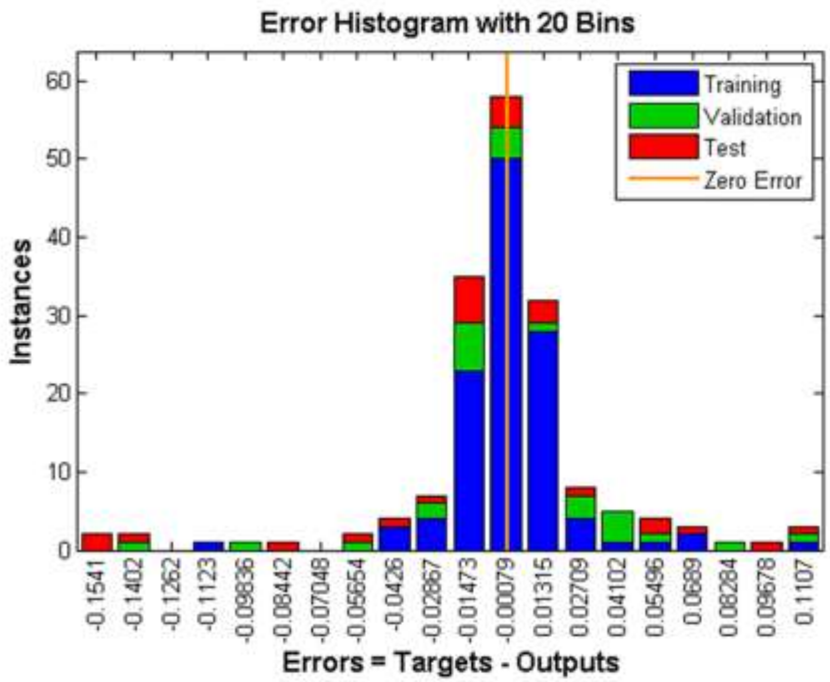


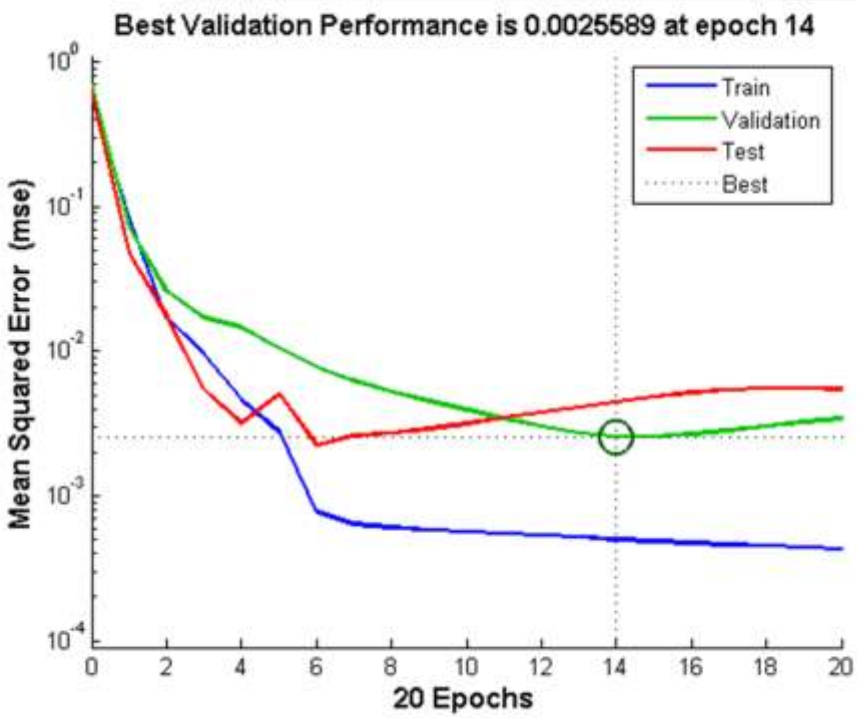
59 training, 13 validation, 13 testing sets
75/15/15 % optimal – R > 0.95 acceptable

The **validation** data set is used to **minimize "overfitting"**, increase accuracy for data not in training.

The **testing** data set is used only for the final solution to **confirm ANN predictive power**.

