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The Enabling Criteria of Electrochemical Heat: Beyond Reasonable Doubt

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Abstract

One hundred sixty seven papers from 1989 to 2007 concerning the generation of heat from electrochemical cells were collected, listed, and digitally posted to a CD for reference, review and study. A review showed four criteria that were correlated to reports of successful experiments attempting replication of the Fleischmann-Pons effect. All published negative results can be traced to researchers not fulfilling one or more of these conditions. Statistical and Bayesian studies show that observation of the Fleischmann-Pons effect is correlated with the criteria and that production of "excess heat" is a real physical effect "beyond a reasonable doubt."

Introduction

The field of Condensed Matter Nuclear Science began March 23, 1989 when Fleischmann, Pons and Hawkins reported the generation of electrochemical heat intense enough to be classified as nuclear in origin [1]. Mainstream science embraced the possibility briefly but soon the embrace turned into a strangle hold that has marginalized the field. Funding, patents and acceptance have been denied for 19 years due mainly to early failed experiments, conducted before the most conducive experimental conditions and criteria were widely known. This work is a telling of how those criteria came to be known and how we have become certain beyond reasonable doubt that the Fleischmann-Pons Effect is real.

Enabling criteria

In their seminal paper, *Electrochemically Induced Nuclear Fusion of Deuterium* [1], Fleischmann and Pons reported electrode power densities in excess of 10 watts per cubic centimeter and figures of merit normally associated with nuclear reactors. (See Table 1.)

Table 1. From Ref. 1. The results shown here pushed the limits of credibility but the science community suspended its disbelief, owing mainly to the reputation of Martin Fleischmann.

Generation of excess enthalpy in Pd cathodes as a function of current density and electrode size

Electrode Type	Dimensions /cm	Current density /mA cm^{-2}	Excess rate of heating /W	Excess specific rate of heating /W cm^{-3}
Rods	0.1 × 10	8	0.0075	0.095
		64	0.079	1.01
		512 [a]	0.654 [a]	8.33
	0.2 × 10	8	0.036	0.115
		64	0.493	1.57
		512 [a]	3.02 [a]	9.61
	0.4 × 10	8	0.153	0.122
		64	1.751	1.39
		512 [a]	26.8 [a]	21.4
Sheet	0.2 × 8 × 8	0.8	0.153	0
		1.2	1.751	0.0021
		1.6	26.8	0.0061
Cube	1× 1 × 1	125	WARNING! IGNITION? See text	
		250		

[a] Measured on electrodes of length 1.25 cm and rescaled to 10 cm.

The four enabling criteria found in most successful Fleischmann-Pons experiments were present in their first paper. Their presence is subtle but clear when viewed with the advantage of hindsight. We use the term "criteria" to indicate some condition believed to influence the probability of the desired result of observing excess heat. One should remember that these are used in a statistical sense and that correlation is not causation. That is, they seem to help enable a researcher trying to reproduce the effect. Exact operational definitions were used to evaluate the papers; however their exact forms are too lengthy for this paper. For example, the lowest current density used in any runs within each paper was used when multiple cells where reported. Also, terms like "care in selection" was given an arbitrary operational definition for evaluation of the criteria. In that case, the term depended not on what the material was but that the paper included a statement on its source and or purity. All decisions were reduced to Boolean logical 1 or 0. Here is the abbreviated description of the criteria that entered our statistical analysis.

Criterion 1 is deemed fulfilled when at least one of these conditions is met:

1. Cathode is likely or claimed to be loaded to at least 0.85 D/Pd
2. Cathode loading was slow and current density below 100 mA/cm^2 (1)
3. Open cell voltage was measured during loading
4. Loading was done at or below 15°C (2)
5. Cathode resistance was monitored during loading

(1) As Storms points out, loading at a low current density does not necessarily lead to high loading or excess heat; however the authors have observed that there is a statistical correlation between loading at a low current density and excess heat (~ 55%).

(2) Loading the cathode at a low temperature does not necessarily lead to high loading or excess heat; however, the authors' combined experience in loading approximately 1,000 cathodes suggests that it is helpful in producing the excess heat effect. Other factors such as the nature of the palladium are likely to be more important than loading temperature but are difficult to measure in small laboratories.

Criterion 2 is deemed fulfilled when any of these conditions is met:

1. The source, preparation or purity of cathode is stated.
2. The purity, source or handling of the heavy water is stated.
3. The preparation or formulation of the electrolyte is stated.
4. The chemical procedures used were stated or documented.
5. Additives were used to poison recombination or to seal the cathode against D.

Criterion 3 is deemed fulfilled when at least one of these conditions is met:

1. The cell was operated at current density of at least 200 mA/cm^2
2. Special current systems were used (for example, current pulses, hi-low loading)

Criterion 4 is deemed fulfilled when this condition is met:

1. Non-equilibrium conditions are applied to cathode (i.e. heat pulse, current pulse, lasers, magnets, RF, acoustic energy, superwaves)

Criterion 1 was met in their seminal paper because Fleischmann and Pons loaded at a low current density and ran "long duration" experiments (page 304 of their paper [1]). This is now thought to produce a loading ratio sufficient to produce excess power in many cases (D/Pd >0.85). Also they state:" Electrode potentials were measured with respect to a Pd-D reference electrode charged to the α-β-phase equilibrium" which can be use to give a lower bound to their loading ratios.

Criterion 2 was met because Lithium ions were present in the electrolyte and because of their clear statement: "0.1 M LiOD in 99.5% D_2O + 0.5% H_2O solutions."

Criterion 3 was met because Fleischmann and Pons operated some cells at a current density of 512 mA/cm^2 which is above the 200 mA/cm^2 current density threshold.

Criterion 4 was met because Fleischmann and Pons used calibration heaters that were periodically pulsed, providing non-equilibrium thermal conditions. Also the act of rapidly increasing the current density served to produce non-equilibrium conditions.

These four enabling criteria were not widely known in 1989 but their importance cannot be overstated. Every failed experiment in 1989 and 1990 was lacking in one or more of the criteria and it was the early failed experiments that isolated Condensed Matter Nuclear Science (CMNS) from mainstream science.

An early D-Pd replication attempt of the Fleischmann-Pons experiment was made by Armstrong et al published June 23, 1989 [2], exactly 3 months after the original publication of Fleischmann and Pons. The Armstrong experiment failed because it only met Criterion 2. A total of five replication attempts failed before Kainthla published a successful replication of the Fleischmann-Pons Effect. Kainthla's paper was an early replication but likely not the first [170].

Table 2. Positive experiments compared with negative experiments

Experiment	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Excess
F&P	Yes	Yes	Yes	Yes	Pos.
Armstrong	No	Yes	No	No	Neg.
Armstrong	No	Yes	No	No	Neg.
Balej	No	Yes	No	No	Neg.
Blaser	No	Yes	No	Yes	Neg.
Chu	No	Yes	No	No	Neg.
Kainthla	Yes	Yes	Yes	Yes	Pos.

The five failed experiments (Table 2) had several deficiencies in common. The failed experiments did not load at a low enough current density to meet criterion 1. The later failed experiments that actually measured the loading ratio reported D/Pd ratios less than 0.8. Although a few systems have worked at lower ratios, we know that 0.8 is too low to produce the FPE reliably. Four out of five negative experiments in table 2 failed to increase the current density above the loading current density. In short, the failed experiments used a current density too high for a good load and too low to trigger the FPE.

Summarizing the enabling criteria (3)

The four criteria can best be understood and remembered by thinking in terms of four questions:

1. Criterion 1 asks "was there a demonstrable statement that showed concern about the loading ratios of the palladium?
2. Criterion 2 asks "was there a demonstrable statement that showed concern about cathode and electrolyte purity and were chemical procedures documented?"
3. Criterion 3 asks "Was the cathode operated at a high enough current to be above some current density threshold (note: some researchers find much higher densities are required to see the effect)
4. Criterion 4 asks "was a trigger applied to provide non-equilibrium conditions at the cathode to change the flux of the deuterium?"

(3) Please note that the four criteria mentioned in this paper are correlated with excess heat production but correlation is not causation; it is possible that an experimenter can meet all four criteria and still not produce the excess heat effect. Based on many experiments from many diverse researchers, these criteria will increase the probability of a successful experiment but they will not guarantee the success of a single experiment.

Two failed experiments that mattered

Later in 1989, two failed experiments (Table 3) produced the most important papers in the field of Condensed Matter Nuclear Science; they were important not for what they contributed to the field but for what they took away: funding, patents and access to the mainstream scientific community.

In August 1989 Nathan Lewis' group from Caltech published a negative paper *Searches for Low-temperature nuclear fusion of deuterium in palladium* [10] in the mainstream science journal, Nature. In November 1989, D.E. Williams' group at Harwell Laboratory published a negative paper *Upper bounds on cold fusion in electrolytic cells* [15] in Nature. Mainstream science writers and patent agents have referred to these papers for years when seeking to deny scientific legitimacy or patent protection for CMNS researchers. The failed papers have made a lasting impression since Nature refuses to publish more recent experimental results. The editors consider the matter settled: the Fleischmann-Pons Effect is not real.

