COLD FUSION, LENR, the Fleischmann-Pons Effect; ONE PERSPECTIVE on the STATE of the SCIENCE

Michael C. H. McKubre
Director,
Energy Research Center,
SRI International, Menlo Park, CA.

The 15th International Conference on Cold Fusion, ICCF15
Roma, Italy
Monday, October 5, 2009.
March 23rd 1989 Fleischmann and Pons reported results of: an anomalous heat effect resulting from the extensive, electrochemical insertion of deuterium into palladium cathodes occurring over an extended period of time by means of electrolysis of heavy water in alkaline electrolytes.

This heat effect was at a level consistent with Nuclear but not Chemical energy or known lattice Storage effects, but occurred (mostly) without penetrating radiation (α, β, γ, n°) or activation (3H).

Nuclear level heat effects have been observed in the D/Pd system with energies 100’s or 1,000’s times known chemical effects.

We are concerned with answers to the following questions:

- What do we think we know?
- Why do we think we know it?
- Why do doubts still exist in the broader scientific community?
- How do we propose to make progress?
Background

- Critical activities at SRI:
  - The measurement and importance of D/Pd loading
  - The role of chemical additives and poisons in loading and interfacial dynamics
  - Design, construction and successful implementation of a novel, high-accuracy, fully-automated mass flow calorimeter
  - Replication studies:
    - Fleischmann Pons (Excess Heat)
    - Miles and Bush (\(^4\)He)
    - Case (Heat and \(^4\)He)
    - Arata and Zhang (Heat, \(^3\)H and \(^3\)He)
    - Energetics (High level excess power and energy)

- Encouragement and participation in a number of significant and long-standing research partnerships and collaborations:
  - Stanford University [Huggins, Crouch-Baker]
  - Texas A&M, Cyclotron Center [Wolf, Jevtic]
  - MIT [Hagelstein, Smullin, Chaudhary]
  - Osaka University [Arata, Zhang]
  - ENEA Frascati [Violante, Sarto, Castagna]
  - Energetics [Dardik, El Boher, Greenspan, Lesin, Zilov]
  - University of Rome [Bertolotti, Sibilia]
  - NRL [Hubler, Grabowsky, Knies, Melich, Nagel]
Object

- To define and develop an experiment-based understanding of new physical effects in metal deuterides with primary focus on:
  - High loading and flux.
  - Lattice heat generation not consistent with known chemistry or storage effects.
  - The appearance of new elements or isotopes.
  - The registration of energetic particles.

- Review methodology:
  - What initial hypothesis was proposed?
  - What experimental methods were employed?
  - What results were obtained?
  - How were these results interpreted?
  - What is the consistency, laboratory-to-laboratory and sample-to-sample?
  - What new understanding was achieved from the analysis of results?
  - How does this knowledge fit in the framework of modern physics?
  - What alternative explanations, or objections have been proposed?
  - How are objections countered or incorporated into an improved understanding?

- What is the status of research?

- What are the prospects and programme for the future?
Order

- Excess Heat from D/Pd
- The “Q” value: Excess Heat and $^4\text{He}$
- $^3\text{H}$ and $^3\text{He}$
- Formation of higher mass isotopes
- Energetic particles and tracks
- $\gamma$ and x-rays
**Excess Heat: Hypothesis 1**

“An unexpected source of heat can be observed in the D/Pd System when Deuterium is loaded electrochemically into the Palladium Lattice... to a sufficient degree.”

**Experiments:**
- **D/Pd Loading.**
  - Electrochemical Impedance (kinetics & mechanism)
  - Resistance Ratio $R/R^\circ$ (extent of loading)
- **Calorimetry**
  - first principles closed-cell, mass-flow calorimeter,
  - > 98% heat recovery (99.3%)
  - absolute accuracy < ±0.4% (0.35%)
Loading Cell and Reactions.

**Wires:**
1 – 3 mm in dia.
3 – 5 cm in length.

1M LiOD Electrolyte

Recombiner Reaction:
\[ \text{D}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{D}_2\text{O} \]

Anode Reaction (+):
\[ 2\text{OD}^- \rightarrow \text{D}_2\text{O} + \frac{1}{2}\text{O}_2 + 2e^- \]

Cathode Reaction (-):
\[ \text{D}_2\text{O} + e^- \rightarrow \text{OD}^- + \text{D} \]
\[ \text{D} + \text{D} \rightarrow \text{D}_2 \]
\[ \text{D}_{\text{Surface}} \rightarrow \text{DLattice} \]
SRI Quartz Calorimeter and Degree of Loading (DoL) Cell
SRI Labyrinth (L and M) Calorimeter and Cell