(Target – Output) Error Histogram and Best Validation





The histogram shows the distribution of error between target and output for training, testing, and validation sets with zero error at the center.

An "epoch" is a single pass through the entire input training set, followed by the validation set, and finally the testing set used to update the connection weights.

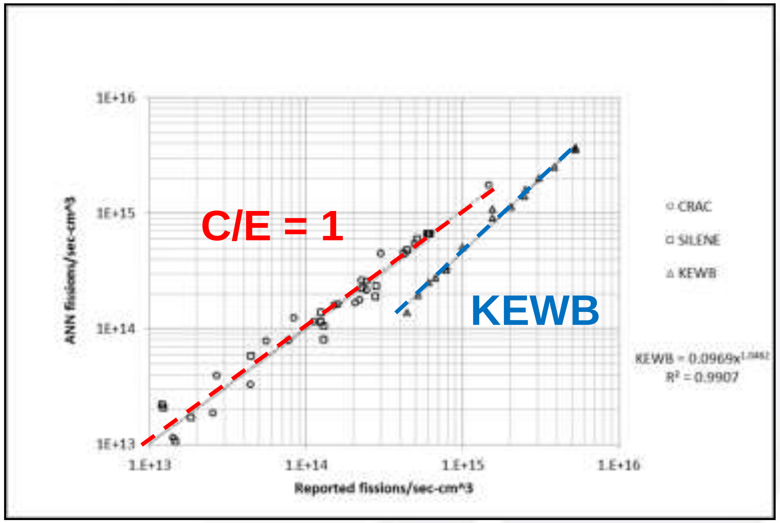
Confident now that the trained ANN can "generalize" over a wide parameter space for HEU solutions

Check ANN with KEWB “B-V” Experiment Data

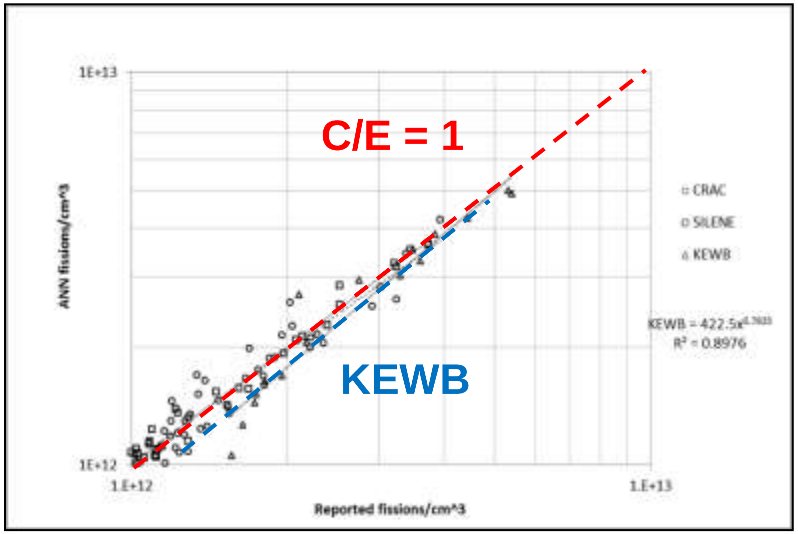
- Present data from 19 KEWB “B-V” experiments (unreflected cylinder) to trained ANN; compare to individual SILENE/CRAC data used in ANN

- ANN SILENE/CRAC specific fissions = 1.69E+12 vs. 1.70 E+12 fissions/cm^3 reported, C/E ~ 1

