The Significance of Replication.

What have we learned in 18 years of experiments performed at SRI, about the experimental conditions for success and reasons for failed replication?

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Notes by M. C. H. McKubre

1989

Faced with a Series of Unanswered Questions

Q1 *Is there unexplained heat?*

Q2 *Is the heat output sensibly correlated with inputs?*

Q3 *Is the heat derived from a nuclear process?*

Q4 *Nuclear ash correlated with the excess heat?*

Q5 *Are their other nuclear effects?*

Q6 *What is the nuclear process?*

Q7 *What is the future?*

At the beginning one might have posed this set of questions. This would have helped, if more people had done it in a sequential process. There is no point jumping ahead until you are sure of the basis. The particle physicists began with Question 4. Theorists began with Question 6. MITI, with their NHE project, began with Question 7.

1992

<u>Q1</u> *Unexplained heat source?* **YES!!!**

- Effect Evidenced on numerous occasions (*>70 at SRI*)
- Typical P_{xs} 3 - 30% (±0.5%) of Total P_{in} (340%)
- Up to 90σ observation of excess power effect
- Duration several hours to 1 week
- Sustained, unidirectional heat burst exhibit an integrated energy at least 100 times greater than conceivable energy storage effects
- Heat production observed for over half the operation time of one cell (C1).
- Similar heat production observed using 4 different calorimetric methods.

YES!!! Emphatically: Bold, with 3 exclamation points. By 1992 I had reached the 99+% conviction level that there was an <u>unexplained</u>, nuclear level, heat source in the D-Pd system.

1995

<u>Q2</u> *Sensibly correlated with inputs?* **YES!!!**

- Necessary conditions:

Maintain High <u>Average</u> D/Pd Ratio	(*Loading*)
For times >> 20-50 x $\tau_{D/D}$	(*Initiation*)
At electrolytic i >250-500mA cm^{-2}	(*Activation*)
With an imposed D Flux	(*Disequilibrium*)

- Heat correlated with:
  - electrochemical current or current density
  - D/Pd loading
  - $V_{ref.}$ surface potential
  - Pd metallurgy
  - Laser stimulus

- For 1mm dia. Pd wire cathodes:

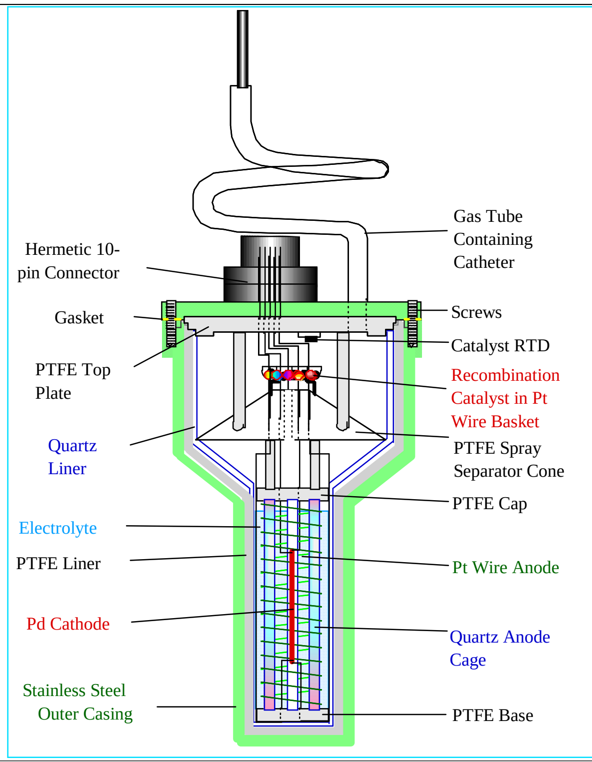
$$P_{xs} = M\,(x-x^{\circ})^2\,(i-i^{\circ})\,|i_D|$$