By the time the Caltech and Harwell experiments were conducted, a few of the required experimental factors were known from the Kainthla and Fleischmann-Pons papers. The lead investigators chose to follow their own protocol resulting in two failed experiments and a negative image for CMNS.

Table 3. The Caltech (Lewis) and Harwell (Williams) papers

Experiment	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Excess
Lewis	No	No	No	No	No
Williams	No	No	No	Yes	No

The Lewis experiment failed in a manner very similar to the earlier 1989 papers: they did not load to a high D/Pd ratio and they didn't run for extended periods of time – two or three months. The Harwell experiment was a larger effort and did change the current from low to high in some but not all experiments. The Harwell and Caltech experiments tended to load at higher levels and to run for fairly short periods. They also used large area cathodes and small currents. Cravens & Letts work with small cathodes on the order of 0.15 g. The authors recommend loading for 10E7 coulombs per atomic mole atom of Pd. Our cathodes load for 120 hours and run for a minimum of 60 days (1440 hours). Harwell's longest run was 917 hours on a cathode that weighed 1.4 grams – 10 times the mass of our cathodes – and was tested for about half as long. On page 380 of their paper, the Harwell group reports the D/Pd ratios were in the 0.76 to 0.84 range – too low to produce the FPE reliably. In summary, both experiments failed to achieve high loading.

Teaching Papers

In the early nineties, CMNS researchers began to build on the foundation laid by Fleischmann and Pons; the enabling criteria were learned and taught to others at a rapid rate. From the digital databases, we identified seventeen positive electrochemical heat experiments in 1990, compared to just two in 1989. The enabling criteria identified in this review paper were discovered and quantified by several key researchers and then taught by conference papers and personal communications. Table 4 contains a listing of CMNS researchers who we believe made key contributions to identifying / quantifying the enabling criteria or taught methods to fulfill them.

Table 4. Papers that identified enabling criteria or taught how to fulfill them (bulk loaded Pd-LiOD)

Year	Author	Criteria
1989	Fleischmann & Pons [1]	Criteria 2- 4
1989	Kainthla [8]	Criteria 2-4
1990	Appleby [17]	Criterion 2-4
1990	Guruswamy [26]	Criteria 1-4
1990	Lautzenhiser (Amoco) [28]	Criteria 2-4
1991	McKubre [49]	Criterion 2-4
1992	McKubre [56]	Criterion 1
1992	Takahashi [60]	Criterion 1 Low-high loading
1993	Bockris [62]	Criteria 2, 4
1993	Cravens [63]	Criteria 2-4
1993	Storms [71]	Criterion 3
1996	Celani [90]	Criterion 1 Pulse loading
1996	Miles [96]	Criterion 1 Boron alloy
1996	Storms [100]	Criteria 1-4
1998	Arata & Zhang [107]	Criterion 1 Double cathode
1998	Storms [119]	Criterion 1 OCV method
1999	Storms [121]	Criterion 1 Lattice expansion
2000	Miles [125]	Criterion 4 Current trigger
2001	Miles [131]	Criterion 1 Boron alloy
2003	Dardik [148]	Criteria 1,4 Superwave
2003	Letts & Cravens [149]	Criterion 4 Laser trigger
2004	Apicella [155]	Criterion 4 Laser trigger
2005	Violante [162]	Criterion 4 Laser trigger

Discussion of the Teaching papers

Fleischmann & Pons [1] laid the foundation for a scientific field of study that has endured 19 years. Their first paper has motivated 14 international conferences, thousands of experiments, papers and many books. Most of all, their paper inspired many to believe that important science could still be done by dedicated individuals.

Criterion 1 (Bulk loading considerations)

In 1990 an excellent positive experiment was reported by Guruswamy and Wadsworth in their paper, *Metallurgical Aspects of Cold Fusion Experiments* [26]. This appears to be a superior paper but is perhaps underappreciated. Criteria 1 is fulfilled in this paper by measurement of cathode enlargement as the cathode filled with deuterium. The authors reported a D/Pd ratio of 0.93. Criteria 1 was fulfilled. The loading current density used was higher than one might normally use – 100 mA/cm^2. The authors reported the use of arsenate to poison the surface. This may have helped seal the palladium surface and reduce the loss of deuterium, resulting in a high D/Pd ratio even with a higher-than-normal current density.

This 1992 paper, *Excess Power Observations in Electrochemical Studies of the D/Pd System: the Influence of Loading* [56], is one of the great teaching experiments that came from McKubre's group at SRI in the early to mid-nineties. If these high quality experiments had been available in mid 1989 to support the seminal work of Fleischmann and Pons, perhaps the Caltech and Harwell experiments would have succeeded and our history might have been written differently.

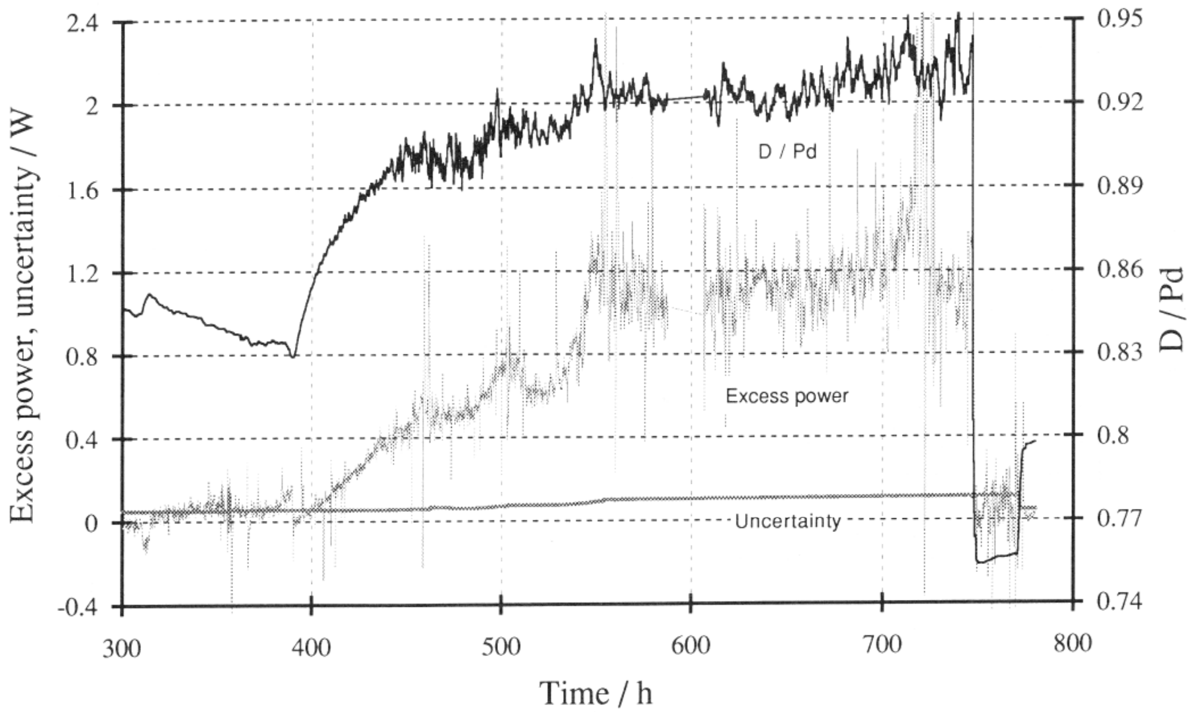

Figure 1. Output from SRI experiment showing that excess power appears at a D/Pd ratio of 0.8 but is more robust above 0.85.

In 1992, Takahashi produced an interesting paper, *Anomalous Excess Heat by D_2O/Pd Cell under L-H Mode Electrolysis* [60], about how to achieve Criterion 1; the Takahashi method taught that the anode should be a square geometry evenly spaced around the cathode. The cathode was a large 2.5 cm square plate. Counting both sides, its effective area was 12.5 cm^2.

Takahashi loaded the cathode low, at 20 mA/cm^2 for 6 hours, and then high at 336 mA/cm^2 for 6 hours. He repeated this for about two weeks, at which time excess power began to appear. Takahashi estimated that the loading ratio was ~ 0.9. The high loading drove the cell to boil and produced excess power of approximately 90 W.