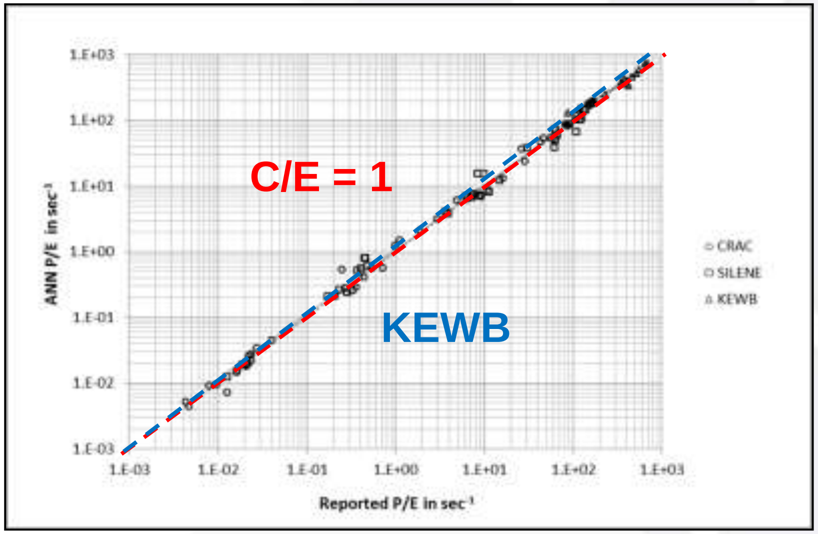
- ANN SILENE/CRAC specific power 1.1E+14 vs 1.0E+14 fissions/cm^3-s reported C/E ~ 1.1



Specific Spike Power



Specific Spike Fissions



Specific Spike Power/Fissions

Check ANN with Additional CRAC Experiment Data

Experiment ID	ANN Specific Spike fissions/cm^3 ×10^{12}	ANN Spike fissions ×10^{16}	Reported Spike fissions ×10^{16}	ANN/ Reported Spike Fissions	Hansen 10% Spike fissions (Lower bound) ×10^{16}	Hansen 50% Spike fissions (Best Estimate) ×10^{16}	Hansen 90% Spike fissions (Upper Bound) ×10^{16}
CRAC05	**1.02**	5.73	6.16	0.93	3.89	6.64	11.1
CRAC06	1.03	5.78	6.74	**0.86**	3.84	6.39	10.6
CRAC10	1.28	3.86	4.23	0.91	1.68	2.21	3.21
CRAC13	1.26	4.62	5.11	0.90	3.67	6.56	11.2
CRAC21	1.15	3.58	3.11	1.15	2.13	3.98	6.87
CRAC22	**2.38**	4.77	4.20	1.13	2.04	3.99	6.95
CRAC27	1.62	4.61	3.41	**1.35**	3.64	6.79	11.7
CRAC29	1.15	3.53	3.39	1.04	2.13	3.97	6.83
CRAC50	1.16	3.49	3.30	1.06	1.52	2.01	2.94
CRAC52	1.40	4.05	3.48	1.16	1.62	2.18	3.22
CRAC54	1.17	3.26	2.61	1.25	1.28	1.73	2.56
CRAC55	1.31	3.65	3.35	1.09	1.3	1.76	2.6
CRAC56	1.17	3.23	2.70	1.19	1.24	1.68	2.49
CRAC63	1.20	3.21	2.94	1.09	1.25	1.7	2.52

ANN specific energy 1.3E+12 fissions/cm^3
Reported specific energy 1.2E+12 fissions/cm^3

ANN/Hansen (10%) μ 2.06 σ 0.55
ANN/Hansen (50%) μ 1.37 σ 0.54
ANN/Hansen (90%) μ 0.89 σ 0.44