Accuracy: ±0.35%
Operation: 100 mW – 30W
Stability: > 1000 hours
P15 1M LiOD + 200ppm Al, 3cm x 3mm Pd Wire cathode.

\[ P_{\text{Total}} = 12 \text{ W} \]
SRI FPE Replication

a) Nuclear-level heat release (1000’s of eV/Pd Atom).
b) Current threshold and linear slope.
c) Loading threshold and parabolic rise of $P_{XS}$. 
M4: The Dynamics of D Flux

Time (hours)

Loading

Excess Power (W/cc)

Loading

Excess Power
M4: Excess Power Fitting Function

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

\[ x^\circ = 0.833, \quad i^\circ = 0.425, \quad r = 0.853, \quad \text{Correl.} = 73\% \]
Correlations observed in SRI results

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

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

- **For Pd wire cathodes* Mode A heat production:**
  \[ P_{xs} = M (x-x^o)^2 (i-i^o) |i_D| \]
  \[ x = D/Pd, \ x^o \sim 0.875, \ i^o = 75-450 \text{mA cm}^{-2}, \ i_D = 2-20 \text{ mA cm}^{-2}, \ t^o > 20 \tau_{D/D} \]

* 50 \mu m foils follow a similar equation with lower current thresholds
Observations

- Effect Evidenced on numerous occasions (>70 at SRI)
- Up to $90\sigma$ observation of excess power effect
- $P_{XS} > 1 \text{kW/cm}^3$ (transient)
- $P_{XS} \sim 150 \text{W/cm}^2$ (1 month)
- $P_{XS} / P_{\text{Electrochem.}} > 3$
- $E_{XS} > 100 \text{ MJ}$
- $100 – 2,000 \text{ eV/ Pd Atom}$
- Positive Temperature Coefficient
Salient* Criticisms

- “The experiments/results are not reproducible”:
  - Some teams see no results (football teams / nationality)
  - Different results in different laboratories
  - Inconsistent results in the same laboratory with similar samples

- “The results are inaccurate”:
  - Mis-measurement of input power
  - Mis-measurement of output power
  - The delta ($P_{XS}$) is not outside the measurement uncertainty

- “The heat is real but is due to unknown or unaccounted chemical effects or lattice energy storage”:
  - Over-accounting for electrolysis products ($V_{TN}$)
  - Chemistry in the electrolyte volume
  - Energy storage and release (small % $\int$ energy)
  - Hydrinos or “new” chemistry [Black Light Power]

- “Missing nuclear products”:
  - Quantitative energetic products not seen (“ash”)
  - Difficulty of measuring $^4\text{He}$ in the presence of $D_2$ and ambient

* Salient |ˈsālɪənt; -lēənt| adjective
1 most noticeable or important : it succinctly covered all the salient points of the case. • prominent; 2 Heraldry (of an animal) standing on its hind legs with the forepaws raised, as if leaping.
“The experiments/results are not reproducible”

- Electrodes made from the same lot of materials (Pd) produce consistent levels of excess heat
- $P_{xs} = M (x-x^0)^2 (i-i^0) |i_D|$, $x^0 \sim 0.875 \text{ D/Pd}$, all terms are important!
Electrodes capable of attaining and maintaining high loading – are capable of producing excess heat.

Figure 1  Maximum loading, D/Pd, attained in experiment; determined by R/R°.
Electrodes made from the same Material Lots – produce similar excess heat in different calorimeters

Cathode: Pd foil 50 µm
Annealed at $870^\circ$C in vacuum for 1h
prepared by V. Violante, ENEA Frascati

**ENEA Mass Flow Calorimeter**

**Energetics Isoperibolic Calorimeter (also used at SRI)**
15 experiments performed using SRI DAQ.

### Energetics (SW) Replication

11 (73%) produced excess heat above 3\(\sigma\).

