Review of cold fusion

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Experimental results on Cold Fusion are reviewed. Most experiments find no effect and the upper limits are appreciably lower than the positive effects claimed in some experiments. It is concluded that: (a) there is no excess heat production and (b) the balance of evidence is strongly against fusion products. A curious Regionalization of Results is observed where only negative results are found in some parts of the world and only positive results in other parts. Further, the ratio of positive to negative results varies with time. Previous studies of palladium indicate that fusion should not occur inside the metal. Cold Fusion is best explained as an example of Pathological Science.

1. INTRODUCTION

We are all ecologists now. So when Profs. Fleischmann and Pons announced on 23 March 1989, that at Utah (USA), they had caused deuterium ions to fuse giving out heat using electrolysis in a simple cell at room temperature—Cold Fusion—we all wanted to believe it. At first we were a bit sceptical, but then came more information—they had measured excess heat and also observed neutrons, gammas, and tritium! And the next day there were reports of independent confirmation from Steve Jones[1] of nearby Brigham Young University. Other confirmations followed quickly. The early days of April were the high point when perhaps 500 million people had heard of Cold Fusion, Fleischmann and Pons, and had dreams of sea water yielding limitless amounts of heavy water that could provide energy without pollution!

But scientists quickly realized a terrible discrepancy—for each watt of power there should be a million million neutrons per second but only a few were observed—less than one per second for Jones. Thus, the dream of power from fusion divided into two experimental sets of results, firstly reports of excess heat and secondly reports of the observation of fusion products such as neutrons—but the two results were not compatible. The dream had gone.

Hopes were briefly revived again on 18 April when Prof. Scaramuzzi of Frascati (Italy) showed results of apparently high statistical significance and suggested fusion was a dynamical effect. Since then hundreds of experiments have been reported and most of them found no effect while some found positive results.

The world became divided between "Sceptics" and "Believers" with the latter concentrated in some parts of the world such as Utah and Texas. After a while one felt that Cold Fusion could not be understood by normal science alone and pathological science was invoked. This review presents the status of experimental results and attempts to understand the phenomenon of Cold Fusion.

It has been well known for a century that palladium and certain other metals can absorb large quantities of hydrogen. The idea came independently to Fleischmann and Pons and to Jones that if deuterium could be forced into palladium, two deuterium nuclei would come so close together as to fuse giving out more power than was being put in. To do this they used a simple electrolytic cell with heavy water as the electrolyte and with palladium or titanium as the cathode at which the deuterium would be released.

The d-d fusion processes are well-studied and are

$$\mathrm{d} + \mathrm{d} \rightarrow 3\ \mathrm{He}(0.8\ \mathrm{MeV}) + n(2.45\ \mathrm{MeV}), \quad (1)$$

$$\mathrm{d} + \mathrm{d} \rightarrow t(1.0\ \mathrm{MeV}) + \mathrm{p}(3.0\ \mathrm{MeV}), \quad (2)$$

$$\mathrm{d} + \mathrm{d} \rightarrow 4\ \mathrm{He} + \mathrm{gamma}(23.8\ \mathrm{MeV}). \quad (3)$$

This paper is an update of an article "The rise and decline of Cold Fusion" which appeared in the February 1990 edition of Physics World.

The other and preceding speaker at the 24 July Plenary Session was Dr. John O'M. Bockris of Texas A&M University.

2. MILESTONES

—13 March	Fleischmann informs David Williams at Harwell who starts experiments.
—23 March	Fleischmann and Pons, hold press conference, claim heat, neutrons, gammas and tritium.
—24 March	News that Jones of BYU claimed observation of neutrons.
—31 March	Fleischmann lecture at CERN—very successful but admits they had not tested with normal water.
—7 April	Meeting of American Electrochemical Society, Texas—great triumph.
—9–12 April	First copies of Fleischmann and Pons paper[2] received—found to be unsatisfactory. Growing doubts, especially because of discrepancy between amount of excess heat and very low numbers of neutrons claimed. David Williams says Harwell has not observed neutrons at the levels claimed. The number of characteristics of Pathological Science keeps rising.
—15 April	Most people believe in Cold Fusion except those receiving electronic mail news who know of null experiments and of major discrepancies.