In 1993 at ICCF4, Cravens presented a conference paper, *Factors Affecting The Success Rate of Heat Generation in CF Cells* [63] **,** that listed in detail all of the techniques that he had learned from others and methods that he had discovered in his own lab. The paper was unique enough to prompt Martin Fleischmann to comment that if any investigators were having reproducibility problems, they should read the Cravens paper. Quoting his 1993 abstract is instructive:

> A series of low cost, low precision experiments were conducted to screen for factors which may affect the successful observation of heat from palladium/ heavy water electrolytic cells. Critical factors include the selection of the

palladium and the experimental protocol during the initial loading to the beta phase. It was found that bubble patterns, volume expansion, and surface appearance can be used as early predictors of ultimate success. Since large scale defects are detrimental, methods of avoiding cracking are discussed. These include alloying, preparing a uniform surface, loading at a slow rate at low temperatures, delaying use of additives to the electrolyte, and uniform loading techniques. Methods of achieving the later and larger heat releases were found to include: rapid increase in the current density above a threshold value and raising the temperature. A reflux calorimeter design is presented that allows for continuous studies at boiling temperatures of the electrolyte. Unexpected and unexplained occurrences of heat bursts by magnetic fields and radio frequency fields are reported.

It can be clearly seen that a self-funded researcher had taught himself how to do the Fleischmann-Pons experiment successfully; he learned by reading other papers and noting the common factors in successful experiments. Over the years since then, these common factors have become the four “criteria” or “conditions” we are discussing in this work. When Letts began experimenting in 1992, it was Cravens who taught him how to produce a successful Fleischmann-Pons experiment by using the “Cravens criteria.” We tend to forget that many excellent CMNS researchers are also excellent teachers, so it was natural that colleagues would learn from colleagues.

In 1996, Celani and his group produced a paper, *Reproducible D/Pd Ratio>1 and Excess Heat Correlation by 1 Micro-Second Pulse, High Current Electrolysis*, which described a novel method to fulfill Criterion 1 by using pulsed current to load palladium with deuterium to a D/Pd ~ 1 or slightly above. The method seemed to involve the surface and did produce a high D/Pd ratio reproducibly. However, even with high loading, not all cathodes produced excess power. The investigators concluded that the deuterium absorption rate seems related to excess power production more than just the loading ratio. High absorption rates of deuterium by palladium seem to be related to excess power production.

Also in 1996, Miles and his collaborators produced a paper, *Electrochemical Loading of Hydrogen and Deuterium Into Palladium and Palladium-Boron Alloys* [96] , proposing that a small amount of boron alloyed with palladium helps fulfill Criterion 1, producing a high loading ratio. In a personal communication, Miles explained that he thought that Pd-B is a two phase material and high loading may exist in small regions, perhaps reducing the need for a bulk loading ratio near 0.85.

Storms contributed a paper in 1996, *How to Produce the Pons-Fleischmann Effect* [100], that like the Cravens “Factors” paper provided an experimental handbook on how to produce the Fleischmann-Pons effect (FPE). On page 3 of this paper Storms identifies the critical deuterium content as the most important requirement in order to produce the FPE. Fulfillment of Criterion 1 is the same as achieving the critical deuterium content. In this paper Storms identifies loading at 20 mA/cm^2 as the best loading current density to use. Storms’ paper [100] is an excellent resource for new researchers wanting to avoid a high number of failures before seeing the Fleischmann-Pons heat effect. Had this paper been available in mid 1989, many CMNS image problems would have been avoided.

In 1998 Arata & Zhang proposed a new type of cathode design to improve the chances of fulfilling criteria 1. Their paper, *Anomalous Difference between Reaction Energies Generated within D_2O Cell and H_2O Cell* [107] reported results from their new design called a double structure cathode. The methods are meant to fulfill Criterion 1 with high reproducibility. A small amount of finely divided (nano) particles of palladium was sealed inside of a palladium cylinder. The cylinder was evacuated and then run as a cathode in a traditional Pd-LiOD electrolytic system. Deuterium diffused through the palladium cylinder and entered the inner evacuated region of the cylinder. Pressure increased as more deuterium diffused into the cylinder's inner space. The nano palladium black absorbed the deuterium to a very high D/Pd ratio. The Fleischman-Pons effect self-triggered and the entire palladium cylinder heated up, producing large amounts of excess power/energy. The effect was reported to be 100% reproducible. A new version of this experiment was conducted as a working demonstration in Japan during the spring of 2008 and produced positive results.

Storms contributed a useful paper in 1998, *Relationship between Open-Circuit-Voltage and Heat Production in a Pons-Fleischmann Cell* [119]. In this paper, Storms explores how the open circuit voltage predicts the fulfillment of Criterion 1. According to Storms, open circuit voltage of 1 to 1.2 Volts indicates a D/Pd ratio around 0.8 to 0.9, the minimum requirement to fulfill Criterion 1 and produce the Fleischmann-Pons effect. An excellent discussion of the mechanics of hydrogen loading and loss through a network cracks in a palladium cathode is also presented in this paper. A graphic from the paper (Fig. 2) is instructive.

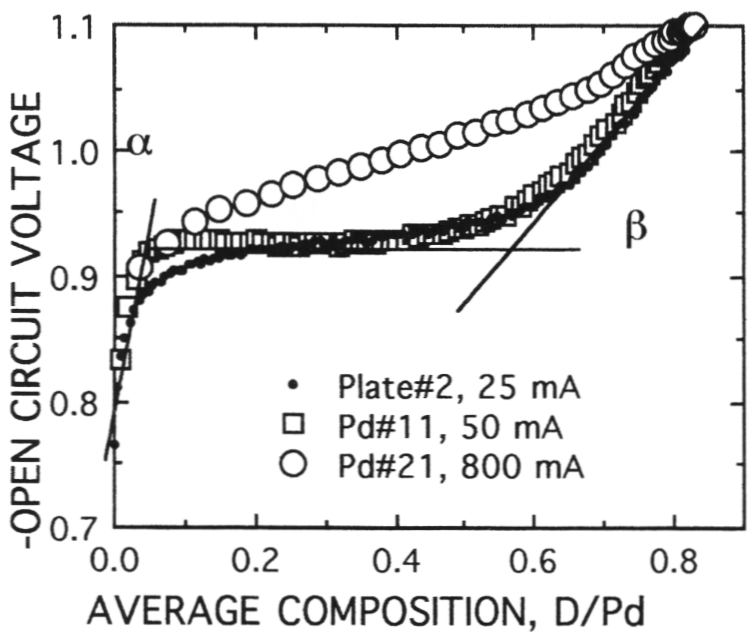

Figure 2. OCV versus D/Pd ratio

The following year, 1999, Storms contributed another excellent teaching paper, *Anomalous Heat Generated by Electrolysis Using a Palladium Cathode and Heavy Water* [121], reporting how lattice expansion may serve as an indicator of Criterion 1 fulfillment. Storms teaches that high loading is not likely when the palladium cathode expands more than about 13% during formation of the deuteride, as illustrated in Fig. 3. Cracks are likely to form.

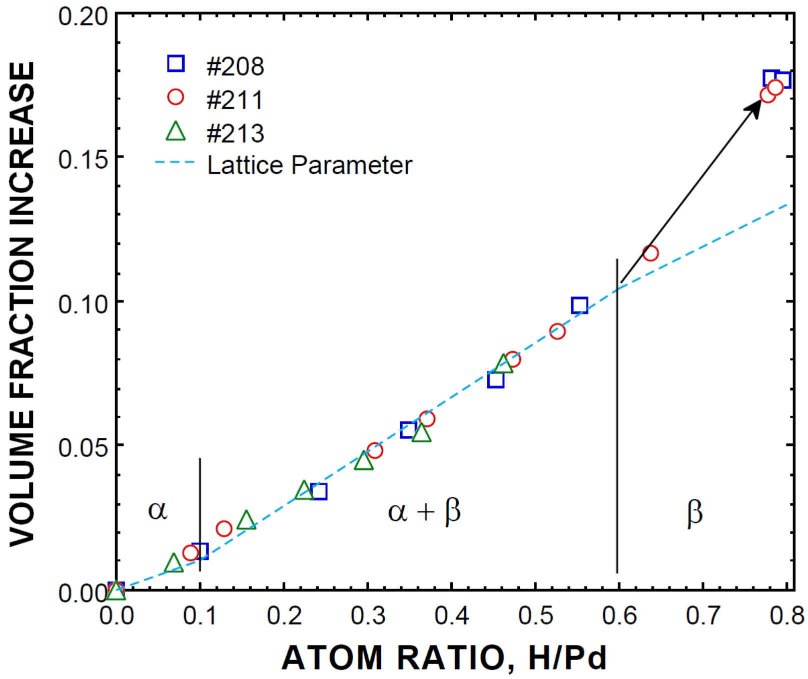

Figure 3. Vertical scale is cathode volume fraction increase

The next Criterion 1 teaching paper, *Calorimetric Analysis of a Heavy Water Electrolysis Experiment using a Pd-B Alloy Cathode,* [131], was contributed by Miles, Imam and Fleischmann in 2001. This paper taught that Criterion 1 could be fulfilled by adding boron to the palladium cathode. This paper is another study of the importance of boron when alloyed with palladium, confirming the observations reported in the 1996 paper by Miles and collaborators [96]. Again, Miles reported to the authors that the Pd-B alloy may produce high local loading, reducing the need to load the bulk cathode to 0.85 D/Pd or above. Storms also reported to the authors that he was unable to load bulk Pd-B above 0.67 D/Pd. So there appears to be the need for some more detailed work to clarify the issue of high loading in a bulk Pd-B cathode.

