

Review of the "Cold Fusion" Effect

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Abstract — More than 190 studies reporting evidence for the "cold fusion" effect are evaluated. New work has answered criticisms by eliminating many of the suggested errors. Evidence for large and reproducible energy generation as well as various nuclear reactions, in addition to fusion, from a variety of environments and methods is accumulating. The field can no longer be dismissed by invoking obvious error or prosaic explanations.

I. Introduction

More than seven years ago, Profs. Stanley Pons and Martin Fleischmann (Fleischmann *et al.*, 1989) (then at University of Utah) claimed production of excess energy by electrolyzing palladium in $D_2O + LiOD$ electrolyte. In addition, they claimed the heat resulted from $d + d$ fusion. Both claims met considerable skepticism that continues to this day (Huizenga, 1993; Taubes, 1993; Hoffman, 1995). The first claim has been attributed to poor calorimetry or the presence of undetected chemical reactions. The second claim has been deemed impossible by conventional nuclear theory. Furthermore, if these reactions should occur, certain types and amounts of radiation must be produced. Because the expected radiation is not found, many scientists do not believe the claimed phenomena are real. In spite of these reasons to reject the claims, active programs are underway in Japan (Ikegami, 1991, Asami *et al.*, 1995), India (Iyengar and Srinivasan, 1991), Italy (Scaramuzzi, 1993); Russia (Tsarev, 1993); China (Zhong, 1994) and in the U. S. However, efforts are still handicapped in some countries by funding and publication restraints. In addition, a great deal of effort has been devoted to proof-of-principle studies rather than to understanding and amplifying the effect. In spite of these handicaps, much has changed since the early work was reported and these new observations need to be considered by the general scientific community.

Most physicists say there is no convincing evidence. Consequently, the entire phenomena is ignored or is dismissed by using very improbable prosaic explanations. On the other hand, a supporter of the field believes some of the reported observations might be false but, because there is little experience and no accepted explanation, does not want to reject a potential truth just because it conflicts with conventional thinking or contains a few errors. Therefore, a broad benefit-of-doubt is used during this early stage. The latter approach will be favored in this discussion. I am fully aware that claims in conflict with con-

ventional theory will be rejected out of hand by some people, sometimes along with the messenger. Nevertheless, the full range of observation has been described here for the benefit of more open minded readers. Because these observations run the full range from being basically correct to being only suggestive, their inclusion should not be considered an endorsement.

This paper intends to help resolve the present stalemate by showing how the various criticisms have been answered by recent work. In addition, I will also attempt to reveal the consistent, albeit amazing, patterns created by the emerging data, and to show a devoted student where more information can be found. Unfortunately much of this information is still available only in conference proceedings' because many journals will not publish papers advocating "cold fusion". Nevertheless, a group of papers from the 4th Cold Fusion Conference (ICCF-4) has been peer reviewed and recently published in *Trans. Fusion Technology*, Vol 26, 1994.

The reader should realize that much more background work is available than can be reported in papers or in this review. In addition, much information is proprietary and not available to the public because patent protection is not being granted in the U. S. Even if these problems did not exist, it would not be surprising in a field so new and unusual to find much work inadequately described even in the available literature. The issue at stake is not whether the results are completely accurate, well presented, or even explainable. Rather the issue is whether sufficient evidence is available to support a belief that a real and novel phenomenon has been discovered deserving objective analysis and general interest. An explanation and detailed understanding will follow later after more information becomes available. A major problem at this time is that in the absence of this belief, such information is being obtained very slowly and is not available to the average scientific reader.

Indicators of the effect are listed in Table 1. Although these indicators imply a wide range of nuclear reaction rates and a variety of nuclear products,

'Copies of the various conference proceedings can be obtained as follows:

- Proc. of the Second Annual Conference on Cold Fusion (ICCF-2), Como, Italy, June 29-July 4, 1991, "The Science of Cold Fusion", Vol. 33 (T. Bressani, E. Del Giudice and G. Preparata, eds), Published by Societa Italiana di Fisica, Bologna, Italy.
- Proc. Third International Conference on Cold Fusion (ICCF-3), October 21-25, 1992, Nagoya Japan, "Frontiers of Cold Fusion", (H. Ikegami, ed.), published by Universal Academy Press, Inc., Tokyo, Japan.
- Proc. Fourth International Conference on Cold Fusion (ICCF-4), Lahaina, Maui, Dec. 6-9, 1993, EPRI TR-104188-vol (1994), published by Electric Power Research Institute 3412 Hillview Ave., Palo Alto, CA 94304.
- Proc. Cold Fusion Symp., 8th World Hydrogen Energy Conf., Honolulu, HI, July 22-27, 1990, published by Hawaii Natural Energy Institute, 2540 Dole St., Holmes Hall 246, Honolulu, HI 96822.
- Proc. Anomalous Nuclear Effects in Deuterium/Solid Systems, Provo, UT, Oct. 22-23, 1990, published by American Institute of Physics, #228.
- International Symposium, "Cold Fusion and Advanced Energy Sources", Belarusian State University, Minsk, Belarus, May 24-26, 1994. Source book can be obtained from Fusion Facts, P. O. Box 58639, Salt Lake City, UT 84158.
- Proc. Fifth International Conference on Cold Fusion (ICCF-5), Monte Carlo, Monaco, April 9-13, 1995 can be obtained from IMRA Europe, SA, Centre Scientifique, BP-213, 06904 Sophia Antipolis Cedex, France.

all are attributed to "cold fusion". Clearly, many of the products result from nuclear reactions other than fusion. In view of these new observations, the effect might better be called "Chemically Assisted Nuclear Reactions" (CANR) (Storms, 1994). The indicators will be discussed in the order listed.

TABLE 1
Indicators of the "Cold Fusion" Effect
(Implied nuclear reaction rates listed)

II.	Anomalous Energy Production (10^{10} – 10^{15} events/sec)
III	Nuclear Ash
III.1	Neutron emission (10 – 100 n/sec excluding bursts)
III.2	Tritium production (10^7 – 10^8 atoms/sec)
III.3	Helium production (0.5 to 1.0 times energy production rate)
III.4	Charged particle emission
III.5	Gamma emission from radioactive isotopes
III.6	Non-radioactive isotope production

II. Anomalous Energy Production

Heat production in excess of applied energy is the most useful but the most difficult claim to accept because of the implied high nuclear reaction rate. If this high rate is to be believed, conventional physics requires various nuclear emissions or products to be detected, the so-called nuclear "ash". Evidence for the "ash" will be discussed in Section III. First, we will examine evidence supporting heat production by various methods.

Anomalous energy has been reported using at least 10 different methods as listed in Table 2. Many of these methods produce nuclear reactions other than fusion. Some of these methods are reproducible and generate significant energy while several have experienced very few attempts at replication. These methods can be said to produce a special condition of matter (SCM) containing a nuclear-active state (NAS) in which the anomalous reactions occur. The challenge for a theoretician is to find what the regions created by the different methods have in common. Each claim will be discussed in the order listed.

TABLE 2
Methods Claimed to Produce Excess Energy
(Reported useful temperatures listed)

II.1	Electrolysis of D_2O -based electrolyte using a Pd cathode (20 – 100 °C).
II.2	Electrolysis of H_2O -based electrolyte using a Ni cathode (20 – 100 °C).
II.3	Electrolysis of KCl-LiCl, D electrolyte using a Pd anode (450 °C).
II.4	Various solid compounds in D_2 (700 – 800 °C).
II.5	Gas discharge using Pd electrodes in hydrogen.
II.6	Gas discharge using Pd electrodes in deuterium (< 500 °C).
II.7	Gas reaction with Ni under special conditions (400 °C).
II.8	Enhanced reaction involving D_2O and various metals using an acoustic field.
II.9	Enhanced reaction in H_2O using microbubble formation (20 – 100 °C).
II.10	Reaction of finely divided palladium with pressurized deuterium gas.

In general, anomalous energy seems to be triggered by reacting a material with hydrogen or deuterium using one of the following techniques:

1. Reaction with pressurized gas using specially treated metal,
2. Reaction using electrolysis, both solid and liquid electrolytes,
3. Reaction using gas discharge that results in ion implantation, or
4. Reaction using bubbles generated by several methods within a liquid.

These methods impart energy to the reacting hydrogen isotope, roughly increasing in the order listed. This energy addition appears to be important, with more energy giving a more robust result. Insufficient information is yet available to know the full range of materials able to exhibit this effect or the full range of initiating methods. Positive results are claimed using various metals (especially palladium), several superconductors, and ceramic materials.

11.1. D_2O -Based Electrolyte

Energy production using D_2O -based electrolytes, the so-called Pons-Fleischmann Effect, is the method most studied. Over 125 attempts to measure excess energy have been reported, more than a third of which achieved positive results. Included in this list is a well done null result by Green and Quickenden (1995). This large failure rate has been used to suggest that the effect is not real because it can not be reproduced. Failure to produce a positive result neither proves nor disproves claims for excess energy. Simple logic argues that such failure may also demonstrate the difficulty inherent in initiating the effect. This problem is expected to be reduced by recently published procedures (Storms, 1996; McKubre *et al.*, 1995).