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—18 April Scaramuzzi (Frascati)[3] apparently finds strong evidence for a dynamic origin for Cold Fusion using titanium, D_2 gas pressure and temperature variations.

—24 April Report that Fleischmann and Pons claim helium has been detected. Doubts about Scaramuzzi results on E-mail Network.[4]

—2–3 May American Physical Society meeting. Strong negative results from Nathan Lewis (CalTech)[5] and Moshe Gai (Yale-BNL).[6] Regionalization of Results reported—negative results in Northern Europe and in Region 1 of the USA (major labs plus North-East). Positive results from Southern and Eastern Europe, Region 2 of the USA, and the rest of the world. High score[7] on Pathological Science characteristics—7 out of 12.

—8 May American Electrochemical Society meeting—media triumph for Cold Fusion—but sceptics are excluded except token ones after protests.

—23–25 May Santa Fe meeting on Cold Fusion organized by Los Alamos for DOE. Most Americans (though not Fleischmann nor Pons) plus some others attended. Attention given to neutron bursts reported by Menlove of Los Alamos and Jones.[8] Gai and Jones agree to do joint experiment at Yale. Although there were more negative results than positive, the organizers tried to be "fair" and have equal numbers of positive and negative results presented so that for most watching on satellite TV the conclusions were unclear.

—15 June Harwell press conference[9]—major series of experiments costing \$0.5 million and using \$6 million worth of equipment, found no effect and hence were stopped. And this despite initial help from Martin Fleischmann. However, other positive and negative results continue to be reported. Utah particularly encouraged by reports of large amounts of tritium found at Texas A&M.

—12 July DOE panel interim report[10] concludes: "...the experiments reported to date do not present convincing evidence that useful sources of energy will result from the phenomenon attributed to cold fusion...." "...No special programmes to establish cold fusion research centres...are justified...."

—August National Cold Fusion Research Institute established in Utah with money from the State of Utah. It is hoped to get funding from the EPRI (Electrical Power Research Institute) which has been subsidizing other groups.

—August Japanese Fusion Research Institute gives \$0.1 million for Cold Fusion studies.

—15–16 Sept. Conference in Varenna. Most Italian groups either cannot repeat positive results or find alternative explanations of effects.

—September Reports of experiment[11] in Pons' lab with counters under a table which had Pons' cells on top. They did not find neutrons or gammas. Lecture in Utah[1)] summarizing for the first time both positive and negative results and concluding that this is pathological science. Director of National Cold Fusion Research Institute, Hugo Rossi says they have found nothing so far and if still unsuccessful by February will consider stopping. Interviews of people or administrators working on Cold Fusion not allowed—cencorship?

—28 Oct. Gai and Jones report no neutrons nor neutron bursts.

—October NSF and EPRI sponsor conference in Washington—restricted attendance with token Sceptics—media success for Cold Fusion.

—12 Nov. DOE Panel final report confirms earlier opinion.

—November Rossi resigns as Director of National Cold Fusion Research Institute.

—December Japanese press (and Wall Street Journal) gives prominence to reports of large number of neutrons from two Japanese groups (later examination causes these results to be doubted—see below). Reports of some 200 scientists working on Cold Fusion. Book of papers[12] from the Bhabha Atomic Research Centre, Bombay, describing some six experiments where neutrons or tritium were observed. Over 50 scientists and engineers, besides a large number of technicians from more than ten divisions, worked on these experiments.

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—January Pons starts series of 32 experiments to be followed by a second series of 32 experiments at the National Cold Fusion Research Institute.

—29–31 March First Annual Conference on Cold Fusion, Salt Lake City (USA). Most of 200 participants and all talks are positive, but world media and even local media is critical.

—April Lawyer of Pons and Fleischmann threatens possible legal action against University colleagues.

—May Discovery of misuse of funds, University of Utah president asked to resign.

—June Report in Science magazine of possible tritium contamination in experiments at Texas A&M.