ANN/Reported μ 1.07; σ 14%

50% < ANN/Hansen (μ=1) < 90% probability

ANN vs Reported Spike Power and "b" Parameter

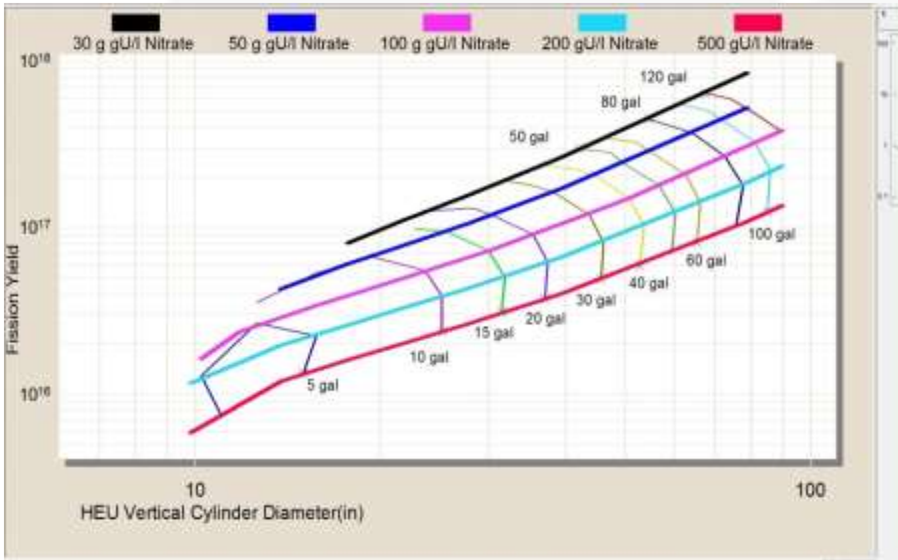
Experiment ID	ANN Specific Spike Power fissions/cm^3-s×10^{12}	ANN Spike Power fissions/s ×10^{16}	Reported Spike Power fissions/s ×10^{16}	ANN/ Reported Spike Power	ANN NF derived b δk/fission ×10^{20}	CRAC regression derived b term δk/fission ×10^{20}	NF Max Power fissions/s ×10^{18}
CRAC05	1.23	6.9	6.2	1.11	11.5	2.0	5.1
CRAC06	1.49	8.4	6.7	**1.24**	12.1	2.0	5.5
CRAC10	4.51	13.6	19.9	0.68	21.1	5.0	5.5
CRAC13	7.69	28.1	54.8	**0.51**	23.6	3.8	8.7
CRAC21	1.95	6.1	7.8	0.78	23.3	4.8	5.3
CRAC22	199.02	398.0	540.0	0.74	34.2	9.2	29.8
CRAC27	9.76	27.7	36.9	0.75	35.2	5.5	14.4
CRAC29	1.94	6.0	7.4	0.81	23.0	4.9	5.1
CRAC50	1.95	5.9	9.9	0.59	23.0	5.1	5.0
CRAC52	9.64	27.9	40.6	0.69	21.0	5.3	6.3
CRAC54	1.91	5.3	7.2	0.74	23.7	5.7	4.6
CRAC55	5.55	15.5	25.1	0.62	21.5	5.7	5.2
CRAC56	1.97	5.4	7.5	0.73	22.9	5.7	4.4
CRAC63	2.28	6.1	8.8	0.69	24.6	6.0	4.7

Average ANN/Reported Spike Power $\mu = 0.8$ $\sigma = 0.2$
Average "b" term ANN/"b" term CRAC $\mu = 4.7$, $\sigma = 0.9$

The smaller **ANN spike power is conservative for a minimum fission rate**

Use Trained ANN for a Slide Rule "Test Set"

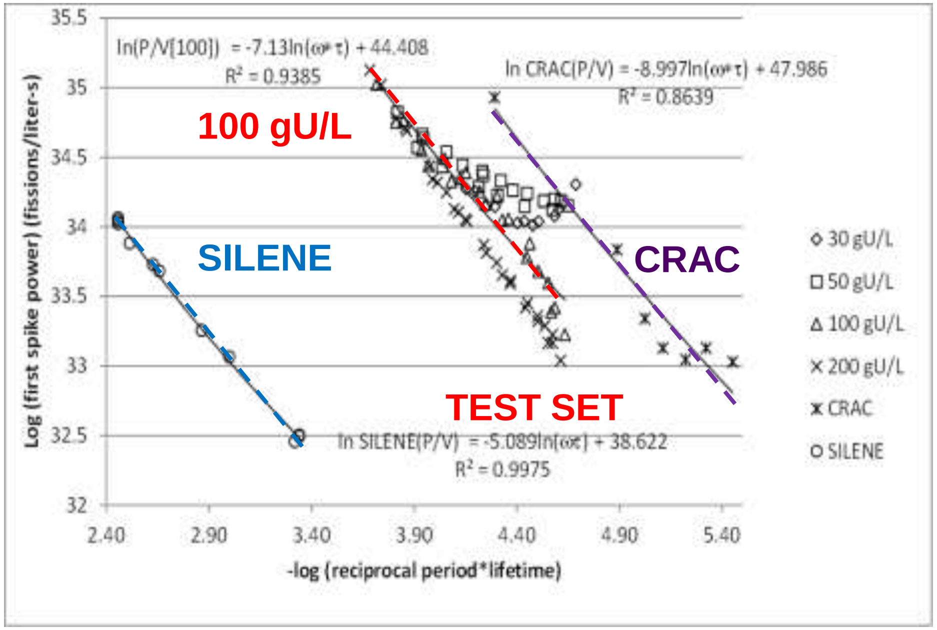
- Slide Rule Test Set – **80 additional cases** – HEU Vertical Cylinders
- Generic ramp feed and weak source
  - Solution density 30, 50, 100, 200 gU/L
  - Drum sizes 5, 16, 30, 55 gal
  - Flow rates of 1, 2, 5, 10, 15, 30, 45 GPM
  - Reactivity addition rates > 0.05 $/s
- Kinetic parameters from CRAC data
  - Determine Δk, critical and prompt critical heights (volume) from diffusion theory
  - Determine ω from Inhour Equation
- Compare with CRAC/SILENE ramp data
- Compare with Slide Rule spike fissions
- **No "b" term required a priori for ANN**