Thirty studies are listed in Table 3, many of which produced excess energy using several independent sources of palladium. Only work reporting a quantitative measurement of heat production is listed along with the stated or estimated uncertainty. The highest reported values for power and energy production are listed and are compared assuming the effect is related to cathode surface area. Reported total excess energy is determined partly by how long the cell was allowed to operate and partly by how long the effect lasted. Some effects last only hours while others go on for weeks before they are terminated. There is no reason to believe that the highest possible power and energy levels have yet been achieved.

The question remains, does this body of data represent reproducibility? An answer to this question rests on how well the various potential errors have been addressed. This subject will be discussed in later sections. The intention here is to show that many attempts have reported significant excess energy using a variety of calorimetric methods.

A calorimetric must demonstrate a null result when no energy production is expected and give an accurate value when energy is detected. Such tests are done using several techniques. Studies using light-water in place of heavy-water or platinum in place of palladium, demonstrate a null result and are indi-

cated by "B" in the table. Most studies also test the apparatus by comparing the measured power with the applied power during the long interval before excess heat is first seen. Thus, the calorimeter is calibrated using the same conditions that exist when excess energy is detected. This method allows relative calorimetry to be used without the need for high absolute accuracy.

The electrolytic cell can be studied in the open mode ("O") during which the gases are vented to the atmosphere, or in the closed mode ("C"), during which the gases are recombined by an internal catalyst. The latter method allows the cells to be sealed and pressurized so that material can neither enter nor leave the cell. Pressure changes can be monitored to show changes in the hydrogen content of the cathode. When open cells are used, they are frequently examined for evidence of unexpected recombination (reduced Faraday efficiency) by comparing the amount of water lost to the amount of current passed through the cell. Use of this technique is noted. Recombination is not observed in properly designed open cells, the experience of Jones (1995) notwithstanding. A few studies used both the electrolytic and internal heater calibration methods, designated "dual calibration". These techniques will be discussed in the following sections.

TABLE 3
Energy Production in Electrolytic Cells Using D₂O-based Electrolyte

Investigation	Calorimetric Factors	Excess Energy		Excess Power	
		MJ	MJ/cm ²	max.W	W/cm ²
Aoki <i>et al.</i> (1994) Japan	F, O, B, $\pm 0.5W$ No neutrons, tritium or gamma detected during heat. ⁴ He amount was much too small to account for heat.			25	1.7
Appleby <i>et al.</i> (1990) US	D, O, C, B, $<1mW$ No recombination detected. Heat production dropped when LiOD was replaced by NaOD. No change found when ⁷ Li was replaced by ⁶ Li.	0.01	0.07	0.049	0.31
Arata and Zhang (1994) Japan	F, C Used palladium-black in D ₂ gas generated by electrolysis. Active area unknown.	200		125	
Bertalot <i>et al.</i> (1995) Italy	F, O, $\leq 100mW$ No recombination detected.			11	17
Bertalot (1993) Italy	F, O, B, $\pm 25mW$ Pd sheet loaded from one side. High-Low loading method used.			≈ 3	≈ 3
Bertalot <i>et al.</i> (1991) Italy	D, O, $\pm 5mW$ No recombination detected. No excess tritium or neutrons detected.	0.057		0.08	
Bush (1991) US	I, C, B, $\pm 0.3W$	0.35	0.088	6.0	1.5
Celani <i>et al.</i> (1994) Italy	F, O, B, $\pm 1.5\%$ High-power pulsed current used. No recombination detected. Used dual calibration. Total energy measured from start.			5.0	0.4

TABLE 3 (continued)
Energy Production in Electrolytic Cells Using D₂O-based Electrolyte

Investigation	Calorimetric Factors	Excess Energy MJ	Excess Energy MJ/cm ²	Excess Power max.W	Excess Power W/cm ²
Fleischmann <i>et al.</i> (1990) Japan	I, O, B, $\pm 5\text{mW}$	22	14	2.8	3.6
	Total heat measured from start. No recombination detected.				
Gozzi <i>et al.</i> (1990, 1991) Italy	I, O, $\pm 0.5\%$	18.6	>1.7	12.8	>1.2
	Dual calibration used. Blank run using inert cathode				
Guruswamy <i>et al.</i> (1989) US	I, O, $\pm 0.5\text{W}$	2	0.16	8	0.6
Hasegawa <i>et al.</i> (1993) Japan	I, C, B, $\pm 10\text{mW}$			0.5	0.25
	Calorimeter sealed and pressurized. Published values are given as W/cm ³ . Values listed here are estimates because Pd size was not given				
Hugo (1994) US	F, C, B, +4%			23	>12
	Cylinder of Pd charged unequally from two sides.				
Hutchinson <i>et al.</i> (1990) US	I, O, $\pm 1\text{W}$	2	0.1	3	0.15
	No recombination detected. Total energy measured from start.				
Kainthla <i>et al.</i> (1989a) US	I, O, $\pm 50\text{mW}$			1.1	≈ 0.4
	No recombination detected.				
Klein <i>et al.</i> (1990) US	I, O, B	8.1	0.64		
	Insufficient detail given.				
Lewis and Skold (1990) Sweden	F, O, B, $\pm 0.2\text{W}$	0.1	0.1	1.0	1.0
	Studied Pd and Pt cathodes in H ₂ O as blank. Calculated heat using fluid-flow and temperature change methods. Power bursts up to 2W observed.				
McKubre <i>et al.</i> (1994a) US	F, C, B, $\pm 50\text{mW}$	1.0		3.0	
	Cells sealed and pressurized. Many samples and calorimeter designs studied. Cathode area unknown. Total energy measured from start.				
Miles <i>et al.</i> (1990a) US	I, O, B, $\pm 5\%$	0.11	0.04	0.14	0.05
	No recombination detected. Electrolytic calibration used.				
Mizuno <i>et al.</i> (1993) Japan	I, C				0.22
	Heat produced near 100 C using a sealed, pressurized cell. Electrolytic calibration used.				
Okamoto <i>et al.</i> (1994) Japan	F, O, B, $\pm 3.7\text{W}$			7	1.4
	Determined energy source is Pd cathode.				
Oriani <i>et al.</i> (1990) US	S, O, B, $\pm 0.2\text{W}$	0.06	0.04	3.6	2.6
Ota <i>et al.</i> (1994) Japan	F, C, B, $\pm <0.3\text{W}$	3.6	2.3	11.3	7.2
	Used 90Pd-10Ag alloy.				
Schreiger <i>et al.</i> (1990a) US	I, C, B, 20.5%	0.64	0.27	0.7	0.3
	Total heat measured from start.				

TABLE 3 (continued)
Energy Production in Electrolytic Cells Using D₂O-based Electrolyte

Investigation	Calorimetric Factors	Excess Energy		Excess Power	
		MJ	MJ/cm ²	max. W	W/cm ²
Scott <i>et al.</i> (1990b)	F, C, B ± 0.3 W			2.5	0.18
Storms (1993a) US	I, C, B ± 0.4 W Calorimeter sealed. Dual calibration used. Total heat measured from start. Determined that the energy source is the Pd cathode.	1.1	0.17	7.5	1.1
Takahashi <i>et al.</i> (1993) Japan	I, O, ± 1 W Electrolytic calibration used a "dead" cathode. Used High-Low charging method.	166	27	130	21
Yang <i>et al.</i> (1990) Taiwan	I, O Dual calibration used.			12.9	2.3
Yun <i>et al.</i> (1991) Korea	I, C, B, ± 50 mW Dual calibration used.			0.24	1.5
Zhang <i>et al.</i> (1990) China	I, O, B, < 1 mW Dual calibration used.			0.015	

Calorimeter Type: Closed = C; Open = O; Fluid Flow = F; Isoperibolic = I; Differential = D; Seebeck = S; Blank = B; Stated or estimated uncertainty shown.

A consistent pattern has emerged from many studies showing a clear relationship between the applied current density and the resulting power density. Some recent results are shown in Figure 1. Older data can be found in reference (Storms, 1991a). Although the data show a variety of slopes, an onset current density is evident. Most studies find this onset between 100 and 200 ma/cm² although occasionally the value can be much larger. Once the current is above this critical value, power production increases as the current is increased. This behavior can be used as a reliable indicator that the claimed excess energy is not being caused by error. Use of insufficient current density is one reason why some studies have failed to produce the Pons-Fleischmann Effect.

This relationship results because power production is proportional to the deuterium concentration at the surface which is increased by a larger current. Examples of the relationship between the average composition and excess power are shown in Figs. 2 and 3. Figure 2 shows the measurements of McKubre *et al.* (1992) who used the resistivity to determine the average composition of a single sample. Figure 3 shows the relationship for six samples studied by Hasegawa *et al.* (1994) using pressure change in a sealed system to determine the average composition. As yet, no plausible explanation based on error or chemical reaction has been able to account for this behavior.