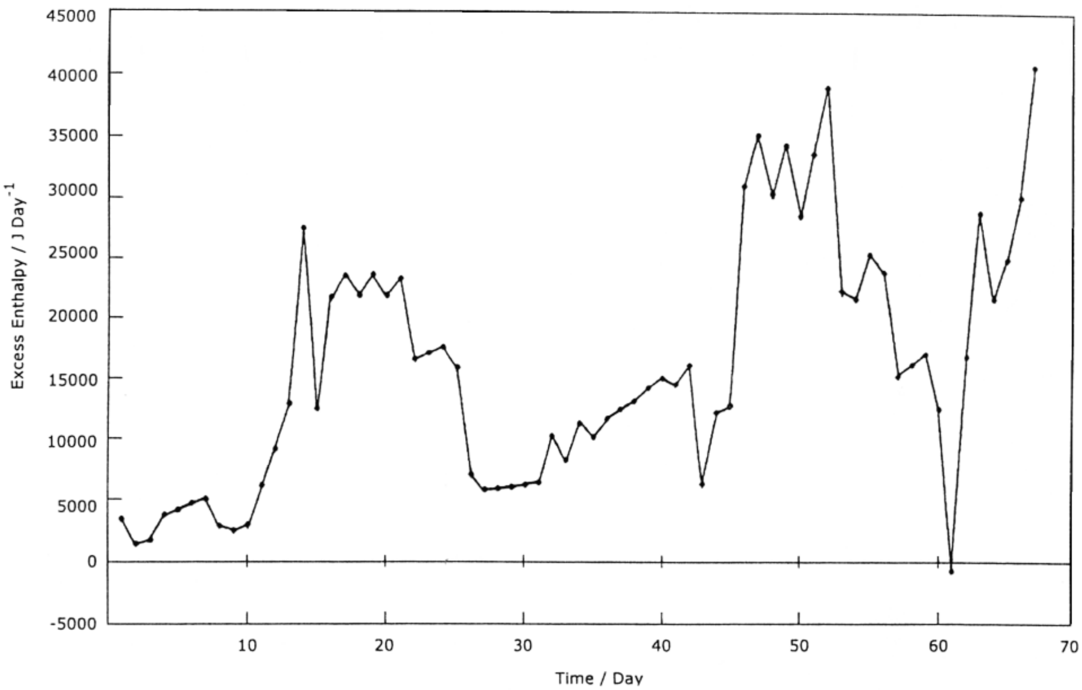

Figure 4. Excess enthalpy produced by Pd-boron cathode

In 2003, Dardik and his collaborators produced the final Criterion 1 teaching paper in Table 4, *Intensification of Low Energy Nuclear reactions Using Superwave Excitation* [148]. Figure 5 shows an image of the Superwave applied to a palladium cathode that resulted in much higher loading at 0.96 D/Pd.

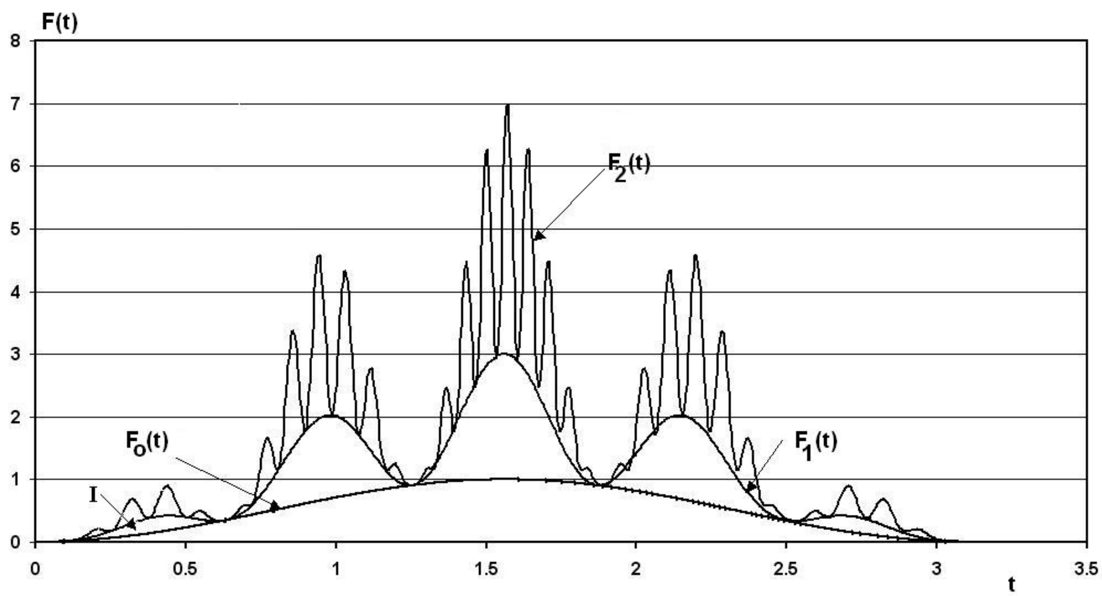

Figure 5. Application of a Superwave to a palladium cathode resulted in a D/Pd ratio of 0.96 compared to 0.88 for DC.

Criterion 2 (Chemical considerations)

Criterion 2 is concerned with providing a chemical environment that improves the chances of producing the excess heat effect; criterion 2 was met in Fleischmann and Pons' first paper because of their clear statement regarding electrolyte composition: " 0.1 M LIOD in 99.5% D_2O + 0.5% H_2O".

The next paper in Table 4 teaching Criterion 2 is the paper from Bockris' group, *Sporadic Observation of the Fleischmann-Pons Heat Effect* [8] by Kainthla. This paper fulfilled Criterion 2 by reporting the electrolyte composition as "0.1 M LiOD" and by stating the cathode purity was 99.9%. The last three cells (out of 10) produced excess power, which shows that being concerned about chemical purity might be helpful in producing the excess heat effect.(4)

Appleby's 1990 paper, *Anomalous Calorimetric Results During Long-Term Evolution of Deuterium on Palladium from Alkaline Deuteroxide Electrolyte* [17], is an excellent example of paying attention to Criterion 2. Note that Appleby reported that LiOD worked but NaOD did not (Fig. 6). The chemical environment is important.

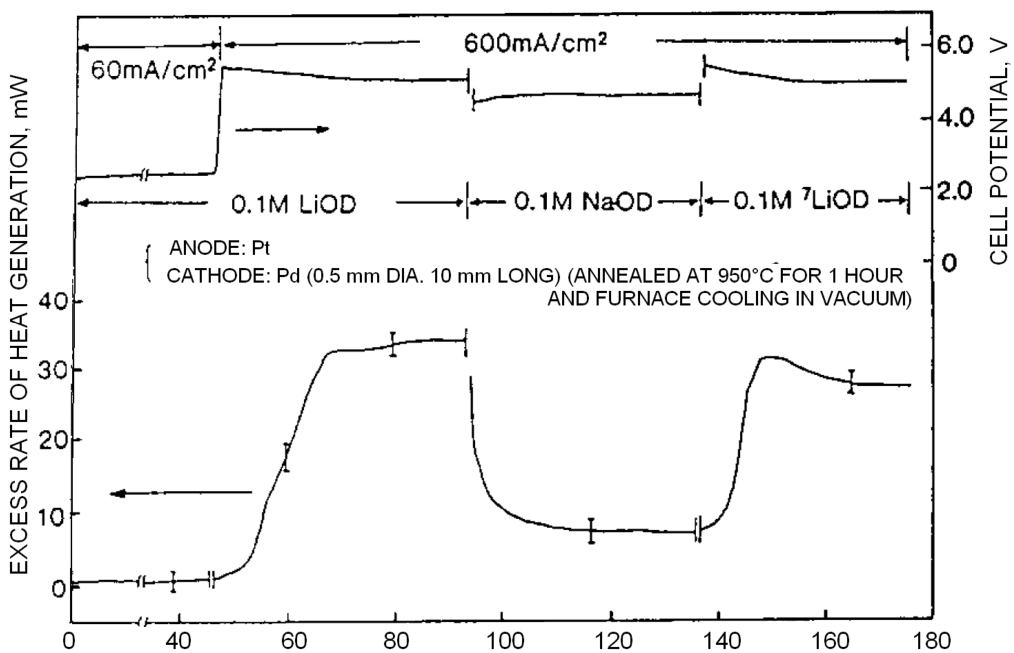

Figure 6. From Ref. 17, shows the importance of Criterion 2 with regard to ions. LiOD produces the FPE but NaOD does not.

Another paper that demonstrates consideration of Criterion 2 is the paper by Guruswamy and Wadsworth, *Metallurgical Aspects of Cold Fusion Experiments* [26]; this early paper from 1990 loaded at a relatively low current density and produced excess power while anticipating many of the issues that would become important in the field of CMNS over the next decade: electrode purity, electrolyte purity, electrode geometry and triggering. This insight is collected in the authors' table 1 and is shown here in Table 6.