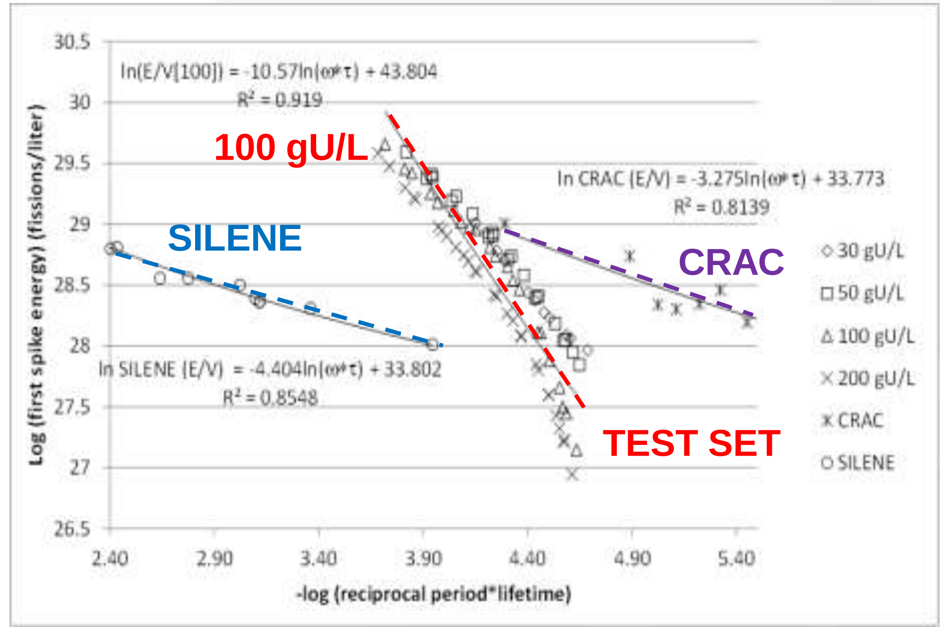
HEU Vertical Cylinder 1 GPM

HEU Vertical Cylinder 45 GPM

SR Test Set Comparison to ANN CRAC and SILENE Data



Initial spike specific power



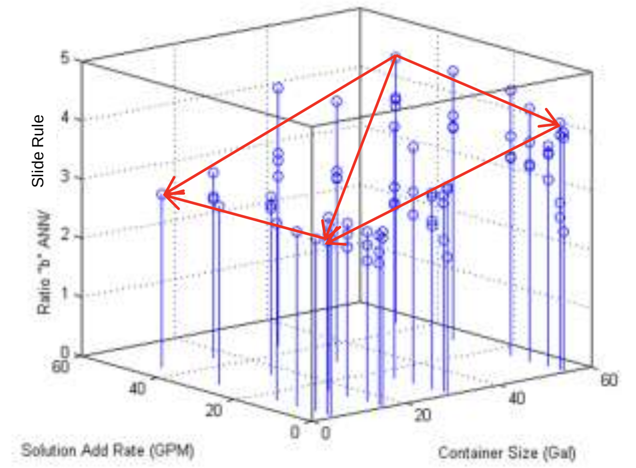
Initial spike specific fissions

ANN-derived values for the Slide Rule Test Set
are **bracketed** by SILENE and CRAC $(\omega\cdot\tau)^n$