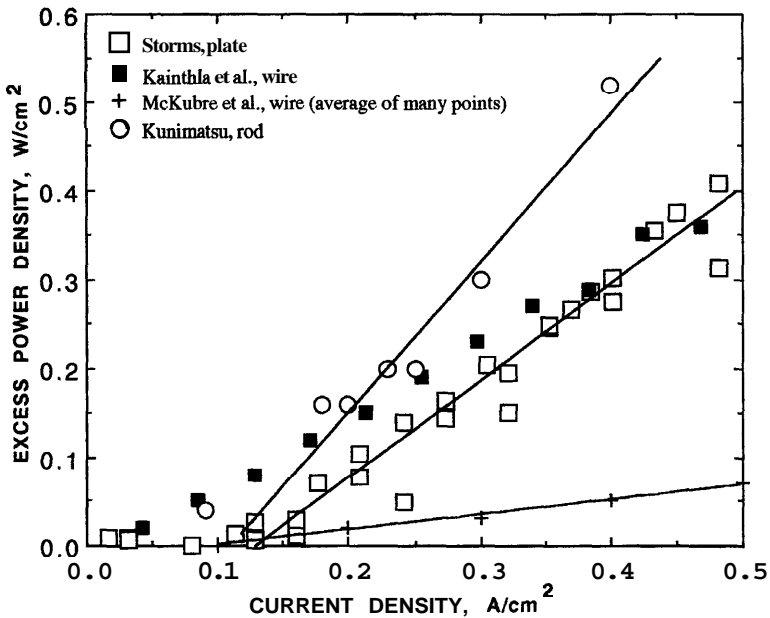


Fig. 1. Relationship between current density and power density. An onset value is evident. The slope of the line is affected by sample geometry and by temperature changes produced by the changing current.

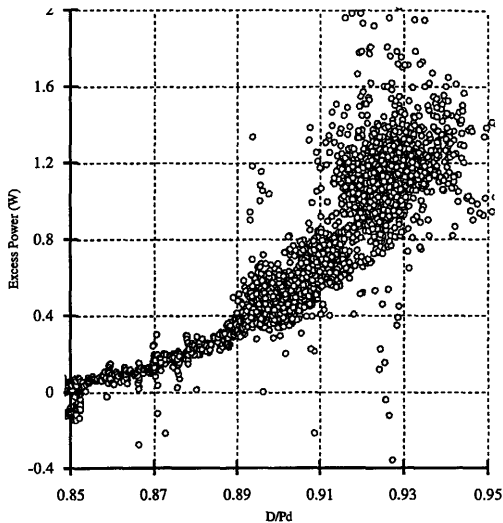


Fig. 2. Effect of loading on excess power. Data were obtained using palladium wire after it was electrolyzed for 300 hr and was exposed to various current densities. A flow-type, closed calorimeter was used.

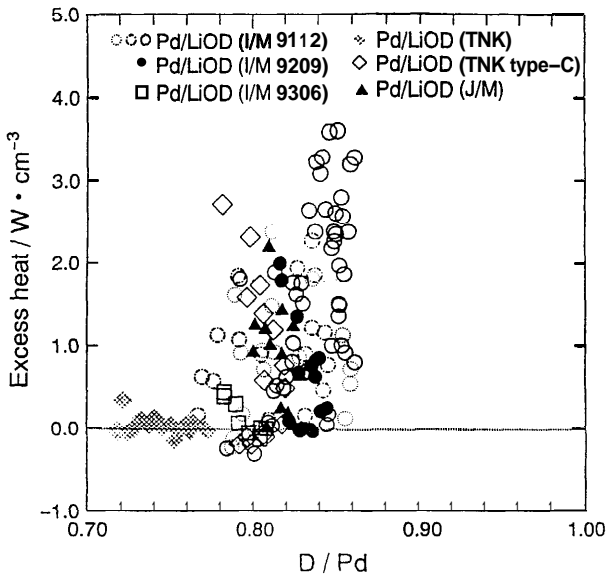


Fig. 3. Relationship between excess W/cm^3 and D/Pd ratio in a sealed system. Results from different samples of palladium are compared.

Calorimetry measurements can suffer from various errors as listed in Table 4. Because these perceived errors provide the major reasons for rejecting calorimetric data, they will be examined in detail in the following sections.

TABLE 4
Major Suggested Errors for Excess Energy

II.1.1.	Improper calibration
II.1.2.	Failure to properly account for the energy leaving open electrolytic cells as D_2 and O_2 gas
II.1.3.	Failure to account for energy produced by various chemical or mechanical reactions taking place in the cell
II.1.4.	Failure to measure heat balance during the long time before excess energy was seen, thereby allowing the possibility of overlooked energy storage processes that might suddenly release energy
II.1.5.	Failure to consider energy transfer processes caused by the applied current

II.1.1. Improper Calibration. This criticism has been directed mainly at the work of Pons and Fleischmann, the most detailed effort being in a paper by Wilson et al. (1992). This and other criticisms are answered in several subsequent publications and by several independent and very thorough analysis (Hansen, 1991; Swartz, 1994). A recent independent study of the calorimeter used by Pons and Fleischmann has revealed several problems that can be corrected by using a slightly different analytical equation. (Saito *et al.*, 1995) Al-

though heat measurements by Pons and Fleischmann (1993) can be analyzed in different ways to give slightly different results, their conclusion of excess energy production has been supported.

An early major issue was the effect of temperature gradients within a non-stirred calorimeter calibrated by an internal heater (Miskelly *et al.*, 1989). To answer this criticism, Fleischmann *et al.* (1990), Klein *et al.* (1990), Takahashi *et al.* (1993) and Guruswamy *et al.* (1989), among others, demonstrated that mixing produced by bubble generation is sufficient to eliminate serious gradients in their cells. In contrast, active stirring is used by some workers while others use calorimeter designs that are completely immune to the effect of temperature gradients. Furthermore, the use of electrolytic calibration, as described below, significantly reduces the error caused by the remaining gradients. Excess heat is still detected after all of these effects are taken into account. While a few studies may suffer from the effect of a temperature gradient, this potential error can not be used to dismiss all claims of excess heat.

Some studies combined two independent calibration techniques; electrolytic and internal heater. The electrolytic technique uses a "dead" cathode² and applies electrolytic power in the same manner as used for an active cathode. Consequently, many of the suggested errors or potential chemical reactions, real or imagined, cancel out. The internal heater method applies known energy using a resistor located within the electrolyte. Close agreement between calibration constants obtained using these two methods shows that major errors are not introduced by the electrolytic process. Furthermore, this comparison also "verifies actual performance using an accurately known enthalpy change", as suggested by Buehler *et al.* (1992). In this case the "known enthalpy change" is a known electrolytic reaction produced by known applied power.

It is ironic that careful analysis (Hansen and Melich, 1994; Noninski and Noninski, 1993; Miles *et al.*, 1994b) of a few high profile negative studies reveal errors that might have over-shadowed excess energy production had the effect been initiated. Clearly, if negative studies are used to judge the claims, they need to be examined with as much rigor as applied to positive results.

II 1.2. Uncertain Recombination. Open cells, such as those used by Pons and Fleischmann as well as by many other workers, allow the D₂ and O₂ gases to leave the cell, a process that removes energy. This energy loss can be calculated and corrections made if no recombination occurs. The amount of recombination within a cell can be determined by monitoring the volume of make-up water. At least seven (7) users of open cells noted in Table 3 employed this technique and found no detectable recombination. Indeed, several studies produced so much energy that excess heat production would still be indicated

²Calibrations are frequently done using the palladium cathode before it has achieved the conditions needed to make excess energy.

even if 100% recombination had occurred. On the other hand, Jones *et al.* (1995) found significant recombination in their study using light water and a nickel cathode. Surprisingly, they used this limited experience to reject all studies.

The recombination problem is completely eliminated when the cell contains a catalyst to recombine the gases back to water. Such thermodynamically closed cells can be sealed so that no gas enters or leaves the cell. Ten laboratories using this design give evidence for excess energy of various amounts well above the precision of the different calorimeter designs, as noted in Table 3.

While uncertain recombination can be used to dismiss a few efforts, at least 17 claims can not be rejected using this argument. Surely this experience is sufficient to eliminate recombination as a universal reason to reject all claims for excess energy.

Several of these studies produced energy from multiple pieces of palladium while using several calorimeter designs. This experience reduces the role of an error that might be unique to a particular experimental arrangement.

11.1.3. Chemical Reactions. Various chemical reactions take place within an electrolytic cell. If one or several of these reactions suddenly occurred and gave off heat, this source could be mistaken for excess energy. A number of such possibilities were examined early in the field's history and found to be insignificant (Kainthla *et al.*, 1989b).