(4) Storms told the authors that as little as 1-2% of H contamination in the electrolyte can terminate the excess heat effect.

Table 6. From Ref. 26. Guruswamy and Wadsworth's insight into Criterion 2, especially points 2, 3 and 4.

1. EXPERIMENTAL CONDITIONS
    - CURRENT DENSITY
    - TEMPERATURE
    - ELECTROLYTE COMPOSITION
    - POISONS IN ELECTROLYTE
    - NEED FOR INITIATION (ELECTRICAL, MAGNETIC, THERMAL or ULTRASONIC SHOCK)
    - H, CO_2 PICK UP
    - CELL DESIGN

2. ELECTRODE PURITY
    - SUBSTITUTIONAL IMPURITIES
        - PRIMARY Pd (Cu, Ni, Fe, Zr, Te, As, Sb, Cd, Mg, Ca, Li...)
        - RECYCLED Pd (LARGE NO. OF ALLOYING ELEMENTS)
    - INTERSTITIAL IMPURITIES
        - PICKED UP DURING PROCESSING & HANDLING (C, O, N, H)

3. IMPURITIES IN ELECTROLYTE
    - IMPURITIES FROM PROCESSING & HANDLING (C, S, Cu, Zr...)

4. ELECTRODE MICROSTRUCTURE
    - GRAIN SIZE, DISLOCATION DENSITY & DISTRIBUTION

POSSIBLE ROLE OF A THIRD ELEMENT IN THE NUCLEAR REACTION

CELL DESIGN: ELECTRODE GEOMETRY, ELECTRODE SPACING, ETC.

The next paper in Table 4 that fulfilled Criterion 2 was the Lautzenhiser and Phelps paper**,** *Cold Fusion: Report on a Recent Amoco Experiment* [28]; the experimenters reported the purity of their heavy water and the purity of their palladium cathode in the materials section. They also reported many of the impurities present in the cathode, showing concern for criterion 2.

The next paper in Table 4 that met criterion 2 is the paper by Bockris and his collaborators, *Triggering of Heat and Sub-surface Changes in Pd-D Systems* [62] from 1993. This paper reported electrolyte and cathode purity on page 3 in the material science section.

The Cravens paper, *Factors Affecting The Success Rate of Heat Generation in CF Cells* [63], discloses the importance of chemical considerations. On page 8, Cravens recites the importance of contamination avoidance in producing the excess heat effect. He reported the use of a dummy cathode to remove contaminants and the importance of avoiding H contamination. Cravens also reported the importance of surface chemistry - a polished cathode worked best (Fig. 7).

Surface conditions – use a smooth surface

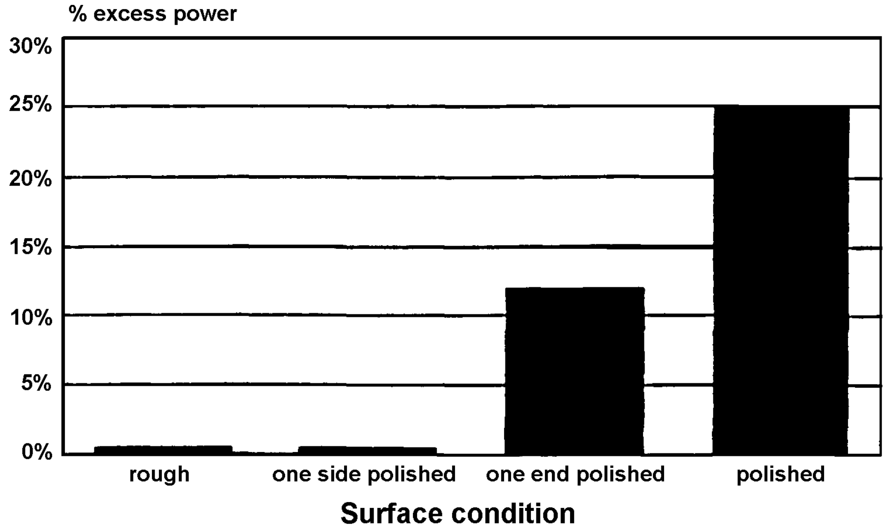

Figure 7. A polished cathode works best to produce the FPE.

Storms, in his well known paper from 1996, *How to Produce the Pons-Fleischmann Effect* [100], succinctly describes the importance of cathode surface conditions: (quoted from page 5)

> . . . Aluminum metal (2-20 ppm) added to the electrolyte after the palladium has achieved its maximum deuterium content is sometimes useful in initiating excess heat production. Thiourea also has been used with limited success. Preoxidizing the surface at 600-750°C in air improves the loading rate because the very thin layer of oxide is quickly reduced to a pure, very chemically active layer of palladium once electrolysis starts. Absence of certain surface impurities such as copper, lead or silver (from solder) is also important. However, a thin film of gold (≈7000 Å) on the palladium surface can increase the limiting D/Pd ratio.[34] The benefits of lithium and platinum, two impurities normally observed on and within the surface region, are still unknown. Other impurities not yet studied may have both good and bad effects.

Cravens and Storms are in agreement that cathode surface conditions are vital to consider when attempting reproduction of the Fleischmann-Pons Effect (FPE).

Criterion 3 (high operating current density)

Table 1 from the 1989 Fleischmann and Pons paper, *Electrochemically Induced Nuclear Fusion of Deuterium* [1], shown above, demonstrates that operating current density is proportional to observed excess power. The importance of loading at a low current density and running at a much higher current density was known to only a few researchers in 1989.

As mentioned earlier in this review paper, investigators began to learn or discover the current density requirements; In June , 1989 the Kainthla paper, *Sporadic Observation of the Fleischmann-Pons Heat Effect* [8], reported modest excess power production after loading at 60 mA/cm^2 for 18-30 days, followed by running above 400 mA/cm^2**.**

The Guruswamy and Wadsworth paper, *Metallurgical Aspects of Cold Fusion Experiments* [26] reported excess power production after loading at the somewhat high current density of 100 mA/cm^2. Later they increased current density to 200 mA/cm^2 and saw bursts (Fig. 8).

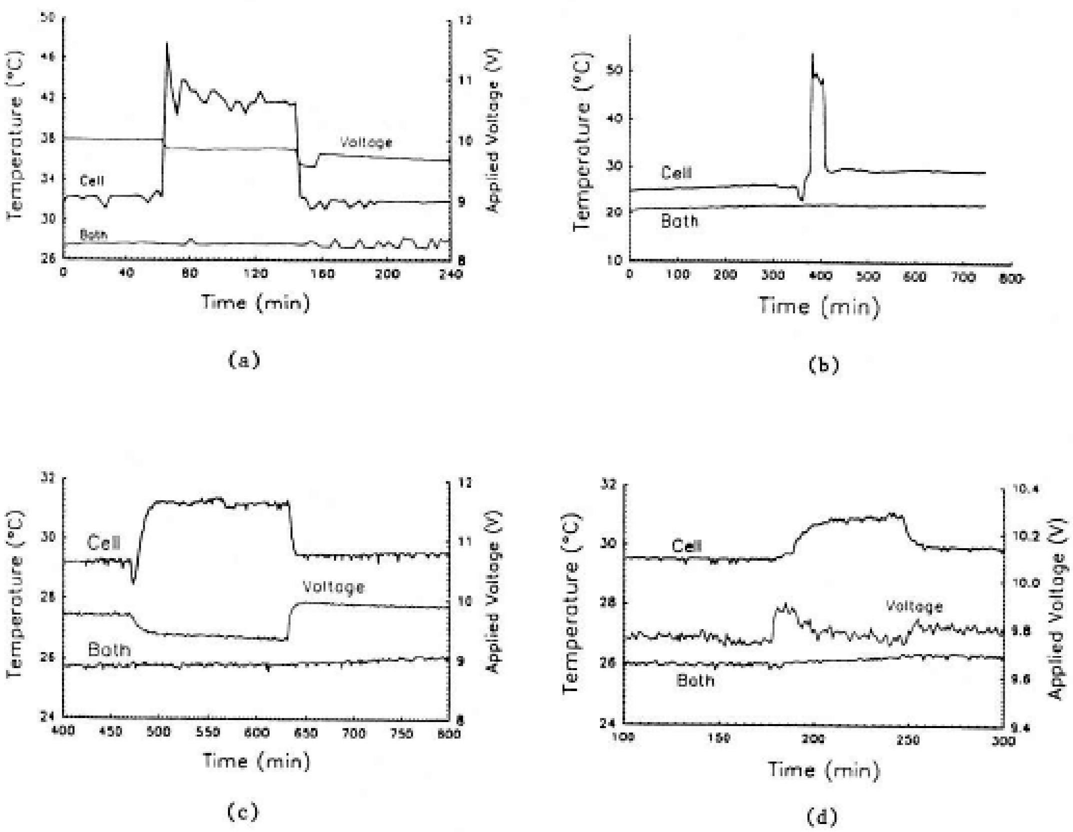

Figure 8. Unexpected heat spikes

With respect to current density, the Lautzenhiser (Amoco) paper, *Cold Fusion: Report on a Recent Amoco Experiment* [28], is unusual. The cathode for that experiment loaded at 3 mA/cm^2 and ran at only 15 mA/cm^2. The paper reported a small amount of excess power – 40-90 mW, seen in a high-precision micro calorimeter. We would not expect that a current density of only 15 mA/cm^2 would trigger excess power, yet it did. Notice that they saw a small amount of excess heat even though they did not fulfill the criterion. It is important to notice the difference in the statistical terms of correlation and saying that something is "essential". Adherence to the criteria does not guarantee success nor does ignoring criteria doom an experiment. The criteria are only "enabling" in that they increase the probability of the desired outcome.