x = D/Pd, x° ~0.875, i° =50-400mA cm^{-2}, i_D=1-10 mA cm^{-2},

t° >200 $\tau_{D/D}$

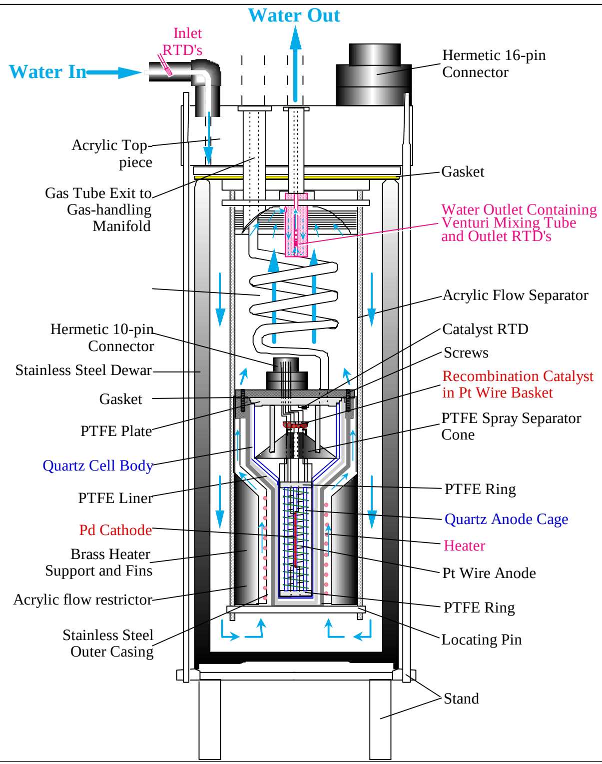
This heat effect also sensibly correlates with plausible input variables.

The bottom function is plotted in Slide 13. The critical thing learned in 1995 was the role of interfacial D flux - which - incidentally - Peter Hagelstein had predicted.



SRI Quartz Calorimeter *and* Degree of Loading (DoL) Cell

Cell used in 90% of our degree-of-loading and early calorimetry studies.
Important feature: control of impurity sources and distribution.



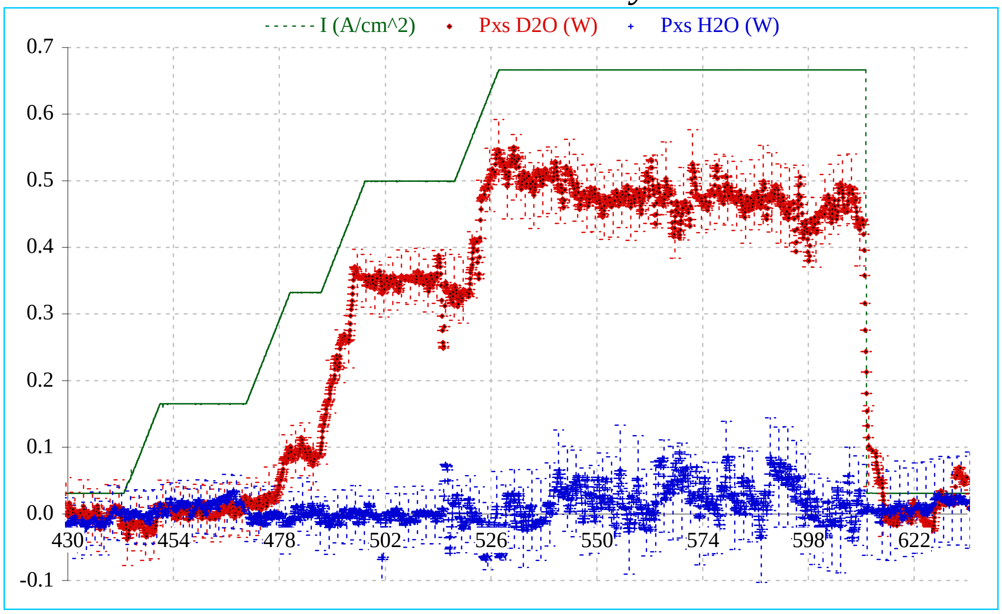
SRI Labyrinth (L and M) Calorimeter and Cell

99.3% Thermal efficiency. Only the remaining 0.7% needs independent calibration (for high accuracy). Also, only this 0.7% can drift (but it did not).

The cell shown in the previous slide goes inside the labyrinth.