Because only a few chemical compounds and metals are present in a cell, the number of possible chemical reactions is limited. As pointed out by Storms (1991a), any chemical reaction between a mixture of stable materials, as normally present, require energy. Such reactions, when initiated, will use energy supplied by the electric current, thereby causing an apparent energy loss. Heat gain will only be seen if the chemical products should return to their original state. Examples of such reactions are:

1. Peroxide formation
2. Deposition of Li and formation of Pd-Li alloy at the cathode
3. Dissolution of Si and B from the glass container and their deposition onto the cathode
4. Dissolution of Pt from the anode and its deposition onto the cathode
5. Formation and deposition of colloids
6. Formation of PdD by electrolysis

The first five of these reactions are known to occur, but at such low rates that trivial amounts of reaction product are produced, hence trivial amounts of energy. The last reaction is more complex. Formation of PdD by electrolysis requires energy. As the deuterium content is increased, a composition is reached above which energy is stored in the deuteride. The amount of energy depends on just how far above this critical composition the average composition has

gone. This energy would be returned to the calorimeter should deuterium be released. The process will be discussed in more detail in the next section.

A process whereby the latent heat of vaporization is released from heavy-water by "Jahn-Teller Symmetry Breaking" is proposed by Johnson (1994) to explain excess energy. Electrolysis is thought to break D-O bonds allowing D to diffuse into and through a proposed γ -PdD phase. Energy is extracted as D moves within the lattice and eventually reforms D₂. Energy from this process can only be released if a suitable change of state occurs between the initial and final form of deuterium. The explanation is not consistent with the observations for the following reasons:

1. Thermodynamically closed cells are found to produce excess energy. In this situation, all D-O bonds broken during electrolysis, except for the few required to saturate the palladium with deuterium, are reformed at the internal catalyst. Therefore, there is no net change in state. In addition, excess energy is not observed while palladium is being saturated with deuterium or for long periods after a limiting composition has been reached, as would be expected from the model.
2. Open cells normally are operated at cell currents between 1 A and 3 A. This current range decomposes 0.019–0.057 moles of D₂O per hour. Even if the claimed latent energy of 8 MJ/gal (0.038 MJ/mole D₂O) is correct, this current would result in only 722–2166 J/hr or 0.2–0.6 W. This power is far below many of the reported results.
3. Direct measurements using open cells and inactive palladium cathodes before excess energy production starts show that electrolysis of D₂O uses an amount of energy consistent with its known Gibbs energy of formation. Therefore, no novel process is operating.
4. Excess energy is not observed when the D₂O contains excessive H₂O. The argument that the effect is prevented by sluggish hydrogen diffusion is not consistent with other phenomena in which diffusion plays a role. For example, palladium can be charged electrolytically with either D or H at very nearly the same rates and, indeed, to a higher hydrogen content compared to deuterium.
5. A form of deuterium more stable than D₂, as required by the model, has not been observed.

II.1.4. Release of Stored Energy. Stored energy can take the form of accumulated chemical products within the cell and mechanical stress within the palladium. Sudden stress release is proposed to produce fractofusion, a process that will be discussed later.

During any energy storage process, energy will be removed from the applied electric power. In addition, chemical species will accumulate. If the storage process is sufficiently slow during the long charging required before excess energy is seen, the energy loss might be missed. Nevertheless, a significant accu-

mulation of chemical products should be visible in the cell. After all, measured excess energy sometimes represents 10–20 watts of power lasting many hours to many days. The total energy generated by typical cells can involve a few to more than hundred megajoules. This amount of chemical energy stored in the small amount of material used in the cells would demonstrate the most energetic of known chemical reactions. This suggestion, if believed, should at least get the attention of battery designers.³

Suggestions have been made that deuterium is suddenly released from the palladium, thereby producing excess energy. This can not be the explanation because the deuterium content of palladium has been monitored during several studies and found to be relatively stable during heat production, and because a sudden release of deuterium from palladium only produces a little heat for a very short time. (Yamaguchi, and Nishioka, 1993) In addition, typical cells do not contain sufficient excess oxygen to contribute significant energy should the conditions allow a recombination reaction to take place.

Stress can build up in palladium as it is converted to the hydride. Local release of this stress produces a variety of small cracks. (Kumar *et al.*, 1991; Lynch *et al.* 1973; Matsumoto 1991b; Storms and Talcott-Storms 1991) Clearly, this stress release involves only a small fraction of the bulk palladium. The uncracked metal still retains a significant amount of the stored energy. Therefore, even the most optimistic calculations fall short of generating the observed energy. However, these cracks have been suggested to create conditions that can cause a brief, hot fusion reaction, so-called fractofusion. (Abu-Taha, 1990; Amato, 1990; Bagnulo, 1991; Chechin *et al.*, 1990; Kiihne, 1994; Mayer *et al.*, 1990; Preparata, 1990; Takeda and Takizuka, 1989; Yasui, 1993; Zhang, 1992; Golubnichii *et al.*, 1989) Because this process involves ions accelerated by high voltages generated within the cracks, products similar to those observed from hot fusion should be detected. Indeed, conditions expected to produce cracking do seem to generate neutron bursts (Derjaguin *et al.*, 1989; Dickinson *et al.*, 1990; Klyuev *et al.*, 1986; Shirakawa *et al.*, 1993) as well as charged particles (Price, 1990). However, the number of neutrons generated is much too small to produce measurable energy and the expected 14 MeV neutrons are not observed. In spite of considerable thought that has gone into this process, there is no evidence for believing fractofusion produces more than a few neutrons and charged particles.

II.1.5. Failure to Consider Energy Transfer Processes Caused by the Applied Current. The Peltier Effect (Handel, 1994; Keesing *et al.*, 1991) is proposed to pump energy into the cell at junctions between dissimilar metals. This effect would only be a possible source of additional energy if the junction is within the active region of the calorimeter and if the junction is between metals having much different Peltier coefficients. Most papers do not describe this aspect

³It is worth noting that a common automobile battery contains 35 MJ of energy, occupies 10 liters of volume and weighs about 30 kg. A typical cold fusion cell occupies 0.2 liter and weighs about 0.5 kg.

of calorimeter construction in sufficient detail to completely rule out this energy source in all cases. Nevertheless, a few designs have eliminated the Peltier Effect as a significant energy source or have canceled out the effect by using electrolytic calibration. A comparison between calibrations based on electrolysis and joule heating demonstrates that the Peltier Effect is not a significant source of energy in these cases (Storms, 1993a). Even if this energy source should exist, it can only contribute a fraction of a watt to the observed energy no matter how poorly the calorimeter is designed or how extreme the assumptions about Peltier coefficient values might be. Consequently, it can not explain the more energetic examples.

Discussion. Because a wide range of skill and accuracy is represented, most studies by themselves are not convincing to determined skeptics. No one should be surprised that many attempts to measure excess energy, including those giving negative results, would fall short of accepted standards. However, viewed as a group, combined with a few very complete measurements showing the same patterns, the collection creates an evidence set that is very hard to dismiss.

The listed studies achieved excess energy production using several calorimeter types at levels well in excess of stated calorimeter precision and absolute error. Some investigations have produced excess energy from many pieces of palladium. In addition to this data set, a significant number of studies have detected energy production without making quantitative measurements.

A wide variation in reported W/cm^2 values (or W/cm^3 for that matter) is evident in the data. Some of this variation is caused by differences in current density and some is caused by differences in cathode temperature. Both variables are known to influence power production. Other factors such as low or nonuniform deuterium content, presence of localized impurities and dislocations, and crystal size also play major roles. Electromagnetic energy application by bubble formation or by external generation may have a significant effect and is now being explored. Quantitative reproduction of heat generation will not be achieved until at least these known variables are understood and controlled.

On the other hand, qualitative reproducibility is no longer a major issue. If the known variables, initiation techniques, and methods used to identify 'good' palladium are taken into account, the Pons-Fleischmann effect can be reproduced with a success rate typical of any new phenomenon. Clearly, the required conditions are complex and not easily created without some skill. Other methods and materials have shown better success rates.

Of the direct electrolytic results listed in Table 3, one study stands out by virtue of its large energy production and another by its attention to detail. Takahashi (1992) generated very large power (130 W) and total energy (166 MJ) using a piece of palladium sheet found to be very productive by other

workers. A different batch later produced energy but at a much lower rate. Clearly, this power level is well in excess of any trivial explanation or error in spite of the relatively crude calorimetry used at the time. McKubre *et al.* (1994b) at SRI have explored the phenomenon using a variety of carefully analyzed calorimeter designs. Energy production, although not large, has been demonstrated to greatly exceed all known calorimeter errors and to be clearly related to the nature of the palladium. They conclude that if proper conditions in the palladium are created, excess heat is always obtained.

Levels of total excess energy between 0.1 MJ and 200 MJ have been reported in cells containing, at most, a few 100 ml of electrolyte and frequently much less than 1 cm³ of palladium. If this large excess energy is caused by a chemical reaction, a chemical "ash" must be seen at easily detected concentrations even at the lowest energy levels. This "ash" has not been found. Admittedly, a combination of large energy generation and absence of chemical "ash" does not prove a nuclear reaction. Nevertheless, very large energy production from some unusual source is clearly present. This fact alone should create intense interest regardless of the explanation.

Continued efforts to discredit the heat measurements of Pons and Fleischmann have had little success. This effort is now completely irrelevant because similar results have been obtained by many other researchers. Anyone wishing to understand the effect must include this large and increasingly accurate data set in their analysis, not just concentrate on one or a few studies.