<table>
<thead>
<tr>
<th>Cell Calorimeter</th>
<th>Cathode Min.</th>
<th>Max.</th>
<th>Excess Power</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/R°</td>
<td>D/Pd</td>
<td>% of (P_{in})</td>
<td>(mW)</td>
<td>(kJ)</td>
</tr>
<tr>
<td>1 9-7 E Lot A</td>
<td>1.77</td>
<td>0.895</td>
<td>&lt;5%</td>
<td>340</td>
</tr>
<tr>
<td>2 11-8 E L5(2)</td>
<td>1.67</td>
<td>0.915</td>
<td>60%</td>
<td>460</td>
</tr>
<tr>
<td>3 12-9 E Lot A</td>
<td>1.84</td>
<td>0.877</td>
<td>&lt;5%</td>
<td>340</td>
</tr>
<tr>
<td>4 15-7 E L5(1)</td>
<td>1.77</td>
<td>0.895</td>
<td>&lt;5%</td>
<td>340</td>
</tr>
<tr>
<td>5 16-8 E L5(4)</td>
<td>1.86</td>
<td>0.871</td>
<td>&lt;5%</td>
<td>340</td>
</tr>
<tr>
<td>6 17-9 E L1(1)</td>
<td>1.55</td>
<td>0.939</td>
<td>20%</td>
<td>200</td>
</tr>
<tr>
<td>7 21-7 E # 830</td>
<td>1.92</td>
<td>0.836</td>
<td>&lt;5%</td>
<td>340</td>
</tr>
<tr>
<td>8 22-8 E L5(3)</td>
<td>1.88</td>
<td>0.988</td>
<td>30%</td>
<td>200</td>
</tr>
<tr>
<td>9 35-7 S L17(1)</td>
<td>1.32</td>
<td>0.985</td>
<td>12%</td>
<td>1800</td>
</tr>
<tr>
<td>10 35-8 S L17(2)</td>
<td>0.95</td>
<td>1.059</td>
<td>13%</td>
<td>2066</td>
</tr>
<tr>
<td>11 35-9 S L17</td>
<td>1.39</td>
<td>0.971</td>
<td>1%</td>
<td>340</td>
</tr>
<tr>
<td>12 43-7 S L14-2</td>
<td>1.73</td>
<td>0.903</td>
<td>80%</td>
<td>1250</td>
</tr>
<tr>
<td>13 43-8 S ETI</td>
<td>1.63</td>
<td>0.923</td>
<td>5%</td>
<td>525</td>
</tr>
<tr>
<td>14 43-9 S L14-3</td>
<td>1.61</td>
<td>0.927</td>
<td>1%</td>
<td>340</td>
</tr>
<tr>
<td>15 51-7 S L25B-1</td>
<td>1.55</td>
<td>0.939</td>
<td>12%</td>
<td>266</td>
</tr>
<tr>
<td>16 51-8 S L25A-2</td>
<td>1.52</td>
<td>0.945</td>
<td>5%</td>
<td>133</td>
</tr>
<tr>
<td>17 51-9 S L19</td>
<td>1.54</td>
<td>0.941</td>
<td>43%</td>
<td>79</td>
</tr>
<tr>
<td>18 56-7 S L24F</td>
<td>1.55</td>
<td>0.939</td>
<td>15%</td>
<td>2095</td>
</tr>
<tr>
<td>19 56-8 S L24D</td>
<td>1.84</td>
<td>0.877</td>
<td>4%</td>
<td>340</td>
</tr>
<tr>
<td>20 56-9 S L25B-2</td>
<td>1.56</td>
<td>0.937</td>
<td>3%</td>
<td>340</td>
</tr>
<tr>
<td>21 57-8 S Pd-C</td>
<td>N.A.</td>
<td>N.A.</td>
<td>300%</td>
<td>93</td>
</tr>
<tr>
<td>22 58-9 S L25A</td>
<td>1.69</td>
<td>0.911</td>
<td>200%</td>
<td>540</td>
</tr>
<tr>
<td>23 61-7 S L25B-1</td>
<td>1.63</td>
<td>0.923</td>
<td>50%</td>
<td>105</td>
</tr>
</tbody>
</table>

E = Energetics and S = SRI Data Acquisition.

6 experiments performed using ENEA DAQ, and Mass Flow Cal. produced significant \(P_{XS}\).

<table>
<thead>
<tr>
<th>Data Acquisition</th>
<th>Cathode Min.</th>
<th>Max.</th>
<th>Excess Power</th>
<th>Energy</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENEA</td>
<td>R/R°</td>
<td>D/Pd</td>
<td>% of (P_{in})</td>
<td>(mW)</td>
<td>(kJ)</td>
</tr>
<tr>
<td>ENEA L14</td>
<td>1.54</td>
<td>0.941</td>
<td>80</td>
<td>B</td>
<td>Mode A</td>
</tr>
<tr>
<td>ENEA L17</td>
<td>1.4</td>
<td>0.969</td>
<td>500</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>ENEA L19</td>
<td>1.7</td>
<td>0.909</td>
<td>100</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>ENEA L23</td>
<td>1.69</td>
<td>0.911</td>
<td>37</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>ENEA L25A</td>
<td>1.8</td>
<td>0.888</td>
<td>24</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>ENEA L30</td>
<td>1.78</td>
<td>0.892</td>
<td>7000</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>

The results are inaccurate

“Mis-measurement of input electrical power”:
- Relatively simple measurement (I, V, R, t)
- Slightly more difficult for non-dc input (SW, pulses)
- Use `scopes and transient analyzers to quantify “hidden” inputs
- Calorimeter is the best measure and most experiments for most of the time register no thermal imbalance (calibrations, blanks).