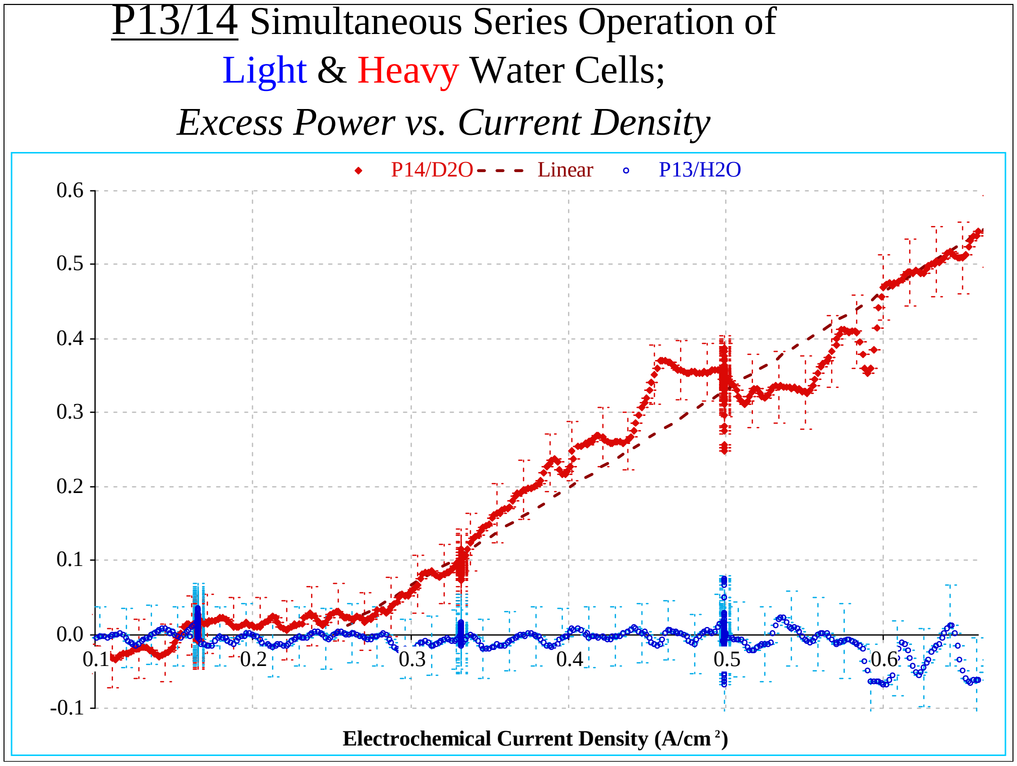
Two or 4 of these objects are placed in a constant temperature bath (±0.003 K) in a constant temperature room (±1 K - on a good day).

P13/14 Simultaneous Series Operation of
Light & Heavy Water Cells;
Excess Power & Current Density vs. Time



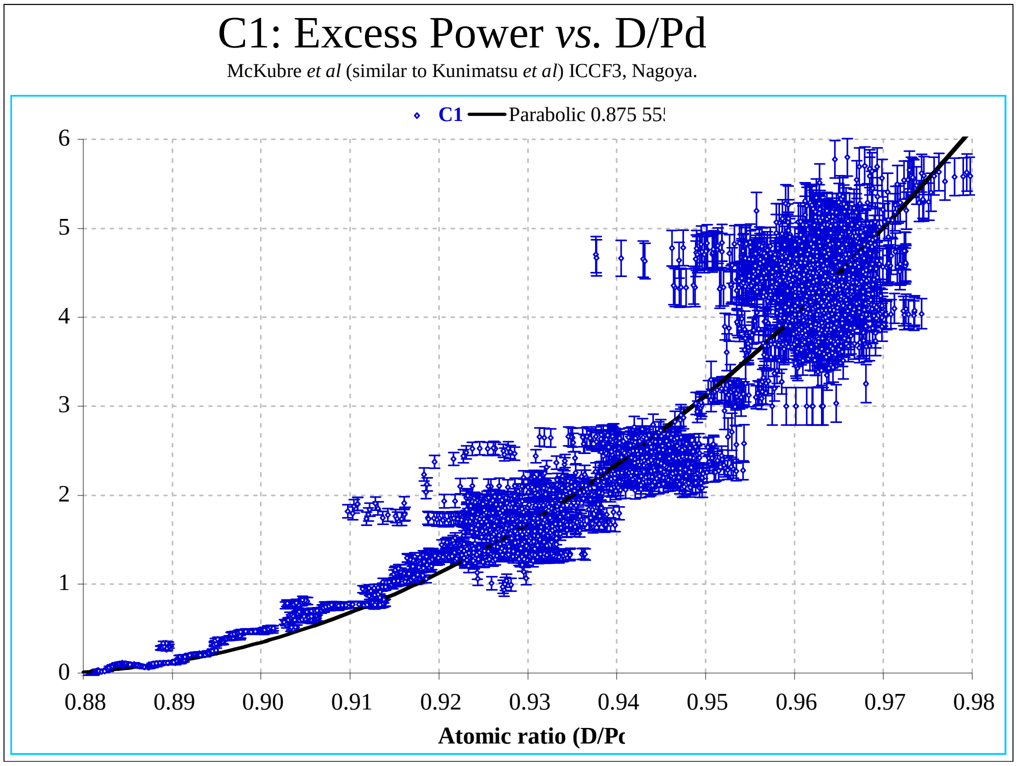
Heavy water works - light water does not.