If the effect is real as claimed, why are so many attempts unsuccessful? The answer to this question is complex because many interacting factors are at work. The known major factors are:

1. The nature of the palladium is the single most important factor. The palladium should contain a minimum of cracks, be free of impurities that cause grain boundary weakness, and be polycrystalline with small crystallites. Most off-the-shelf palladium does not have all of these characteristics. More details are given by Storms (1996) and McKubre *et al.* (1995).
2. Sufficient current density is required to initiate the effect. The onset value can be as high as 0.3 A/cm².
3. Certain impurities including aluminum and silicon deposited on the palladium surface improve success (McKubre *et al.*, 1994c). The use of Pyrex containers guarantees deposition of these elements.
4. Absence of certain impurities including copper, zinc and lead (from solder) is essential. Such impurities reduce the loading rate and the ultimate D/Pd ratio. Use of impure platinum for the anode can also provide "bad" impurities to the cathode.
5. Presence of too much normal water in the D₂O will stop the effect. Many early studies used open cells that were affected by adsorbed water from the atmosphere.

6. Uniform current density is important especially if the palladium is less than ideal.
7. Once a high D/Pd ratio has been achieved, an induction period sometimes lasting more than a week is required. Many failures have resulted because the researcher lost patience too quickly.

While the reason for failure can not always be identified, these factors can account for most occasions. Before a negative study is used to demonstrate lack of reproducibility, it should be examined carefully to see if any of these factors were at work.

II. 2. H_2O -Based Electrolyte

Following the Pons-Fleischmann discovery, Mills *et al.* (1992) proposed and demonstrated (Mills and Kneizys, 1991) excess heat production using a H_2O -based electrolyte and a nickel cathode. Subsequent papers further support his model. (Mills *et al.*, 1994) Heat is proposed to result from a change in the normal electron energy level in hydrogen to a lower-energy state. The change forms the so-called dihydrino molecule. This molecule leaves the cell after depositing energy, goes into the world, and subsequently reacquires energy during its conversion to normal hydrogen. Thus, the excess energy found in the cell would result from an unusual energy transfer process involving a chemical change. Mills suggests the excess energy found using D_2O -based electrolyte results from the same process. This explanation is challenged by several observations described in the next section.

Patterson (1994) claims that significant excess heat can be produced in a specially designed cell containing small plastic beads coated with nickel as the cathode and a $H_2O-Li_2SO_4$ electrolyte. The device has been demonstrated at several international conferences⁴ and has been found to produce excess energy by several major laboratories. Levels of power production having immediate commercial application have been achieved.

Energy generation using light water may mean that normal water is not a reliable "blank" for heavy-water cells. However, a positive error in a blank study reduces the apparent anomalous heat that can be claimed from an active cell. Consequently, such an error does not overstate the claim.

Evidence Contrary to Mills Explanation. Excess energy can only be observed if the dihydrino molecule leaves the cell. If it stays in the cell by recombining with oxygen as in a closed cell, a new form of water would be formed. Evidence for this novel water has not been reported. On the other hand, conversion to normal water within the cell would result in no net energy

⁴This device has been demonstrated at the Fifth International Conference on Cold Fusion, Monte Carlo, April 1995; 16th Symposium on Fusion Engineering (SOFE '95) Urbana, IL Oct. 1995; and Power-Gen Conference, Anaheim, CA, Dec. 1995 where over 1000 W of excess power was claimed while 84 W was being drawn from the mains by all pumps and power supplies.

change. If, as Mills proposes, the dihydrino molecule does not combine with oxygen, pressure would build up in a sealed cell as unreacted oxygen and dihydrino accumulate. Diffusion of the small dihydrino through the cell wall would still leave the excess oxygen, and its resulting pressure. This pressure buildup has not been seen using D_2O -based electrolyte. Experience using H_2O -based electrolyte is consistent with this observation but still rather limited.

Bush (1992) proposes that the excess energy results from a nuclear reaction. Evidence for the transmutation conversion of potassium to calcium by absorption of a proton into the nucleus is reported by Bush and Eagleton (1993), Notoya and Enyo (1993) and Notoya (1995). In addition, the former authors found evidence for rubidium conversion to strontium by the same process (Bush and Eagleton, 1994a). Excess energy is also seen when Cs_2CO_3 is used in the electrolyte (Bush and Eagleton, 1994b). Tritium (Ramamurthy *et al.*, 1994; Notoya and Enyo, 1993) at low levels and other radioactive isotopes (Bush and Eagleton, 1994a) have also been detected. These results will be discussed in later sections.

Conditions affecting Ni- H_2O energy production are different from those affecting the Pd- D_2O method. A comparison is summarized as follows:

1. The Ni- H_2O heat producing reaction starts within less than 1 hour after electrolysis starts in contrast to the long and variable incubation period required for the Pd- D_2O system.
2. Lithium, sodium, potassium, rubidium, or cesium carbonates or hydroxides, and Li_2SO_4 in the electrolyte have been reported to produce excess energy using Ni- H_2O . Only LiOD and Li_2SO_4 seems to be reliable electrolytes for the Pd- D_2O energy producing system.
3. A small amount copper (Bush and Eagleton, 1994b) enhances heat production using Ni- H_2O while chromium (Ramamurthy *et al.*, 1994) or oil (Notoya, 1994) inhibit the effect. Excessive copper will stop the Pd- D_2O energy producing reaction but not the tritium producing reaction.
4. Nickel having a high-surface area is needed to produce significant heat. Such large surface areas are not required when Pd- D_2O is used.
5. Nickel produces excess heat using H_2O -based electrolytes while Pd produces heat only when the D_2O is free of normal water.
6. Both hydrogen isotopes produce more power when the temperature is increased.
7. For the Ni- H_2O system, the amount of excess heat remains relatively constant when the applied current is increased. In contrast, the Pd- D_2O system produces an increase in excess power.

It is obvious that excess heat production in the Ni- H_2O environment has many characteristics that differ from the Pd- D_2O system. These differences suggest that heat production does not result from the same nuclear reaction nor from the same chemical environment. In addition, because of these differ-

ences, energy production using the Ni-H₂O system may be more difficult to scale to industrial levels compared to the Pd-D₂O system. Nevertheless, the Ni-H₂O system is relatively easy to reproduce and has now demonstrated significant energy amplification.

Published Observations. Reported observations of this phenomenon are shown in Table 5. Many of the studies do not report sufficient information to allow the work to be evaluated or properly compared. Most workers report that excess energy is produced without a long initiation period. Calibration can be done electrolytically at any time by temporally reversing the current without stopping heat production once the current is returned to its original di-

TABLE 5
Studies Reporting Excess Energy Using H₂O-based Electrolytes

Investigator	Electrolyte	Excess Energy	Remarks
Bazhutov <i>et al.</i> (1994) Russia	0.74M Cs ₂ CO ₃	34% @ 400 mA	No tritium found.
Bush and Eagleton (1994b) US	0.57M K ₂ CO ₃ 0.57M Rb ₂ CO ₃ (closed cell)	1.1W 0.7W	Ca produced. Sr and X-rays produced.
Criddle (1994)	0.57M K ₂ CO ₃	100% (open cell)	Hard Ni better than US soft. Colloid impurities interfere.
Matsumoto (1993) Japan	0.5M K ₂ CO ₃ (open)	40%	Evidence for emission of multiple-neutron particles.
Mills and Kneizys (1991) US	0.57M K ₂ CO ₃ (open)	75.7W, 228% up to 3766%	Na ₂ CO ₃ predicted and found not to produce energy.
Notoya and Enyo (1994) Japan	0.5M K ₂ CO ₃ (open)	9W 300-400%	Increase in Ca conc. consistent with energy production. Tritium observed.
Noninski (1992) Bulgaria	0.57 MK ₂ CO ₃ (open)	160% @ 83mA	Na ₂ CO ₃ found not to produce energy.
Ohmori and Enyo (1993) Japan	0.5M K ₂ CO ₃ (open)	18%	Na ₂ CO ₃ found not to produce energy with Ni. Au produced energy with Na ₂ CO ₃ and Li ₂ CO ₃ . Ag and Sn also studied as cathodes.
Ramamurthy <i>et al.</i> (1994) India	0.57M K ₂ CO ₃ (open)	0.05W/cm ²	Tritium and heat produced using Na ₂ CO ₃ and Li ₂ CO ₃ . Power independent of current.

reaction. Several studies have been hampered by recombination within the cell, i.e. a less than unity Faraday efficiency.

Discussion. Although most studies used primitive calorimetric methods and open cells, proof-of-principle evidence for excess energy production is strong, especially in view of Patterson's success. In addition, production of short-lived radioactive elements, changes in the isotopic ratio, and changes in amounts of stable elements provide evidence for several nuclear reactions. These products will be discussed in Section 111.6.

Nuclear reactions of the type proposed would imply that even a very large coulomb barrier is easy to overcome in certain chemical environments. On the other hand, if the Mills explanation is even partially correct, major changes in quantum theory must be contemplated.