In 1991 SRI and EPRI collaborated to produce an excellent paper, *Isothermal Flow Calorimetric Investigation of the D/Pd System* [49]; this paper quantified the current density threshold of about 200 mA/cm^2. We usually recognize that 500 mA/cm^2 is a good target current density to maximize the chances of triggering the FPE. The current density threshold is clearly visible in Fig. 9.

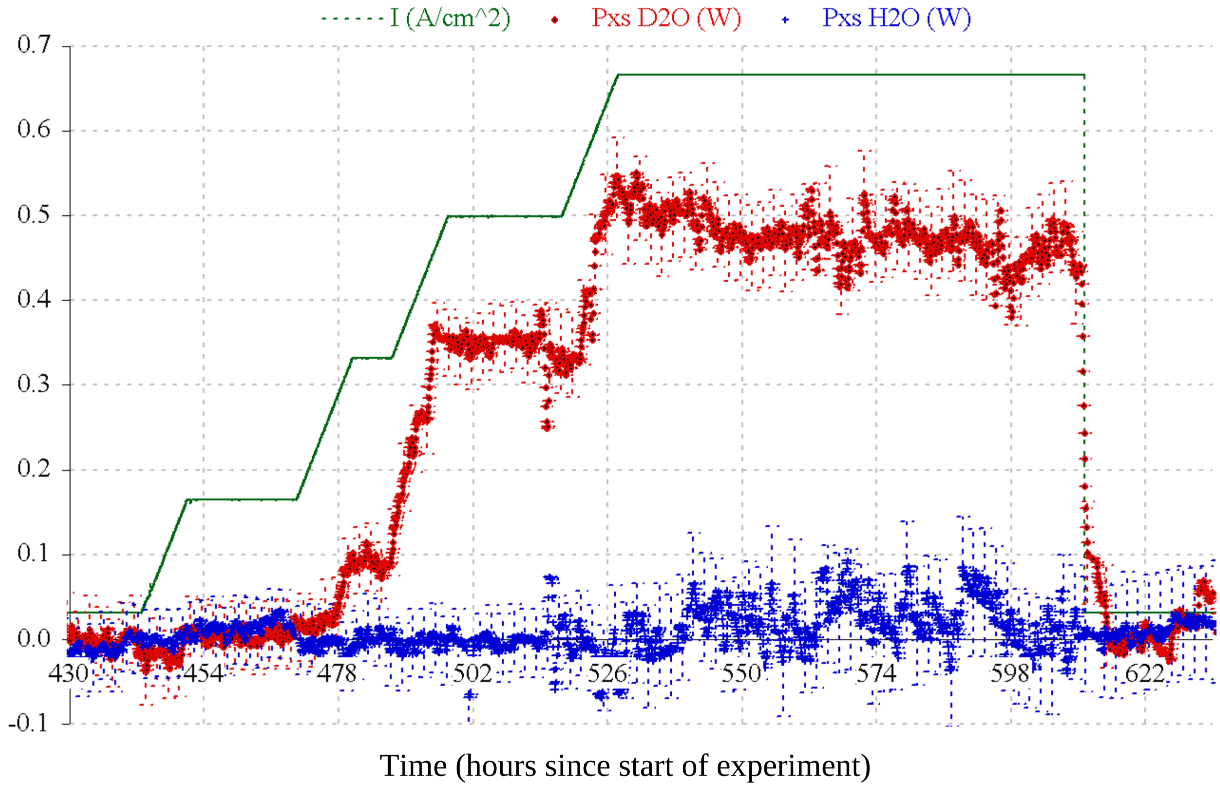

Figure 9. Excess power "switches on" at ~ 200 mA/cm^2

In 1992 Takahashi demonstrated the importance of Criterion 3 by running a cell in the low current-high current mode for many hours, as reported in his paper, *Anomalous Excess Heat by D_2O/Pd Cell under L-H Mode Electrolysis* [60]. After a loading period, the cathode produced ~ 90 W of excess power when running at high current density of 336 mA/cm^2. There was no excess power at low current density of 20 mA/cm^2.

The importance of Criterion 3 (current density) is also addressed in Cravens' 1993 conference paper, *Factors Affecting The Success Rate of Heat Generation in CF Cells,* [63]; in this multi-faceted paper, Cravens shows that an operating current density greater than 120 mA/cm^2 is required to produce the FPE (Fig. 13).

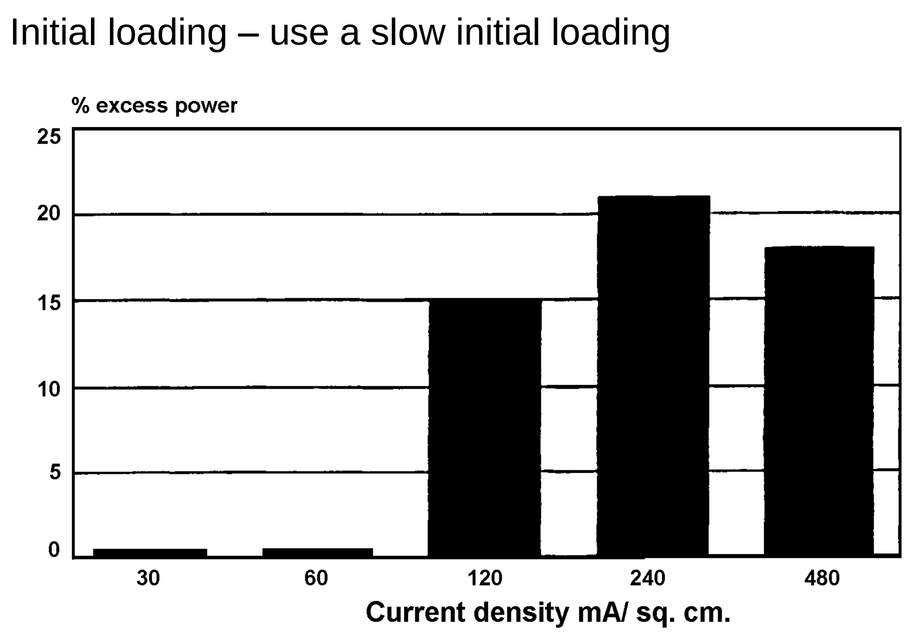

Figure 10. Cravens shows that low operating current densities will not normally produce the FPE.

The final paper in Table 4 discussing Criterion 3 (current density) issues was contributed by Storms in 1993 titled, *Some Characteristics of Heat Production Using the "Cold Fusion" Effect* [71]. In Fig. 11 Storms plots his experimental data with three other data sources. Storms shows that some cathodes "switch on" at a lower current density than many others – perhaps because those cathodes have fewer cracks and can load hydrogen more readily. A more typical value in Storms data appears to be ~ 100 mA/cm^2.