“Mis-measurement of thermal output power”:
- Thermal balance…
- Different calorimetric methods (multiple) show consistent effects
- Mass flow calorimeter:
  - Simple device
  - First principles
  - Very little to calibrate
  - In SS operation the qualitative effect is unmistakable

“\( P_{XS} = P_{Out} - P_{In} \leq \text{measurement uncertainty} \)”:
- Pre- post- and interim calibration
- SRI 90\( \sigma \) observation (P15 – slide 10)
- Hundreds of observations of \( P_{XS} > 3 \sigma \)
- Effects persist for hours, days, weeks, (> 1 month)
- \( P_{Out} / P_{In} > 2, 3, 5, 25! \)
“The effect is due to chemistry or energy storage”

❖ Over-accounting for electrolysis products \( (V_{TN}) \):
  ➢ The effect is seen in closed cells
  ➢ Accurate account is taken for electrolyte watering

❖ “Chemistry in the electrolyte volume”:
  ➢ Effect 100 – 1000 times > sum of all possible chemical reactions*
  ➢ Reactant concentrations are monitored
  ➢ Normalized to Pd (or D/Pd) we measure \( 10^2 – 10^4 \) eV/atom

❖ “Energy storage (slow) and release (rapid)”:
  ➢ \( P_{XS} \) measured for > 50% of some experiments
  ➢ \( 10^2 – 10^4 \) eV/atom would be novel (and useful)
  ➢ \( E_{XS} / E_{In} > 25 \) measured in (at least) 1 experiment

❖ “Hydrinos or other “exotic” chemistry”:
  ➢ This effect not considered here
$\bullet$ **P$_{\text{In}}$ < 1W, P$_{\text{Out}}$ > 34 W, P$_{\text{Gain}}$ > 30.**

$\bullet$ E$_{\text{In}}$ ~40 kJ, E$_{\text{Out}}$ ~1.14 MJ, E$_{\text{XS}}$ ~1.1 MJ, E$_{\text{Gain}}$ > 25, T>100°C.

$\bullet$ 4.8 KeV/Pd atom

$\bullet$ 2$^{\text{nd}}$ burst produced 3.5 MJ and 15.7 KeV/Pd)

---

Energetics Energy Gain [2] ($P_{XS}$)

### Graph Details

- **Graph Title:** Energetics Energy Gain [2] ($P_{XS}$)
- **Graph Description:**
  - **Input Power ($P_{In}$), Output Power ($P_{Out}$) [W]**
  - **Duration:** ~16 Hours
  - **Output Power at t = 0:** 34.4 W

### Graph Axes

- **X-Axis:** Time (s), with markers for 0, 2h, 4h, 6h, 8h, 10h, 12h, 14h, 16h, 18h, 20h, and 71,824 s.
- **Y-Axis:** Power (W), with markers for 0, 10, 20, 30, and 35 W.

### Graph Notes

- The graph shows fluctuations in input and output power over time.
- The output power $P_{Out}$ reaches 34.4 W at $t = 0$.
- The graph indicates a duration of ~16 hours.
Energetics Energy Gain [3] ($E_{XS}$)

Input Energy ($E_{In}$) = 40 kJ

Output Energy ($E_{Out}$) = 1.14 MJ

Excess Energy ($E_{XS}$) = 1.1 MJ

Time (t) = 0, 2h, 4h, 6h, 8h, 10h, 12h, 14h, 16h, 18h, 20h

Energy vs. Time Graph:
- Input Energy (green line)
- Output Energy (blue line)
- Excess Energy (blue line)

Energy Values:
- 200 kJ
- 400 kJ
- 600 kJ
- 800 kJ
“Where is the ash?”