11.3. Electrolysis of KCl-LiD Molten Electrolyte

Liaw *et al.* (1990)(US) used an eutectic mixture of KCl and LiCl containing dissolved deuterium as an electrolyte for producing excess energy near 450 °C. In this case, palladium attracts deuterium when used as the anode. Excess energy nearly 15 times the applied electrolytic power is reported. In addition, helium (Liaw *et al.*, 1993) was detected in the palladium, although not enough to account for the measured energy (see Section 111.3).

One independent study by Yuan *et al.* (1993) claimed heat at 5–108 times the applied power and showed low-level neutron emission at the same time. However, insufficient detail was given about the calorimetric technique to support the claimed magnitude of excess power.

Energy production using this technique has been difficult to reproduce. Nevertheless, energy generation at 450 °C is too attractive to ignore.

11.4. Current Passed Through $Sr(CeYNb)O_3 + D_2$

Mizuno *et al.* (1994)(Japan) claim 50 W of excess energy (≈ 3.6 MJ total, out/in = 7×10^4) while passing a small current (40 μ A) through a ceramic proton conductor bathed in D_2 and heated at 400–500 °C. Energy is generated during deuterium absorption and desorption cycles produced by changing the polarity of the applied voltage (18 V). No heat production was observed when H_2 was used or when $Al_2O_3-SiO_2$ was treated in the same manner using D_2 . Detection of nuclear products has not been reported. Efforts to duplicate this work are underway at several laboratories. Possible chemical explanations are limited because the ceramic is chemically inert to hydrogen; of the two hydrogen isotopes, only deuterium produced the effect; and the amount of energy produced is far above any conceivable chemical reaction.

11.5. Gas Discharge Using Pd Electrodes in Hydrogen

Dufour (1994)(France) claim excess energy production while bombarding palladium with ions generated in an ozoniser. This apparatus creates a dis-

charge in a gas between two electrodes separated by one or more dielectric barriers. Microsparks having high local current are generated by applying an AC voltage. In this case, the gas is H_2 at pressures above 1 bar, the electrodes are palladium, and the dielectric is Pyrex. A mean excess energy of 2.1 ± 0.5 W was reported which is 66% more than the applied power. Nuclear products are presently being sought.

Another study by the same author (Dufour, 1993) used sparks generated between copper points and palladium or stainless steel. Radioactive products and heat were produced using hydrogen or deuterium as the discharge gas.

Recent work using palladium electrodes and hydrogen gas (Dufour, 1995) produced power up to 5.5 ± 0.7 W with an inexplicable disappearance of hydrogen only while excess energy was being produced.

11.6. Gas Discharge Using Pd Electrodes in Deuterium

Karabut *et al.* (1992)(Russia) claim excess energy production ($\approx 500\%$) using DC discharge (100–500 V, 10–100 mA) between electrodes in low-pressure (3–10 torr) deuterium. The cathode is palladium while the other electrode is molybdenum. Various nuclear products were detected and will be described in Section III.

11.7. Gas Reaction of H_2 with Ni Under Special Conditions

Focard *et al.* (1994)(Italy) placed a specially treated nickel rod in hydrogen and, after heating to ≈ 400 °C, reported producing 44 W of excess energy for 24 hrs (90 MJ). Although no neutrons or gamma rays were reported above background, subsequent studies revealed the presence of both emissions in significant amounts. Attempts to reproduce this work have been frustrated because the required special treatment has not been revealed.

11.8. Enhanced Reaction Between D_2O and Various Metals Using an Acoustic Field

Stringham and George (1993)(US) use an intense acoustic field (≈ 20 kHz) to inject deuterium into palladium contained in D_2O . Significant excess energy (10–100 W) and helium production (up to 552 ppm) are claimed. In addition, the $^3He/^4He$ ratio increased nearly 1000 times over the background value when normal water was present in the D_2O . This change cannot be attributed to contamination. Excess heat is not produced by H_2O -Pd or D_2O -stainless steel combinations. No neutron or gamma emissions have been detected. Although publication of this work has been very limited, it has achieved commercial interest.

11.9. Enhanced Reaction in H_2O Using Microbubble Formation (20 to ≈ 100 °C)

Griggs (1994)(US) designed an energy conversion device which later, surprisingly, was found to produce excess energy at high levels and with total re-

producibly. The device converts rotational energy, supplied by a motor having up to 100 hp, to the production of hot water or steam. This conversion occurs in a small gap filled with water between a stationary frame and an internal rotating member. The rotating member has on its surface a series of holes designed to create sonic waves within the water during rotation. Repeated tests and a long history of use has demonstrated excess energy as high as 128% over input. This level of power is no longer a laboratory curiosity nor can it be rejected because of minor errors in measurement. Evidence for nuclear product formation is being sought.

Potapov (1995)(Russia) has designed and is selling in Russia a device that is claimed to produce excess energy by pumping water through a venturi in which cavitation bubbles are produced. This device has been tested at several laboratories in the US with poor success.

II. 10. Reaction of Finely Divided Palladium with Pressurized Deuterium Gas

Arata and Zhang (1990, 1994)(Japan) produced very high, reproducible power (125 W) and total energy (200 MJ) using a palladium tube filled with palladium-black (very finely divided metal powder) as the cathode. A special treatment of the palladium-black is required to remove surface impurities. Energy was produced when pressures of D_2 over 10 atm were accumulated within the cathode tube. This experience suggests that the heat-producing reaction may occur most readily in very small crystallites that require a relatively low deuterium pressure to achieve a deuterium concentration necessary to form the NAS.

Recently, Arata (1995) announced in Japan that sufficient helium to account for the excess energy by a fusion reaction was released after the palladium was heated.

III. Nuclear Ash

Is there credible evidence showing the initiation of a nuclear reaction in a chemical environment? Detection of a nuclear product at a sufficient level above error or background is required before a yes answer can be accepted. Even small reaction rates would require reevaluation of nuclear theory, a non-trivial prospect to some people. The large rates needed to produce measurable heat have more serious consequences to both theory and to possible application.

Many studies have claimed to have detected various products that can only result from nuclear reactions. The next question is, "Are these claimed products indicative of novel nuclear reactions or just the result of error"? This answer rests on the care used in the studies and the magnitude of the products. These claims will be examined starting with neutron emission.

III.1. Neutron Emission

III.1.1. Background. Over 300 attempts to detect neutron emission have been reported, with about a third claiming success. However, very few measurements were made while excess energy was being detected. Therefore, most studies may not have been done while the sought-for phenomenon was occurring. This intense interest results because, of the three possible fusion products, neutron detection has the greatest sensitivity and readily available equipment. In addition, energy measurements can help identify the originating nuclear reaction. The other possible products are tritium and helium which will be discussed in the following sections.

Regardless of expectations, the signals are small and frequently very close to background. Such small and random-like emission has generated much debate as to whether any neutrons are being emitted at all. As a result, most recent studies have gone to great effort to isolate the signal from background using various methods. False signals are known to come from cosmic-ray showers, electrical noise pickup, electrical discharge within the counter, and natural radioactivity in the environment. Some types of counters are worse in these regards than others. Lowering the background by using shielding or veto counters is now common. The use of dual or multiple counters is another way to reduce random false signals. Confidence is improved if the neutron signal is found to have a particular, expected energy. A good discussion of these problems is given by Menlove (1991). A statistical treatment of several studies is given by Hoffman (1995).

Even though all of these methods to reduce error have been used, positive results continue to be reported. The issue may not be that experts in neutron detection are being repeatedly misled by false counts. Rather, the simple answer may be that neutrons are not present except when the rare neutron producing reaction is actually initiated. At least one study (Takahashi *et al.*, 1993) observed neutron production while excess energy was being measured and found a correlation. However, the signal reported by this study, as well as by all other studies, is small and much less than would be expected if the excess energy were resulting from a "hot fusion" reaction. Clearly, neutron production is not a significant part of the Pons-Fleischmann Effect. However, other nuclear-active-states may be more active in this respect.

Neutron production has been claimed during the following processes:

1. Electrolysis of palladium or its alloys in D_2O , especially when the current is changed,
2. During release of D_2 from palladium by heating,
3. During temperature change while titanium is contained in high pressure D_2 and at particular temperatures,
4. During a temperature change after $YBa_2Cu_3O_7$ has been reacted with D_2 , and at a particular temperature,

5. After titanium or palladium are implanted with deuterium to a critical composition,
6. During low-voltage discharge in low-pressure D_2 using palladium electrodes,
7. During the reaction of D_2 with $Na_{<0.9}WO_3$,
8. While pulverizing various deuterium-containing solids.
9. During hardening of Portland cement containing D_2O .
10. While specially treated nickel is heated in hydrogen.

Steady emission of individual neutrons lasting from seconds to hours and brief bursts of many neutrons lasting from 1 psec to 100 psec have been observed. Only those measurements showing unusually high emission, energy measurement, or unusual conditions are listed in Table 6. The table intends to demonstrate that neutrons having the energy expected from a fusion reaction can be produced. A few examples of high flux emission are also listed to demonstrate that occasionally signals can be well above background. A good review of neutron emission during titanium- D_2 reaction has been published by Scaramuzzi (1991) and a brief general review has been presented by Daddi (1995).