3. COMPILATION OF EXPERIMENTAL RESULTS

It is not easy to compile results since many are released to the press, some are conference reports, many are private

reports and only some of all these are finally published much later in journals where they are first refereed. Hence here two compilations will be used: firstly, the experimental situation up to December based on experiments that are at least moderately well described (most are unpublished and are received by electronic mail network or privately, so that the collection cannot be complete but is large and any bias small); secondly, published papers only up to June 1990. There are relatively few papers in the second compilation that were not in the first, but many reports in the first have not been published.

3.1. First compilation—including non-refereed work

3.1.1. Neutrons

(a) Steady production

Ten positive results of which two have been withdrawn (Fleischmann and Pons and Georgia Tech). Of the six of these for which the actual measurement rate (before correction) and the background rate are known, all had a neutron level 3 to 5 times the background. Thus, although the claimed rate varied between 0.04 and 40 000 neutrons/s, no one had observed a rate that was many times background and all were far from the rate of 10^{12} n/s, which one watt of power should give. Nineteen experiments have reported no significant production of neutrons. If we take the level of Jones *et al.*[1] as unity, then in general terms, eight of the experiments report upper limits that are about a factor of ten lower and four give upper limits that are about a factor of a hundred lower than Jones *et al.*

(b) Dynamic effects—temperature and pressure changes, Frascati-type

Prof. Scaramuzzi[3] showed provisional results suggesting that by varying the pressure and temperature, the resulting non-equilibrium conditions could produce neutrons. He has had difficulty in reproducing these results since April. Three other groups were able to observe this effect initially but then were not able to reproduce it and indeed found reasons to explain that their positive observations were mistaken (acoustical effects, humidity, etc.). Four other groups have reported finding no effect and two have given upper limits that are a factor of a thousand less than that of Frascati.

(c) Bursts of neutrons

At Los Alamos, Howard Menlove, Steve Jones *et al.*[8] found bursts of neutrons at a very low level. Four other groups have found no bursts. Steve accepted Moshe Gai's invitation to do a joint experiment at Moshe's lab at Yale. They reported to the Dept. of Energy Panel[13] that they had found no bursts that could not be accounted for by cosmic rays.

In the preceding talk at this Plenary Session,[2)] Dr. Bockris stated that there was an important new result reported in the previous day's Wall Street Journal that was convincing proof of Cold Fusion. This is not a new result—it was known in December, submitted in January and published in April—Wada *et al.*[14] of Nagoya wrote that after a powerful high-voltage discharge through D_2 gas, from lightly loaded Pd cathodes ($D/Pd < 0.3$), three decreasing bursts of neutrons were detected. They were not able to repeat these results later. They claimed a peak rate 10 000 times background but only used one BF3 counter and these are notoriously unreliable, could not check if the counts were caused by neutrons (since the cathode was damaged) and did not try a control with normal hydrogen gas. The most likely explanation is that the physical shock of the discharge on the BF3 counter created apparent bursts of neutrons.

3.1.2. Gammas

The only positive result was that by Fleischmann and Pons and that has been withdrawn. Nine groups have reported finding no gammas, with levels as low as one gamma per second.

3.1.3. X-rays

When palladium is excited it emits 21 keV x-rays. The creation by fusion of protons, tritons,[3] He or gammas in the palladium should cause the palladium to be excited. Four labs have reported that no 21 keV x-rays have been observed giving strong evidence for the absence of fusion products and hence of fusion.

3.1.4. Tritium

The situation is confused. The original claims of Fleischmann and Pons have been withdrawn. Texas A&M[15] report copious production with published rates corresponding to 10^{-3} to 10^{-8} W. In Los Alamos,[16] some cells are said to give tritium but most do not. Two groups have unpublished reports of finding tritium. Workers at BARC[12] report finding tritium in large quantities. Five groups find no tritium production and give low upper limits. If the Texas A&M findings were correct, enormous rates of neutrons should have been produced (since the rates of reactions (1) and (2) are known to be equal) and these are not observed. It is concluded by many believers that the tritium to neutron ratio must be 100 million to one—however this is in disagreement with the many experiments of fusion which all give the ratio of one as expected from charge symmetry. It should be further noticed that cold fusion catalyzed by muons (which is at almost zero energy) also gives a ratio of unity.