These two cells were cells operated at the same time, with the same current source (in series), and interrogated with the same measuring instrumentation.

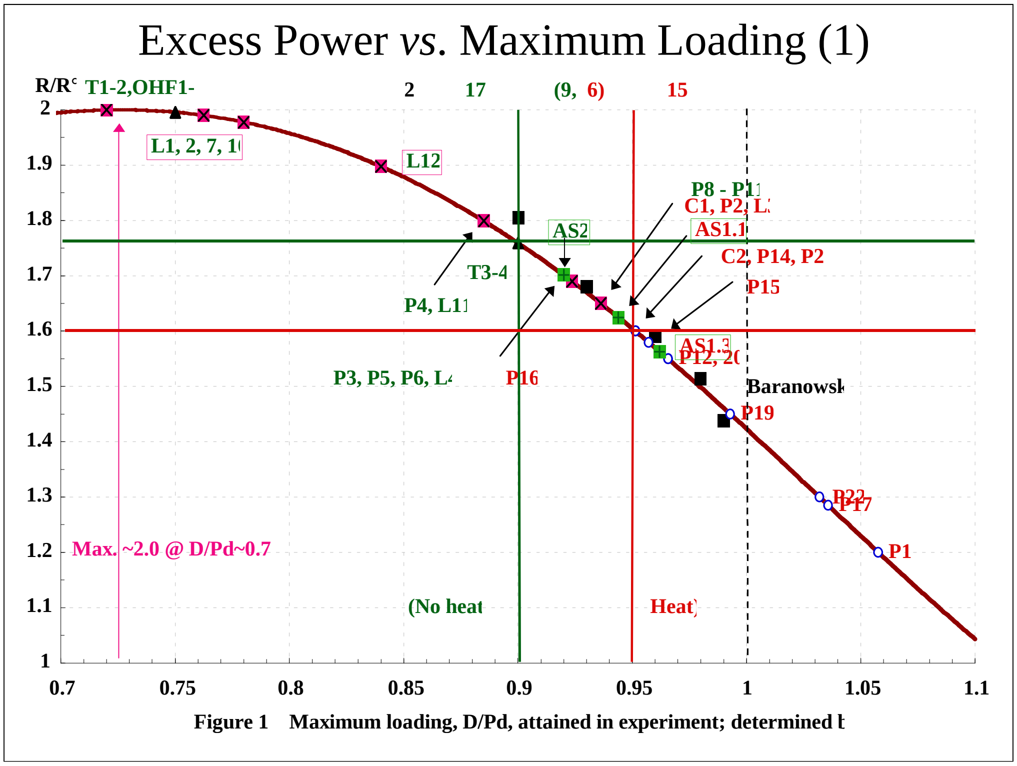


Same data showing the effect of current density: approximately linear above a non-zero threshold.

The scatter is due to departure of the calorimeter from its steady state. At no time have we ever observed a steady state endothermic anomaly.



Parabolic (or asymptotic) dependence on average loading above a (rather high) threshold value.



Top left quadrant Max D/Pd < 0.9 => no heat excess

Bottom right quadrant Max D/Pd > 0.95 => all heat excess

Middle zone 50 : 50

We have done a lot more and I have only one anomalous point which did produce tritium but not measurable heat.

1994-1998

<u>Q3</u> *Is the heat of nuclear origin?* Yes!

- 100's to 1000's of eV's / Pd (D) atom

SRI 2076 eV/Pd,
Energetics >4000 eV/Pd

- Sustained, unidirectional heat burst exhibit an integrated energy at least 10 times greater than the sum of all possible chemical reactions within a closed cell

- Heat effects are observed with **D**, but not **H**, under similar (or more extreme) conditions

McKubre *et al*, ***"Development of Advanced Concepts…",*** EPRI, TR-104195 (**1994**)

The heat is too large to be explained by chemistry.