The listed background value and the signal multiplier are intended as a rough guide for judging the magnitude of the effect. Because the signals are

TABLE 6
Reports of Neutron Emission

Investigation	Counter Type	Background cts/hr	Signal \times BG	Energy MeV	Production Method
Arata and Zhang (1990)	BF,, 3He	1 10	2 (10^8 n/s burst)	≈ 2.5	Electrolysis of special palladium on nickel. Electrolyzing massive palladium. (Signal produced on two counters.)
Beltyukov <i>et al.</i> (1991)	3He	360	10^2 - 10^3		Laser induced in $TiD_{1.97}$ at β - γ transition
Bertin <i>et al.</i> (1989)	NE-213	200	4	≈ 2.5	Ti electrolyzed in D_2O
Bittner <i>et al.</i> (1991)	NE-213	60	2	≈ 2.5	Massive Pd deloaded of deuterium by heating. Two alternate counters used
Bressani <i>et al.</i> (1991)	NE-110, TOF	20	2	≈ 2.5	Ti reacted with D_2 and thermal cycled

TABLE 6 (continued)
Reports of Neutron Emission

Investigation	Counter Type	Background cts/hr	Signal \times BG	Energy MeV	Production Method
Duan <i>et al.</i> (1991)	BF,	$(6 \times 10^5 \text{ n/sec for 10 min})$			D ⁺ implanted into Ti to achieve a critical concentration. Two detectors used.
Fischer <i>et al.</i> (1973)	NE-213	(10^7 n burst)			100 kV discharge through 3–7cm capillaries of Li/ND ₃
Hongyu <i>et al.</i> (1991)	LS	60	40	≈ 2.5	Pd electrolyzed in D ₂ O
Jones <i>et al.</i> (1989)	⁶ Li-glass	2	3	2.5	Ti and Pd electrolyzed in D ₂ O
Karabut <i>et al.</i> (1992)	³ He	$(10^7 \text{ n burst lasting minutes})$			Low-voltage discharge in D ₂ with Pd cathode
McKee <i>et al.</i> (1990)	NE-213, and Ir activation		(130 n/hr)	3–5	Pd and Ti bombarded with 60 keV D ₂ ⁺ . Neutrons detected after critical composition was reached.
Nakada <i>et al.</i> (1993)	NE-213, ³ He		1.1–1.5	$\approx 2.5, 3-7$	Pd electrolyzed in D ₂ O using H/L method. PdD _{>0.7} required.
Okamoto <i>et al.</i> (1994)	NE-213		1.1	$\approx 2.5, \approx 3.6, \approx 5.5$	Pd electrolyzed in D ₂ O. Excess energy produced.
Sanchez <i>et al.</i> (1989)	BF ₃		1–2	10 ⁴	Ti electrolyzed in D ₂ O. Tritium produced with neutron emission.
Shani <i>et al.</i> (1989)	NE-213	180	2	≈ 2.5	Emission is enhanced by bombardment with neutrons.
Takahashi (1992)	NE-213, ³ He	60	1.8	≈ 2.5	Pd electrolyzed in D ₂ O. H/L method used.
Yamaguchi and Nishioka (1990a, 1990b)	³ He, BF,	106			During explosive release of D ₂ from Pd. Signal produced in two counters.

very small, both values fluctuate. In addition, the character and magnitude of the emission frequently changes with time. An absolute comparison of emission rates can not be made using the listed values because the detectors have different sensitivities. However, such information can be obtained from the cited papers.

Discussion. Rejection of studies reporting excess heat because simultaneous neutron measurements were not made is no longer appropriate. Regardless of expectations, very few neutrons are produced during heat generation using D_2O . Therefore, a nuclear explanation for energy production can not depend on whether neutrons are emitted or not. Another nuclear product must be found.

On the other hand, significant neutron emission has been detected using techniques not associated with energy production. Therefore, neutron-producing reactions apparently are possible under conditions not permitted by conventional nuclear theory. Neutron energies near 2.5 MeV are consistent with a d-d fusion reaction. Reported higher energies suggest that either additional types of neutron producing reactions occur or energy transfer to the 3He co-product is reduced by its interaction with the lattice. If the 3He co-product is strongly coupled to the lattice, it may appear to have a greater than normal mass. As a result more energy will be transferred to the neutron — up to 3.2 MeV.

PdD bombarded with neutrons was found to emit more neutrons than present in the bombarding flux (Shani *et al.*, 1989; Stella *et al.*, 1993). On the other hand, Cerofolini *et al.* (1993) claim that the background neutron flux is apparently reduced when H^- and D^+ react to form a DH molecule. Perhaps neutrons produced in an electrolytic cathode are absorbed by the surrounding film of reacting H and D ions. These two unusual effects need further study.

Existence of two different types of neutron emission suggests two different types of production reaction. Short (1–100 μ sec) bursts are generally produced when crack formation is expected, which is consistent with the fractofusion model. However, the expected production of neutrons and tritium in equal quantity during the resulting "hot" fusion has not been reported. On the other hand, the steady, single neutron emission mode, seems to accompany tritium formation but at a level much below the expected neutron/tritium ratio of unity. (Shinojima *et al.*, 1995) Because many neutron detectors can easily confuse brief burst production with a single neutron event, a clear conclusion is still in doubt about the nature of these two behaviors.

111.2. Tritium Production

111.2.1. Background. Tritium is the other major nuclear product expected from a fusion reaction. Skeptics have suggested that any claimed tritium must result from tritium initially present in the palladium cathode or from the external environment, so-called contamination. In addition, a graduate student at Texas A & M was falsely accused of adding tritium to cells (Taubes, 1993) in

order to discredit early work. Hoffman (1995) suggests that the presence of ^{210}Pb might be mistaken for tritium. If tritium can be shown not to result from these sources, a major nuclear product would have to be accepted.

111.2.2. Contamination as an Explanation. Wolf (1990) reported that two pieces of unused palladium and one, having been electrolyzed⁵ in light water, contained tritium. Since then, skeptics have consistently used possible contamination to reject all tritium claims. For example, Hoffman (1995) makes the unsupported assertion that commercial palladium may have been contaminated with tritium because it was mixed with palladium used in the weapons industry for tritium separation.

Only virgin palladium obtained directly from the ore has been used in the major studies. Even if tritium were present, it would show an easily recognizable behavior. The behavior of dissolved tritium in palladium has been studied by Storms and Talcott-Storms (1991). They found that during electrolysis, dissolved tritium (contamination) leaves the cathode and more than 99% appears in the evolving gas. Very little appears in the electrolyte where anomalous tritium is always found. Furthermore, the tritium begins to leave the cathode immediately after electrolysis starts, and one half is gone between 12 and 24 hours later. On the other hand, anomalous tritium takes many days to appear and the appearance is sudden. If the tritium is chemically combined in some mysterious way, as Wolf suggests, this time could be longer. However, no matter what its initial chemical form, once tritium begins to move through the metal on its way to the surface, it will be influenced by the same process observed during the Storms' study. Consequently, it will not be found in the electrolyte. Only tritium chemically combined at the surface would escape this process. Such tritium would be released immediately and would appear in both D_2O - and H_2O -based electrolytes. Tritium never appears immediately and it has never been seen in H_2O -based electrolyte when palladium is used as the cathode.

Considerable experience at the National Cold Fusion Institute (Cedzynska *et al.*, 1990) has failed to reveal the presence of tritium in commercial palladium, including the source used by Wolf. However, they did find that the analytical technique used by Wolf could give false positive results. Claytor *et al.* (1990), working at Los Alamos National Laboratory, also failed to detect tritium in palladium powder, wire and sheet from a variety of commercial sources. Except for the three examples reported by Wolf, no one else has found significant tritium in palladium after many hundreds of tests using many methods and sources.

The quantity of tritium in palladium has been determined by measuring

⁵The electrolyzed piece did not release any tritium into the electrolyte, a requirement for this claimed contamination to be a source of anomalous tritium.

1. the quantity of ^3He , the decay product of tritium,
2. the quantity of tritium removed when palladium is heated in vacuum,
3. the quantity of tritium displaced when palladium is reacted with deuterium or hydrogen,
4. the quantity of tritium found in the electrolyte after palladium is electrolyzed as the anode,
5. the quantity of tritium found in solution after palladium is dissolved in acid, and
6. light pulses generated when palladium is suspended in scintillation fluid.

Tritium is very rare but not absent in a normal environment. Because it is a health hazard, laboratories using the material try to keep it contained and regularly monitor the environment in order to demonstrate success. In addition, studies at the Los Alamos National Laboratory (Storms, 1991) show how the tritium content of a cell would change if tritium were entering from the environment. When this is the source, the tritium increase rate starts immediately and is approximately constant. In contrast, anomalous production only starts after many hours of electrolysis and appears frequently in bursts. In some cases, the claimed amounts are so large that if the tritium originated from the general environment, the required concentrations would pose a health hazard and would be easily detected. While hot spots are occasionally seen in a tritium laboratory, these are areas where tritium can easily concentrate. A sealed cell is not one of these areas.