3.1.5. Charged particles

In a recent headline-making report in Japanese newspapers, Taniguchi *et al.*,[17] of Osaka report measurement of charged particles using a silicon surface barrier detector placed next to one wall of the detector which is actually a 10 micron thick palladium and steel cathode. The counting rates are very low and no attempt was made to exclude cosmic rays which must have given occasional higher counts (as was found for instance by Gai and Jones).

3.1.6. Calorimetry

Although one might think calorimetry to be easy, it is not, unless careful experiments are done.

The original Fleischmann and Pons electrolytic cells had a simple design and are "open" which means the D_2 and O_2 gases produced are allowed to escape. Many later workers used similar cells. The estimates of excess heat depend on the calibration where the cell is heated and its rate of

cooling observed. It has been shown that the results depend critically on the calibration and there are important assumptions frequently employed. A safer technique is to use a constant temperature bath, where the cells and their surroundings are heated to a temperature slightly higher than ambiant—any excess heat is measured by the reduction of heating required to restore the constant temperature. The best design is a "closed" cell where the D_2 and O_2 gases are recombined with a catalyst (usually Pd) inside the cell and the whole kept at a constant temperature.

Of the eight labs that reported excess heat, all were "open" and not kept at constant temperature. While most of the reports were of 8% to 50% excess heat (or more accurately power), Fleischmann and Pons have claimed 10–50 W.

Of the 14 labs reporting no excess heat, seven were of this "open" type and gave upper limits of 0.2% to 2% excess heat of < 0.3 W.

Of the five labs using constant temperature cells, all found no excess heat giving upper limits between 0.3% and 9% or 0.1 W.

Two labs (British Columbia[18] and Karlsruhe[19] used "closed" cells. They gave upper limits of 0.3% of the 4–18 W range and 1–3% of the 10–30 W range, respectively.

The balance of the evidence is that excess heat cannot be produced in a useful manner. The positive results are generally said to give excess heat erratically and in bursts which are claimed to last for many hours. It is hard to prove or to disprove such claims and many neutral people feel that some interesting physics might come out of further careful peer-reviewed studies. On the other hand, when Dr. Salamon and his colleagues[11] had his neutron and gamma detectors installed under the table in Dr. Pons' lab and Dr. Pons' group had four cells running on that table for a total period of five weeks in May and June, it is surprising that they were not able to produce any excess heat for their colleagues and indeed no neutrons and gammas were observed. Similarly when the DOE panel visited Utah, Texas A&M, etc. They were never able to see a cell that was working although their visit was notified well in advance.

3.1.7. Muon-induced fusion

Since it is known that muons can replace electrons in a D_2 molecule pulling the nuclei together and causing fusion (Steve Jones is an expert on this), it was hoped that muons would do the same in palladium. Muon beams have been fired into palladium at MIT and KEK but no effect has been found. KEK deduce that cosmic-ray muons should produce less than $1\ 10^{-6}$ neutrons/s. Tests with cosmic rays confirm this.

3.1.8. High pressure

High D_2 gas pressures of 105 kbar and a megabar have been tried but no appreciable number of neutrons have been observed.

3.1.9. Is there a secret?

In Pathological Science, when an effect cannot be repeated, it is often said that there is a secret and the reason that someone does not find it is not because the effect does not exist, but because he does not have the special technique or secret. Hence in early April both Martin Fleischmann and Steve Jones were asked if there were a secret—both replied laughingly that there was no secret—a simple table-top experiment!

3.2. Compilation of results from published papers

Most experiments are not published. From contacts in many countries, one would estimate that about 80% of experiments are not published, and most of these are negative.

Of 97 experimental papers, 33 are positive, 63 are negative and one is undecided.

Of theoretical papers, 53 are positive, 24 are negative and 14 make no decision. Most of the "positive" papers are of the kind where one assumes the positive experimental result is true and then derives conclusions. Only a very few start from a basic standpoint and derive that cold fusion should exist—have shown these papers to theoretical colleagues and found they do not support them. The nature of the experimental papers are:

Character of experimental works

	Positive	Negative
Excess heat	6	21
Neutrons	27	47
Tritium	5	8
Gammas	6	12
Charged particles	1	3
Helium	2 (both 3 He)	5
Other (x-rays...)	1	5
Fracto-fusion neutrons	2 positive and 3 negative	
Scaramuzzi-type neutrons	2 positive and 11 negative	

3.3. Experimental conclusion

(a) The balance of experimental evidence is strongly against excess heat.