It is too big to be storage (and no time to store and no missing endotherms).

And it works with D not H.

This is (at least) circumstantial evidence that we should be thinking of nuclear effects.

2000

Q4 *Nuclear ash correlated with the excess heat?* Yes!

Q5 *Uncorrelated nuclear products?* Yes!

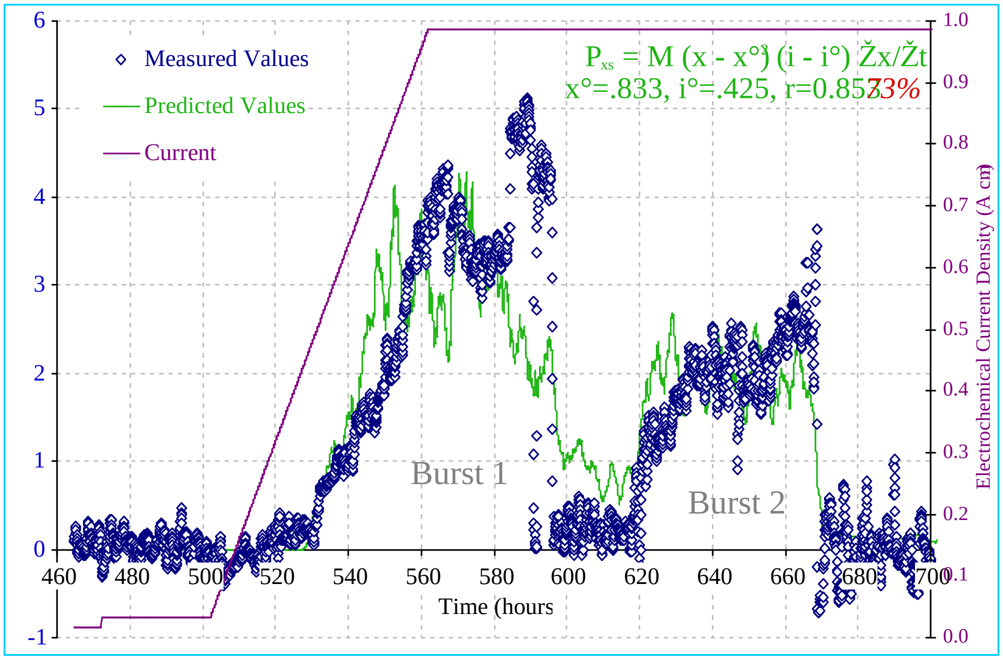
Compelling Evidence:

- ^{4}**He** closely time and quantity correlated with excess heat
- ^{3}**H** observed in some cases only. Not quantity correlated with excess heat (~ 3 - 4 O.M. down)
- Isotopics effects possibly at very low level
- Charged particles: α, β, p^+ possibly at even lower level
- Neutrons not observed at SRI (although they can be found using more sensitive detectors at ~10 or more O.M. down from heat)

It is important to mention that SRI was only replicating helium and tritium results obtained much earlier by others.