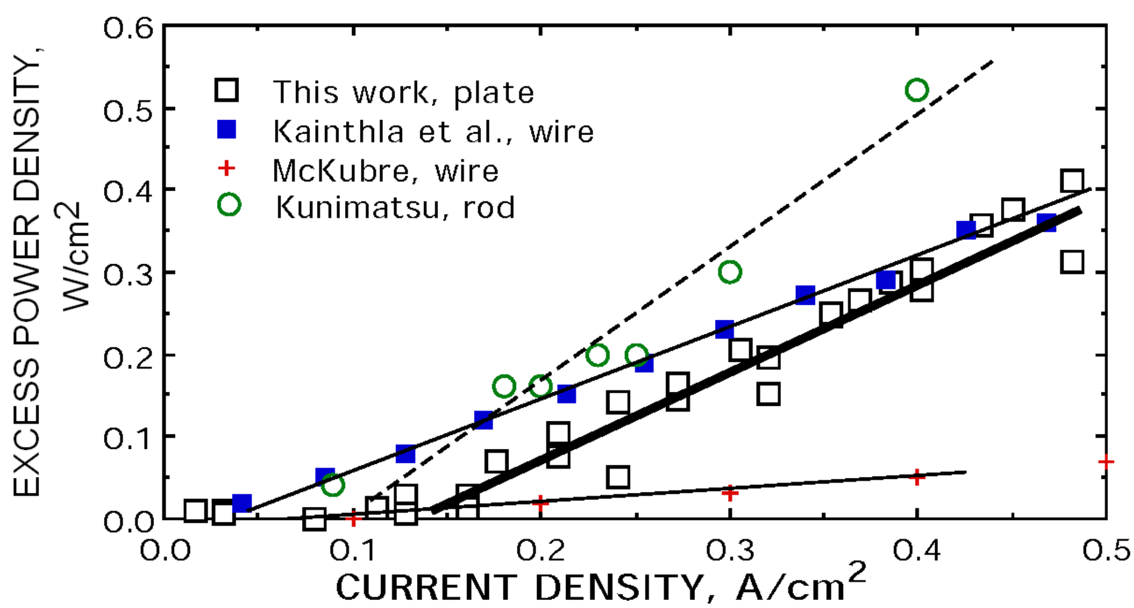

Figure 11. Vertical column is excess power density, W/cm^2

Criterion 4 (External factors – triggering)

In the early years of CMNS (1989-1992), long incubation periods were often required to produce the Fleischmann-Pons effect. It seemed all that was required to produce the FPE was a long, low current loading period followed by an even longer high current loading period. As the Lautzenhiser (AMOCO) paper [28] demonstrated, patience was important. This paper, *Cold Fusion: Report on a Recent Amoco Experiment* [28] reported, "It is important to note that if this experiment had been terminated after only one month, the results would have shown no positive energy production."

The 1990 Guruswamy & Wadsworth paper, *Metallurgical Aspects of Cold Fusion Experiments* [26] anticipated the possibility of triggering as mentioned in Table 6 ("need for initiation") but was not attempted.

As far as we could determine, external triggering of the D-Pd system was not reported until 1993. The Bockris paper, *Triggering of Heat and Sub-surface Changes in Pd-D Systems* [62] and the Cravens paper, *Factors Affecting The Success Rate of Heat Generation in CF Cells* [63] reported triggering the FPE with RF at three specific frequencies of 82,365 and 533 MHz and by imposition of magnetic fields greater than about 200 gauss. One to two watts of excess power was observed within a few minutes following cell stimulation.

Two new types of cell stimulation appeared in 2003. Letts and Cravens reported excess power production in their ICCF10 conference paper, *Laser Stimulation of Deuterated Palladium: Past and Present* [149] and Dardik reported excess power from cell stimulation by Superwaves in the ICCF10 conference paper, *Intensification of Low Energy Nuclear reactions Using Superwave Excitation* [148]. Both types of stimulation appear to create dynamic conditions at the cathode surface favorable to triggering the Fleischmann-Pons effect.

The laser effect has been replicated by Storms [151] , McKubre & Tanzella [172] and advanced by Apicella [155] and Violante [162]. Swartz reported observation of the laser effect before 2003 and reported excess power from laser stimulation in his ICCF10 conference paper, *Photo Induced Excess Heat from Laser-Irradiated Electrically Polarized Palladium Cathodes in* D_2O. [173].

The Dardik Superwave trigger has been replicated at SRI, with help from Energetics Technologies. The Superwave is built up using a series of rectified sine waves. The idea is to begin with a base frequency and then add harmonics to the base such as 2x, 3x...6x. The Superwave is designed to rise to its peak quickly and decay back to base frequency slowly. Dardik's idea is based on how natural systems oscillate. This same rapid up, slow down cycle is apparently effective in providing a flux of deuterium at the cathode surface. Dynamic surface conditions are evidently effective because the Superwave has been reported to trigger excess power of 100-300% over input power. A few 25 to 1 power gains have been reported using the Superwave trigger.

In 2004, Apicella and collaborators reported in their paper, *Some Recent Results at ENEA* [155] that laser stimulation increased excess power reproducibility from 30% to 90% and that ^4He is detected in amounts commensurate with D+D fusion. It was also reported that P polarization of the laser was required to see the benefits of laser stimulation.

In 2005, Violante and collaborators reported in their paper, *Progress in Excess of Power Experiments with Electrochemical Loading of Deuterium in Palladium* [162] that the P polarization is effective because it creates charge separation on the cathode surface. Charge separation on the cathode implies the possibility of creating surface Plasmons (Polaritons) that can interact with the laser. This may be very important as it could provide a connection with Hagelstein's theory and laser stimulated excess power.

Section 4 has discussed several of the papers that demonstrated fulfillment of the four criteria we believe are required to produce the Fleischmann-Pons Effect. These papers are a subset of a larger number of papers that we considered in a statistical analysis of the four enabling criteria.

Statistical Analysis of Papers and Enabling Criteria

The authors selected 167 papers (see references) for this study. These papers reported heat generation from electrolytic systems. As many may recall, it was very difficult for CMNS researchers to get their work published in the two years following the Fleischmann and Pons announcement. We are aware that many viable papers from that period were not included in this study, mainly because they are not yet available in a digital format. Exclusion from this study should not be taken as a judgment about the importance of excluded papers but only their availability. The 167 papers in this study span 18 years, come from vastly different laboratories and were performed by dedicated researchers from a number of political and cultural backgrounds. The diversity of this work is almost as amazing as its consistency, serving as a fair representative sample for statistical input.

Only electrochemical heat papers from the Pd-LiOD system were included in the statistical survey to make the statistics meaningful. Although we directed our efforts to identifying which criteria were fulfilled by each paper, it was not always clear if the criteria were met or not. In those cases, the papers were excluded from the final statistical analysis. Our guiding premise was to allow data into the analysis only if it was clear and unambiguous. We had several alternative ways to signal achievement of each criteria so that more papers could be included. This resulted in 122 papers entering our statistical analysis. The papers were segregated by criterion and each paper was assigned a 1 or 0 based on observation of excess power or not. There were 34 papers in our study that actually measured the D/Pd ratio; there were 49 papers that reported the loading current density; there were 59 papers that reported the operating current density and 122 papers that reported enough data to determine if triggering was used either by increasing the current, the temperature, applying external fields or electromagnetic radiation.

Our analysis shows that there is a 76% overall correlation (Rank) between the four enabling criteria and observation of the Fleischmann-Pons Effect (FPE).

Our analysis of 122 papers shows that if an experimenter met these requirements:

1. Loads below 100 mA/cm^2
2. Achieves a loading ratio > 0.8
3. Runs above 500 mA/cm^2
4. Applies a trigger to the cathode

Then the probability of producing the FPE was ~ 76%. It is obvious that there is a high degree of correlation between the four enabling criteria and the observation of excess power. It was less obvious to us before completing this study that the measured D/Pd ratio was only correlated to excess power by 26% . We noted several papers in our study that achieved a high measured D/Pd ratio but still failed to produce excess power (see the Isobe paper #138). Further, the operating current density was only correlated with excess power production by 21%. The loading current density was negatively correlated with excess power at -55%, confirming that a low loading current density makes excess power more likely. Triggering was correlated with excess power at 65%. All negative papers were seen to have failed in fulfilling one or more of the enabling criteria. If we define a Fleischmann-Pons experiment as one that fulfills all four criteria, then none of the early researchers who published negative papers actually performed the Fleischmann-Pons experiment as we know it today.

Statistical Analysis of Papers Reporting Measured Parameters

In order to include a maximum number of papers in our study, we had to rely on indirect methods to determine if a cathode had achieved a high degree of loading. In this section we discuss our results when only measured parameters are included to more fully investigate the roles of various conditions and to provide a more quantitative view.

Although there is not room to describe in detail our operational definitions used in the statistics, it is important to note that the authors tried to assure objective definitions that lead to unambiguous Boolean binary logical notation for each criterion. This approach was taken to span the greatest number of papers. For example, no attempt was made to evaluate “goodness” of chemical protocols or material sources, only that a protocol was mentioned in the paper. If the material source was mentioned then the paper received a binary 1.

The grading for excess heat was based on any claims of excess heat within the paper and not individual cells or cathodes within a series of runs. Thus, each paper was scored by a single binary number based on objective “operational definitions” (specific statistical term) for each of the 4 criteria and the claim of excess heat.

The original individual criteria were scored as a logical 1 if any of the items existed within the paper. This permitted inclusion of 122 papers out of the original 167 papers investigated. The following analysis was done with restricted single element criteria to provide statistical data based on measured parameters only. Since only a few papers addressed all of the specific issues with measurements, this approach results in only 17 papers entering the analysis. There are very few papers which report specific loading ratios, loading current densities, operational current densities and triggering information. This restricted view is presented here, however the authors caution that it may not be desirable to discard over one hundred papers based on a restricted view of what factors are generally thought to be relevant.

The criteria used for this more restricted statistical study are:

Criterion 1:	Is the loading ratio measured at 0.85 D/Pd or greater?
Criterion 2:	Was the initial loading done below 100 mA/cm^2? (lowest listed when several are reported)
Criterion 3:	Was the cell operated at current densities at or above 200mA/cm^2 (highest listed for multiple listings)
Criterion 4:	Was some triggering or event imposed that would alter the deuterium flux or cause a non-equilibrium condition?
Excess Heat:	Was there any claim of excess heat within the paper?