(b) The evidence against the observations of fusion products is very strong except possibly the tritium observations; however this would require a tritium to neutron ratio of 100 million which is in contradiction with a wealth of good experiments which shows the ratio is unity.

4. THREE EXPERIMENTS CRITICAL FOR BELIEVERS

For scientists who are unbiassed, there is more than enough experimental evidence to indicate that the balance of evidence is strongly against Cold Fusion, but as we have just heard, believers only believe positive results and discount negative results. But there are three critical experiments which should worry believers as they were very carefully carried out and were performed by people having close relations with Fleischmann, Pons or their co-workers.

4.1. David Williams *et al.* at Harwell

This is probably the biggest and most complete experiment performed in the world. It was carried out by scientists of different disciplines, electrochemists, nuclear chemists and physicists. David was and is a good friend of Fleischmann and Pons. He was the first outsider to be told—on 13 March. They have what I consider to be the world's best calorimeter and experts to whom I have described it, do not disagree with this potentially controversial statement. They

found no excess heat, no neutrons, no helium, and no gammas.

4.2. General Electric Company

They had a special arrangement with Pons and Fleischmann and had help from them in trying to repeat their experiments. This work was secret and the GE people have never told me or anyone else, their results (though if they had been able to find excess heat or other effects claimed by Fleischmann and Pons, it would have been surprising if the world had not been informed!). Just before this WHEC meeting, I was invited to give a lecture to General Electric company on Pathological Science (Irving Langmuir's lecture was given there in 1953) and was told that they had carried out a very large series of experiments on Cold Fusion which were completely independent of the confidential arrangement with Fleischmann and Pons. They found no excess heat, no neutrons, no tritium, and no gammas.

4.3. Independent experiment in Pons' laboratory

At the request of the University of Utah and in agreement with Dr. Pons, a group of ten scientists led by Michael Salamon, set up counters below a table in Pons' lab on which four of his cells were operating. Despite efforts to make the cells work, in five weeks in May and June 1989, no evidence for any neutrons or gammas was found giving upper limits of one million millionth of a watt. And this even though at one time a cell was observed to boil, but Dr. Pons said it should not be considered. The experiment was off for 50 h with a power failure. Recently, Dr. Pons announced that for 2 h during just these 50 h, there was an "excess thermal release". At first Salamon *et al.* did not think they could respond, but it was pointed out that they had a sodium iodide counter in which would occur the reaction

$$23\ \mathrm{Na} + n \rightarrow 24\ \mathrm{Na}.$$

The 24 Na isotope decays emitting an electron with a half-life of 15 h which would be good for the detection of fusion products from this "excess thermal release". They reanalyzed their data and found no effect giving upper limits of less than one-hundredth of a watt for tritium production and less than one millionth of a watt for neutron production. This confirms again that whatever is causing "excess thermal relaeases", is not fusion. It was after this that most of the authors were threatened with lawsuits by the North Carolina lawyer of Dr. Pons.

In conclusion, they found[11] no evidence of fusion products from *dd* or *dp* fusion giving neutrons or tritium.

5. PREVIOUS KNOWLEDGE OF DEUTERIUM IN PALLADIUM

It is important to ask if it is reasonable to expect deuterium to undergo fusion when forced into palladium? A major criticism of the original proposers who expected deuterium fusion in metals such as palladium, is that the literature shows that the deuterium ions are actually much further apart in the palladium than they are in simple gaseous deuterium so that no useful fusion is to be expected. In gaseous or liquid deuterium the two deuterium nuclei have a separation of 0.74 Å. The palladium nuclei in the crystal are 3.89 Å apart but as the deuterium is loaded in they are moved apart to 4.03 Å. When the deuterium is first loaded, up to D/Pd = 0.8, the deuterium nuclei go into the octahedral spaces and are 2.85 Å apart. If it is possible to increase the loading (e.g. by ion implantation), then the O–D separation is 1.74 Å. To increase the probability of fusion it is necessary to bring the deuterium ions much closer together, e.g. when a muon replaces an electron, the nuclei are pulled together and the separation is only 0.0035 Å and the fusion rate is reasonable. Thus the expectation of fusion in a continuous fashion is unreasonable. For it to occur in a dynamic fashion is also unlikely as there is lots of space for the deuterium ion to wander between the ions in the lattice. Furthermore, there is a theory of hydrogen ions in palladium which is very well tested (by neutron and muon scattering, etc.) and which describes the distribution of the electrons very completely. Similarly one does not expect muons to cause measurable fusion in loaded palladium.