M4: Excess Energy - expectation function

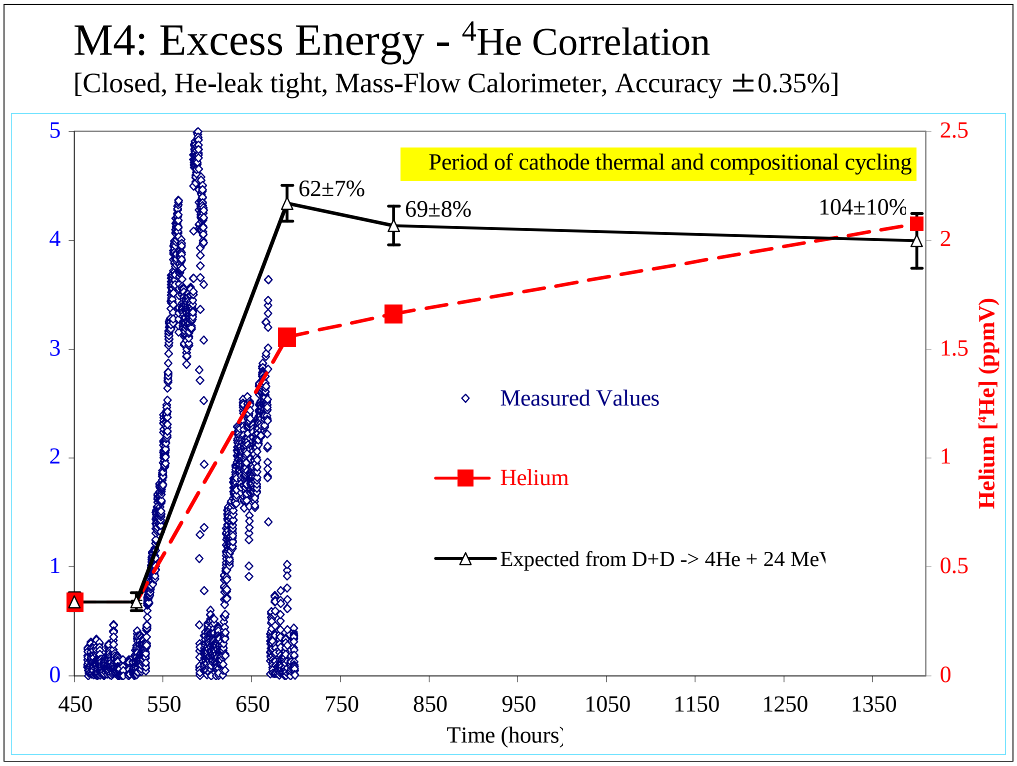
[Closed, He-leak tight, Mass-Flow Calorimeter, Accuracy ±0.35%]



Blue are data points Green is “prediction function” from slide 4. r=0.853 is the cross correlation function between blue and green. 73% is the probability that these two curves are linearly correlated.

The reason for the drop between Bursts 1 & 2 was **primarily** due to a (spontaneous) change in the flux of D across the interface.

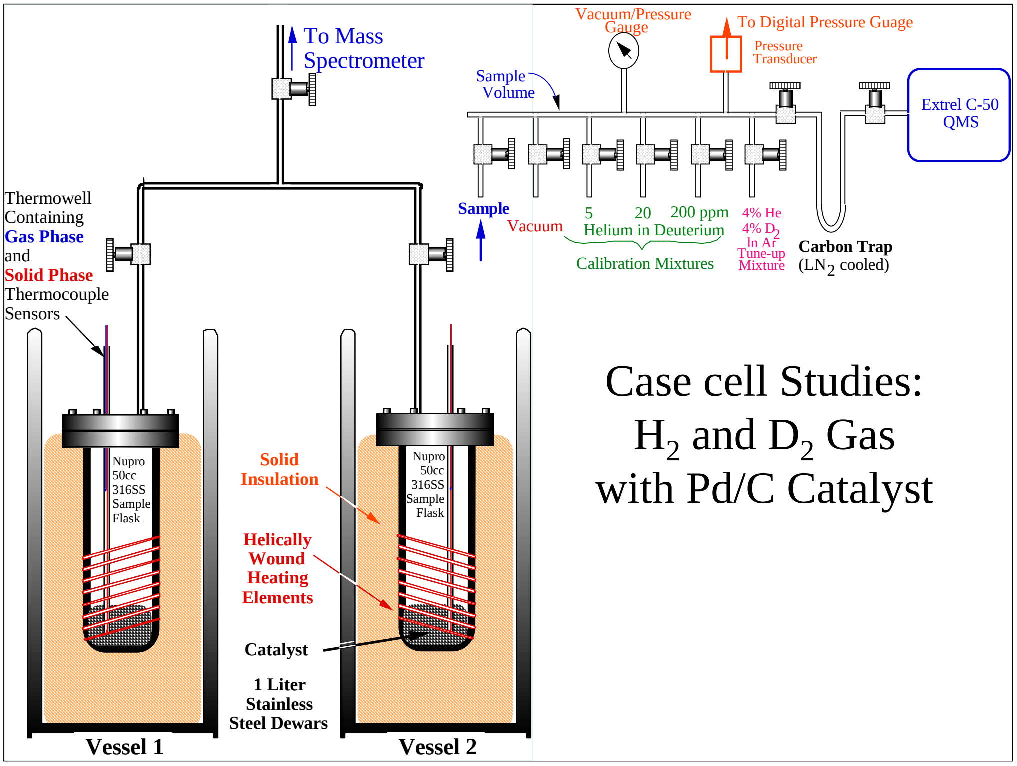
This was for 1 mm dia. Wires. We have checked this function out a lot recently and it seems to work for Vittorio Violante’s foils with superwave stimulation (although the current threshold is much lower).