❖ “The expected energetic radiation does not accompany the (putative) heat production”:
  - “The circumstances of hot fusion are not those of cold fusion”

❖ “The nuclear products claimed cannot account for the excess heat”:
  - $^3\text{H}$ and $^3\text{He}$ are produced in FPE experiments – under special circumstances – largely asynchronous with the excess energy
  - Claims for “massive transmutation” at (or above) the levels needed to account for measured excess energy have yet to be verified

❖ “The claimed quantitative product ($^4\text{He}$) is”:
  a) Impossible to produce
    - This is an experimental question
    - Theoretical denial is unscientific
  b) Difficult to measure ($\text{D}_2$, ambient)
    - True but reliable measurements can (and have) been made with care
  c) Not found in sufficient quantity
    - Where people have looked carefully they have found quantitative or “semi-quantitative” $^4\text{He}$ [more work is needed]
“4He: Hypothesis 2”

“The quantitative product of the heat producing reaction is 4He that evolves primarily without associated energetic byproducts”

Experiments:

- Simultaneous measurement of Excess Heat and gas phase 4He
  - All metal-sealed apparatus – integral
  - Self purging – rate

- Retrospective measurement of metal phase 4He
  - “easy” to find
  - difficult to quantify
“\(^{4}\)He – a little history”

- **Miles-Bush**
  - Self-sparging “open” cells (1990-1994)
  - Statistical analysis of \([\text{Heat}|\text{Helium}]\) (1 in 750,000 random chance)
  - \(1.4 \pm 0.7 \times 10^{11} \, {^{4}\text{He}} \, s^{-1} \, W^{-1}\) (c.f. \(2.5 \times 10^{11}\)) - 54% of “expected” value
  - Confirmed by Bush at SRI \(1.5 \pm 0.2 \times 10^{11}\) - 58% of “expected” value
  - Rate (not integral) measurement, small \(^{4}\text{He}\), sealing?

- **“The Italians”**:  
  - Gozzi *et al* – simultaneous measurements, time correlation
  - De Ninno, del Guidice, Preparata – “super”-quantitative \(^{4}\text{He}\)?
  - Violante *et al* – confirmed SRI/Case – lattice retention

- **Arata and Zhang**
  - \(^{3}\text{He}\) and \(^{4}\text{He}\) in gas and solid phases*
  - \(^{3}\text{He}\) (from \(^{3}\text{H}\) decay) confirmed at SRI
  - *New results from gas-loading studies?*

- **SRI**
  - Case – Pd/C gas phase
  - FPE electrolysis (M4)

* An additional 15 studies found unexpected \(^{4}\text{He}\) in metal cathodes after FPE energy production [Storms].
**SRI Case Replication**

a) Correlated Heat and $^4$He

b) $Q = 31 \pm 13$ MeV/atom

c) Discrepancy due to solid phase retention of $^4$He.
M4: Excess Power Fitting Function

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

\[ x^\circ = 0.833, \quad i^\circ = 0.425, \quad r = 0.853, \quad \text{Correl.} = 73\% \]
Mass balance of $^4$He is quantitatively consistent with $D + D \rightarrow ^4$He $+ 24$ MeV Heat$_{Lattice}$

~ 30 - 40% of the $^4$He is bound loosely at or near the cathode surface
**Preliminary answers**

- **Is the effect real?**
  - The FPE is new effect in physics
  - Requires a new mechanistic description and explanation
  - Very likely associated with a significant number of CMN Effects
  - Once explained the underlying effect will not seem “so strange”

- **What is the effect?**
  - Heat production consistent with nuclear but not chemical energy or known lattice storage effects
  - Temporally and quantitatively accompanied by $^4$He
  - A number of other nuclear products and processes (some of which may be of “more than scientific” interest)

- **How do we make progress?**
  - **Theory:** quantitative, predictive fundamental physics description
  - **Science:** we must engage the broader scientific community
  - **Commerce:** create, market and sell product(s) based on the effect
  - **Public/Politic:** growing public concern/interest in “Alternative Energy” options
Acknowledgements

Funding Support:
EPRI, MITI, DARPA, DTRA

The author is also very much indebted to a group of scientists and engineers which had as it’s core: Yoshiaki Arata, Les Case, Jason Chao, Bindi Chexal, Brian Clarke, Steve Crouch-Baker, Jon McCarty, Irving Dardik, Arik El Boher, Ehud Greenspan, Peter Hagelstein, Alan Hauser, Graham Hubler, Nada Jevtic, Shaul Lesin, Robert Nowak, Tom Passell, Andrew Riley, Romeu Rocha-Filho Joe Santucci, Maria Schreiber, Stuart Smedley, Fran Tanzella, Paolo Tripodi, Robert Weaver, Vittorio Violante, Kevin Wolf, Sharon Wing and Tanya Zilov.