6. PATHOLOGICAL SCIENCE

The overwhelming evidence, both experimentally and theoretically, is that Cold Fusion in metals does not exist. But there are positive results and there are scientists who believe very strongly in Cold Fusion.

How to understand the contradictory results? In 1953 Irving Langmuir gave a delightful lecture on Pathological Science (reprinted in the Oct. 1989 issue of Physics Today) where he discussed some cases such as N-rays, where a number of good scientists reported wrong results. He gave six characteristics of such cases. One, which I have slightly modified, is to say that there are three phases: in Phase One the original report is quickly confirmed; in Phase Two there are about equal numbers of positive and negative results; and in Phase Three there is an avalanche of negative results. In preparing a review of Cold Fusion for the May 1989 APS meeting, I was surprised to find that in Northern Europe and the USA area 1 (the major labs and the North-West) the results were almost all negative whereas in Eastern and Southern Europe, Asia, Latin America and USA area 2 (the rest of the USA) the results were almost entirely positive. The numbers were statistically significant being one positive and 18 negative in the first regions and 25 positive and 2 negative in the second case. Thus the first area was already in Phase Three while the other was in Phase One. During the month of May this Regionalization of Results continued with the first area giving 2 positive and 16 negative while the remaining regions of the world switched to 6 positive and 11 negative, i.e., it entered Phase Two. This regionalization has continued with most of the world finding negative results (in Phase Three) and only Utah, Texas, India, and now Japan being in Phase Two, where both positive and negative results are reported. In 1976 I increased the number of characteristis of Pathological Science to 12 and in 1989 to 15, this then allowed a significant separation between false results and true results (which may have scores of 0, 1, 2, or 3 characteristics. Cold Fusion has close to a maximum score and is significantly far from the score for true results.

The final conclusion may be that a desire to achieve the result expected in one's local community, does influence a certain number of scientists for a long or a short time. Most face up to the totality of evidence fairly quickly, but a few never do. Thus, after Blondlot's *N*-rays were exposed as illu-

sionary, he none-the-less published a book on N-rays a year later, omitting the negative evidence.

7. CONCLUSIONS

Everyone makes mistakes—everyone. It is how you handle your mistakes that makes the difference; it is essential to be self-critical.

Pathological Science will continue, it will happen again and again as it has happened in the past, that a group of believers will continue despite evidence to the contrary.

It is a pleasure to acknowledge that the compilation of published results was largely based on the bibliographic work of Dieter Britz of Aarhus which was distributed by E-mail, and to thank him.

Notes appended by the translator of this article into Russian for publication in Usp. Fiz. Nauk.

(Note from Editorial Board of Usp. Fiz. Nauk). In the journal Uspekhi Fizicheskikh Nauk, there have already been published two articles [cf. Usp. Fiz. Nauk **160**(11), 3 (November 1990) and **161**(4), 152 (April 1991)] [translated as Sov. Phys. Usp. **33**(11), 881 (November 1990) and **34**(4), 340 (April 1991)] devoted to the dramatic history and state of affairs in the problem of low-temperature nuclear fusion. Those articles present considerations in support of the reality of that phenomenon. At the same time it was emphasized that recently an appreciable departure from the initial interpretation of that phenomenon as being the result of "cold" nuclear fusion has occurred. In the article being published above, a chronological sequence of events associated with these investigations is described, and arguments are presented against interpreting this phenomenon as "cold nuclear fusion."

[1)] This was a lecture by D. R. O. Morrison.
[2)] This refers to the conference in Honolulu at which this paper by D. R. O. Morrison was presented.

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