Note: expected values decrease because of withdrawal of samples for analysis with “high” [4He] being replaced with stock D2 containing 0.34±.007 ppmV 4He. This was done in order to keep the internal pressure above ambient.

Our idea was that the “missing” 40% must have been absorbed (or somehow stuck) very close to the Pd surface - maybe in a “junk” layer, and that we could get it out by sloshing D back and forth.

Given the slope I am not sure the compositional cycling did anything - the 4He may have shown up anyway.



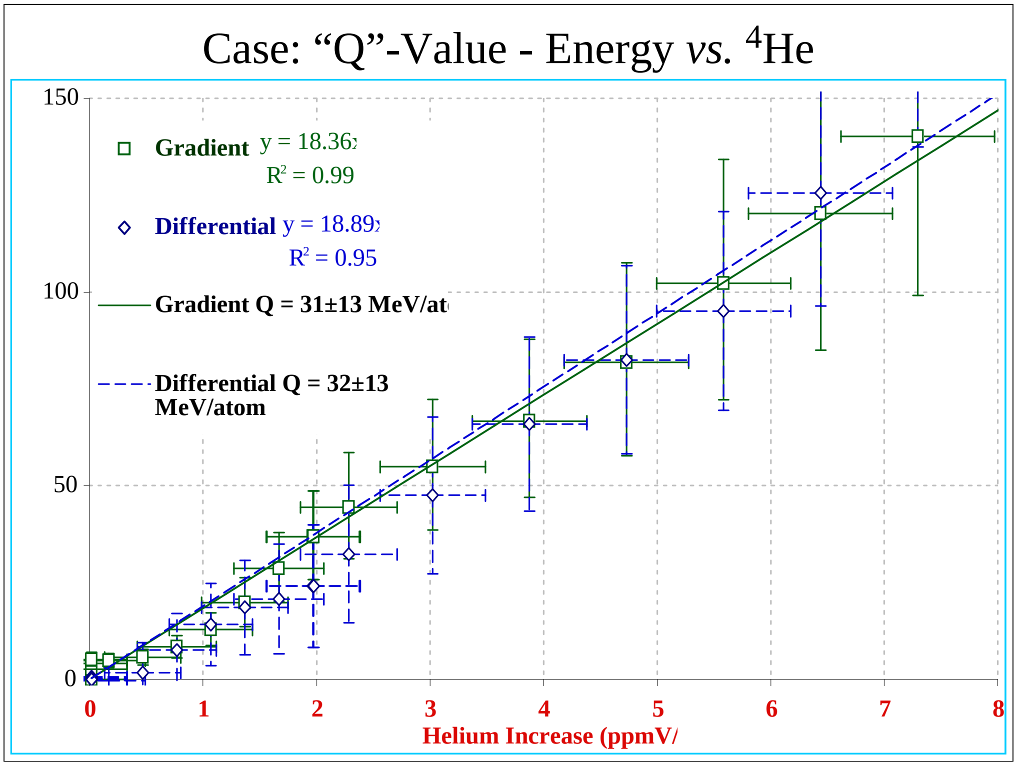
Vessel 1 H2, Vessel 2 D2: 3 Atm. and 200° C. Conflat (Cu) seals - helium leak tested and tight.

Calorimetry was:

Differential (comparison of T measured in the two beds compared to input heater power), and

Gradient assuming a linear gradient between bed - gas - and ambient.

This is not ideal calorimetry (hence the uncertainties in the next slide). But the two methods agreed pretty well.



Ambient helium = 5.22 ppm. Highest measured in Case experiment = 10.8 (±.01) ppm.

The "expectation" value (24 MeV) is inside the uncertainty - but I am more inclined to believe that we had the same 4He retention issue as in the previous electrochemical result (in this case probably in the C). We simply did not wait long enough.

Present

<u>Q6</u> *What is the nuclear process?*

- Primary product ^{4}He with ~24 MeV/^{4}He
- Relevant theory under construction:
  Hagelstein, Chubb[2], *Preparata*, *etc*.

Future

<u>Q7</u> *What is next?*

- Research consortia:
  e.g. SRI/MIT/NRL/ENEA/Energetics

- Technical development:
  > 10 x Heat Out / Power In
  Positive Temperature Coefficient?
  Time for Engineering??