When these were used, the following correlations between criteria and excess heat were found:

Criterion 1: 0.3
Criterion 2: -0.5 (negative correlation indicates lower current densities are beneficial)
Criterion 3: 0.2
Criterion 4: 0.7

Correlation of average of criteria for individual papers: 0.6

Note that significant figures were decreased to reflect more uncertainty due to the reduced number of papers in the restricted study. It is interesting to note that our analysis shows that the loading ratios may not be as significant as many would expect and that the presence of dynamic conditions appears more significant than many would expect. It is important to repeat that "correlation is not causation" and that some researchers have used conditions and materials that result in excess heat at lower ratios and that some fail to see excess at higher ratios. However it remains important for researchers to consider materials, loading, running currents and dynamic conditions.

As we have stated previously, not all experiments that fulfill all enabling criteria will produce the FPE. However, the most likely outcome of an experiment that failed to meet one or more criteria was failure; the most likely outcome for an experiment meeting all criteria was success.

The 122 paper subset we used for this study clearly addressed the criteria used for statistical input; however, they are just a representative sample of the field of electrochemical heat production. It is important to note that our results were statistically significant across many different calorimeters, different cathode geometries, electrolyte concentrations, research groups and spanned 18 years. The criteria are difficult to achieve but once achieved there is a high correlation with the expected outcome of excess power production. There is a clear indication that there is a reproducible Fleischmann-Pons effect but in the minds of some there is still more doubt than certainty.

Quantifying Certainty for the Fleischmann-Pons Effect

As experimentalists, we believe what we can measure but how do we measure what we believe? How do we compute the certainty level of what we believe to be observational fact? This problem is not new.

History teaches that Laplace used probability theory in conjunction with five or six independent astronomical observations to show that Newton's laws govern celestial mechanics with a certainty of 99% [168]. Colleagues have recently suggested to us that perhaps a similar approach could be used to estimate the certainty associated with the Fleischmann-Pons Effect.

Modern seekers of truth use a computerized version of Laplace's approach. The method is based on Bayesian network analysis and is well outside of our realm of experience and the scope of this review. We will, however, quote some interesting results [169].

The Bayesian Network

Johnson and Melich developed a Bayesian network over the last 3 years that captures the basic relationship among the key logic elements of the Fleischmann-Pons experiments to be considered in the Bayesian network.

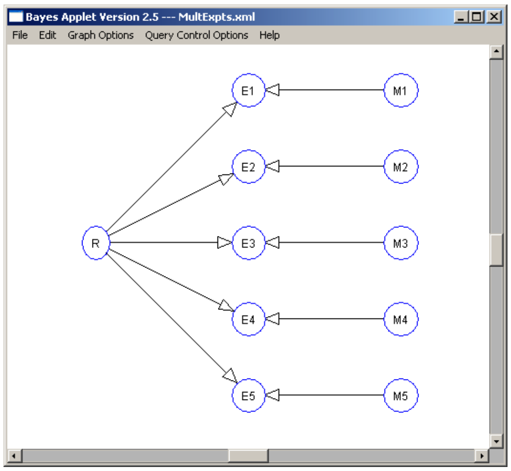

Figure 12. Bayesian logic network for quantifying belief in the Fleischmann-Pons Effect

Figure 12, above, shows the logical relationships between the propositions that the FPE is real, given a number of confirming experiments. The starting assumption is that the FPE is only 10% certain to be a real effect and the experimenters are reliable only 75% of the time. Bayesian software from the Laboratory of Computer Intelligence, University of British Columbia was used to carry out the calculation.

Output from the software package is tabulated in table 8 as 5 positive experiments were reported.

Table 9. Certainty of the FPE over time as replications are reported

Author	Year	Real	Not Real
F&P	1989	10%	90%
Kainthla	1989	31%	69%
Appleby	1990	64%	36%
Arata & Zhang	1990	87%	13%
Guruswamy	1990	96%	4%
Lautzenhiser(Amoco)	1990	99%	1%

With the Amoco experiment, the certainty that the FPE is a real effect has reached 99%; Since the Amoco experiment, more than one hundred positive electrochemical heat experiments have been reported. It is clear that more than one hundred positive experiments from several countries, using isoperibolic, mass flow and Seebeck calorimetry methods suggest a very high degree of certainty in the Fleischmann-Pons Effect [FPE].

A colleague, Dr Tom Grimshaw, suggests that the quality of evidence for the FPE surpassed the 90% certainty level 18 years ago and should now be considered “beyond a reasonable doubt” – a well known phrase from our criminal justice system. [171]

Another Form of Certainty

While we recognize the value of Bayesian analysis, as experimentalists we respond to experimental results more than probabilities. We would like to close with a result from our experimental history (Fig. 13). As experimentalists, we believe these three results suggest certainty in the fact that the Fleischmann-Pons Effect is real. These three independent experiments produced nearly identical results in three vastly different calorimeters, in three very different laboratories and spanned 17 years. Further, all three experiments reproduced perfectly the endothermic precursor to the Fleischmann-Pons heat effect.

Note the sudden dip in cell temperature or excess power just before each cell goes exothermic. We have observed this effect many times since the early nineties and consider it to be a reliable marker for the FPE.

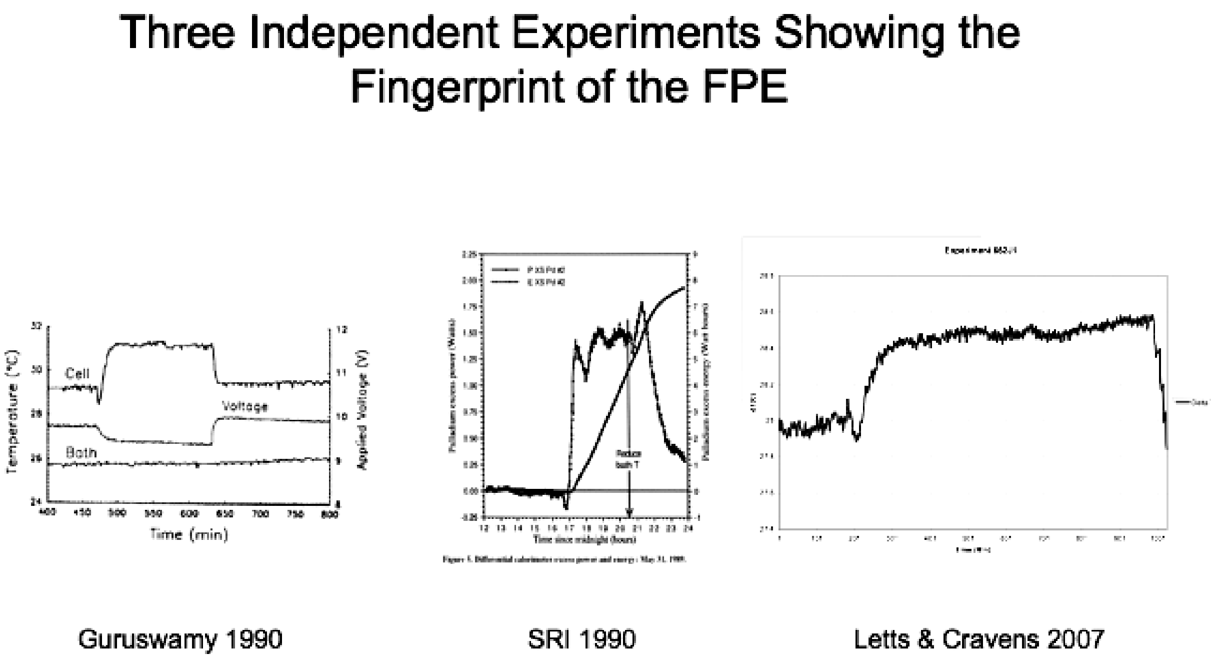

Figure 13. Three independent experiments show nearly identical results and span 17 years. The Guruswamy experiment shows cell temperature, the SRI experiment shows excess power and the Letts-Cravens experiment shows delta T. All three experiments show the endothermic precursor to the FPE.

Summary

Our review has attempted to show that more than one hundred electrochemical heat experiments have taught us that there are basically four criteria that must be fulfilled in order to see the Fleischmann-Pons effect with any degree of reliability. We also showed rather clearly that many of the early experiments failed because they did not fulfill one or more of the required criteria.

We have shown that there is a high degree of statistical correlation between fulfillment of the four criteria and success in producing the FPE. We briefly quoted a method to estimate how certain we are that the Fleischmann-Pons Effect is real. The Bayesian method tells us that by 1990 the Fleischmann-Pons effect had attained a certainty of 99%. This suggests to us that our field of CMNS deserves admission to the mainstream scientific community as a legitimate field of study – as an idea whose time has come.

Acknowledgments

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