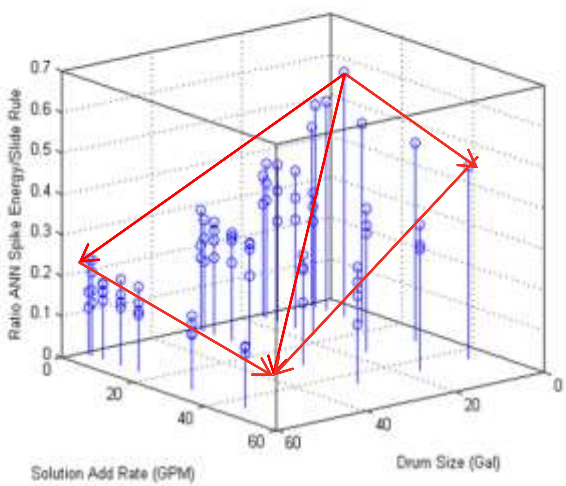
ANN Slide Rule Test Set is **verified** from specific excursion experiment data

ANN Test Set Comparison to Slide Rule Results

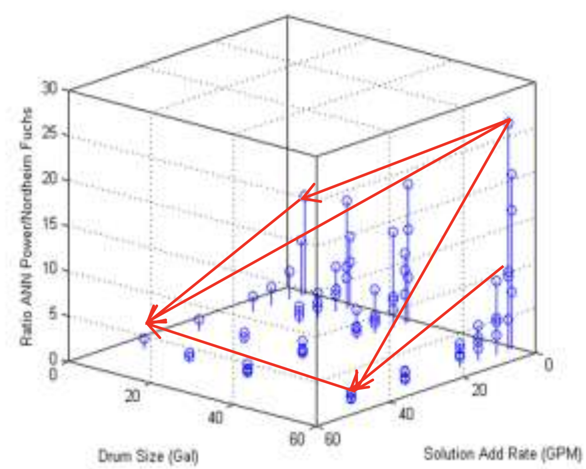
- Stem plots - descending by increasing density (low to high)
- Shows trends and finer structure based on specific variable
- "b" term dependence on combination of variables noted



Ratio "b" ANN/Slide Rule



Ratio spike energy ANN/Slide Rule



Ratio ANN spike power/NF max

Conclusions – Advantages of ANN

- **Advantages of ANN:**
  - Provides a “machine learning” approach for data analysis of **diverse set** of CRAC and SILENE experiments.
  - Results are **tied directly** to implicit relationships between more excursion experiment variables (6 input to 2 output) than a 1-1 regression.
  - Shows where solution addition rate, container size (diameter), and fissile density can also influence initial spike characteristics
  - Spike fissions are determined **without explicit mathematics and regression on “b” term** for experiments with large uncertainties
  - Provides a qualitative and **quantitative comparison/verification** with the Slide Rule spike fissions results

Conclusions – Applications and Enhancements

- **Potential ANN Applications:**
  - Means to realistically determine “predicted accident characteristics”
  - Process-based minimum accident of concern (fissions/L or fissions/L-s)
  - Process-based initial spike fissions input for total fissions over time (e.g. IEZ)
  - Extend approach to CAAS shielding data (dosimetry intercomparisons)
  - Investigate ANN in other areas of NCS data analysis
- **Further ANN enhancements**
  - Additional experiments (LEU) and inputs can be investigated for training
  - Address optimal architectures/missing data (with genetic algorithm)
  - ANN-based uncertainty and sensitivity analysis (robustness)
  - Extend beyond initial spike – ANN based excursion simulator (current effort)
- **Publish**
  - Full paper accepted, to be published in *Nuclear Technology* Spring 2015

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ANN derived "b" and P_{max} – using Nordheim Fuchs

Step increase in reactivity $\Delta k(t) = \Delta k_0 - bE(t)$

For prompt critical,

Total Spike Fissions $E = \frac{2\Delta k_p}{b}$

Spike Half width $t_{1/2} = \frac{3.5\tau}{\Delta k_p}$

Maximum Power $P_{max} = \frac{E}{t_{1/2}} = \frac{2\Delta k_p{}^2}{3.5b\tau} = \frac{E\Delta k_p}{3.5\tau}$

From Chapter III. Power Excursion and Quenching Mechanism's LA-13638