The charge that tritium was added to cells at Texas A & M University can only be described as a "cheap shot" not worthy of a fair and objective assessment. (Taubes, 1993) An investigation by Texas A&M University failed to find any evidence to support this allegation. (Skerrett, 1990) In addition, this unproven assertion has now become completely irrelevant in judging the reality of tritium production because numerous positive results have been reported at many laboratories that can not be explained in this way.

Open electrolytic cells containing D_2O always show an increase in the tritium concentration because deuterium is electrolyzed away faster than is the tritium that is always present. This separation factor is very near 2.0 and independent of the cathode surface. (Boucher *et al.*, 1994) As a result, the tritium concentration can nearly double by an amount that depends on the integrated electrolytic current. This factor needs to be taken into account when open cells are evaluated. (Sevilla *et al.*, 1993) Closed cells, or open cells for which a total inventory is kept, do not have this problem. Both methods have demonstrated tritium production. Electrolytes based on H_2O in which tritium has appeared do not have this problem because normal water contains essentially no initial tritium.

Hoffman (1995) has made a number of unsubstantiated assumptions involving impure heavy water in order to explain away the tritium production claims. The heavy-water used during "cold fusion" studies is proposed to contain used

moderator water from nuclear reactors. Such water is further assumed to contain ^{238}U that decays into ^{210}Pb .⁶ Because this isotope has a β energy near that of tritium, Hoffman postulates that it has been mistaken for the claimed tritium, thus accounting for some positive results. This proposal applies only to the electrolysis of D_2O , not to the many other successful techniques. Each of these assumptions is false. Only virgin, low-tritium heavy water was used during the major studies. Even if ^{210}Pb were present, its concentration would have to increase during the experiment for "tritium" production to be claimed. The maximum rate of ^{210}Pb production from 1 gm of ^{238}U is about one atom/min. Of course, even if the initial assumption were true, the ^{238}U content would be much less than a microgram — a thousand times smaller. As a result, only a very small amount of ^{210}Pb would accumulate and only a small fraction of these atoms would decay to produce a β particle during a typical cold fusion experiment. Taken at face value, this assumed process would fail to generate sufficient β activity to account for the claimed tritium production rates by at least 18 orders of magnitude. Even if the assumptions were true, one has to wonder why such a small effect, would be suggested as a potential explanation.

III.2.3. Reported Tritium Results. Over 100 papers reporting attempts to produce tritium have been published — the first successful result being reported by Packham *et al.* (1989). Most early attempts either failed or were not convincing. Recent studies have eliminated many objections and have achieved greater reproducibility.

Table 7 compares a variety of studies done using some of the necessary precautions. Listed first are abbreviated designations for the methods used. The first Roman number designates the environment in which tritium was produced, as tabulated in Table 8. A wide range of reproducibility and production levels are represented by these environments. The second number designates the detection method, as shown in Table 9. Each method has different precautions to avoid erroneous results and different sensitivity. Nevertheless, the limitations of these methods are well known because accurate tritium detection is important to many areas of science. The third letter shows the type of cell used. For example, some studies used closed, sealed cells, designated "S". Sealed cells contain a recombiner catalyst. Other studies monitored the tritium by keeping a complete inventory of tritium entering and leaving the cell, designated "C". Next shown are the total quantity of tritium atoms produced and the best production rate. Because these amounts have a wide range of values, there is no reason to believe that any study has yet achieved the highest possible level or rate.

If tritium results from the expected fusion reaction $\text{d} + \text{d} = \text{t} + \text{p}$, Any t having an energy above 25 keV is expected to produce 14 MeV neutrons by the reaction $\text{t} + \text{d} = {}^4\text{He} + \text{n}$ with a n/t ratio of about 10^{-4} . Emission of 14 MeV

⁶Only 4 atoms in one million atoms of ^{238}U decay to this isotope of lead. The other atoms produce ^{214}Pb which can not be mistaken for tritium.

neutrons has not been observed when tritium is detected, More will be said about this anomaly later in the paper.

TABLE 7
Tritium Production

Investigator	Methods	Total T atoms	Average Rate atoms/sec	Remarks
Bockris <i>et al.</i> (1993) US	I, 1, C	10^{15}	1×10^8	Tritium production could be turned off and on. Pd was prepurified.
Chêne and Bass (1990) US	I, 1, C	10^{10}		Several assumptions make this value uncertain.
Claytor <i>et al.</i> (1990) US	IV, 2, S		3×10^{11}	Used pulsed current discharge between oxidized Pd and Si in pressurized D_2 . Many cells produced tritium. Pd was prepurified. No tritium when H_2 used.
	V, 2, S	10^{12}	10^7	Wires of Pd reacted with D_2 and heated by passing a current. Wires were prepurified.
	III, 2, S	10^{12}	10^6	Pulsed glow-discharge between Pd plate and Pd wire. Pd was reanalyzed for tritium.
D'Amato <i>et al.</i> (1990) Italy	VI, 2, S	$\approx 10^8$		Ti alloy partially reacted with D_2 and subjected to temperature change. Neutrons detected.
Iyengar <i>et al.</i> (1990) India	I, 1, C	8×10^{15}		Pd-Ag electrolyzed in NaOD- D_2O . Many other electrodes and electrolytes found successful.
Notoya and Enyo (1993) Japan	II, 1	10^{10}	4×10^5	Ni- H_2O cell produced tritium in proportion to the applied current.
Ramamurthy <i>et al.</i> (1994) India	II, 1		10^{14}	14 Ni- H_2O cells produced tritium.
Srinivasan <i>et al.</i> (1990) India	VI, 2,5, S	$\approx 10^{16}$		TiD chips cooled in liquid.
Storms and Talcott (1990) US	I, 1, C	10^{10}		Cells closed and total inventory made. Many cells studied but only a few produced tritium.

TABLE 7
Tritium Production (continued)

Investigator	Methods	Total T atoms	Average Rate atoms/sec	Remarks
Szpak <i>et al.</i> (1991) US	I, 1	10 ¹¹	10 ⁷	Electrodeposited Pd from PdCl ₂ +D ₂ O. Tritium and heat production started within 20 min. Radiation detected.
Will <i>et al.</i> (1994) US	I, 1, S	10 ¹¹	10 ⁵	The 4 successful cells were sealed. No tritium seen when H ₂ O-base was used.

$$1\mu\text{Ci} = 2.2 \times 10^6 \text{ disintegrations/min (DPM)} = 3.4 \times 10^{-11} \text{ mol} = 2.1 \times 10^{13} \text{ atoms} = 3.7 \times 10^4 \text{ Bq.}$$

TABLE 8
Environments Producing Tritium

1.	Pd used as a cathode in D ₂ O-based electrolyte
2.	Ni used as a cathode in H ₂ O-based electrolyte
3.	Low-voltage discharge involving Pd electrodes in low pressure D ₂ .
4.	Low-voltage discharge involving Pd electrodes in high pressure D ₂ .
5.	Rapid gas release from Pd upon heating.
6.	Gas loading of Ti with high pressure D ₂ followed by temperature change.

TABLE 9
Methods Commonly Used to Direct Tritium

1.	Scintillation fluid (or solid) which produces light pulses when the emitted β -particles pass through. This method can also measure the energy of the β -particle. Tritium is generally measured in the form of water. Certain chemicals in the sample can result in a false reading. The usual detection limit is 10 ⁷ atoms.
2.	Ionization chamber in which the current generated by the β -particles is amplified and subsequently measured. This method is used when tritium is in the gas phase and has a detection limit near 10 ⁹ atoms.
3.	Mass spectrometer that measures the amount of material having the mass of tritium. Care must be used to discriminate against impurity ions such as DH ⁺ .
4.	The amount of ³ He that is proportional to how much tritium has decayed since first entering the material. This value gives the weighted average for tritium present in the past. It does not give the present tritium content. The detection limit is near 10 ⁴ atoms when precautions are taken and a modern mass-spectrometer is used.
5.	Autoradiographs that detects β -particles directly or the accompanying X-rays by exposing photographic film. A detailed map of present tritium locations can be created using this method but the detection limit is high, being near 10 ¹²⁻¹³ atoms.

As summarized by Storms (1991), the amount of tritium detected when coupled with simultaneous neutron measurements indicates a t/n ratio between 10^4 and 10^9 . Recent work has not changed these values. A factor of ten in this wide range probably results from error while most of the range is produced by unknown factors involving the different chemical environments and methods used.

Several studies report results in sufficient detail to eliminate most objections. Bockris *et al.* (1993) electrolyzed prepurified palladium in an open cell containing $\text{LiOD-D}_2\text{O}$. Tritium production was monitored by periodic sampling. A similar, nonactive cell was run at the same time in the same room. Figure 4 shows how the tritium concentration changed with time at three different cell currents. Values obtained from the "dead" cell are also plotted. A great deal of turbulence would stop tritium production which could be restarted by applying various initiating techniques. A tritium activity of 2×10^5 DPM/ml (2×10^{12} atoms/ml) was achieved before the experiment was terminated. No aspect of this behavior is consistent with an explanation based on contamination from any source.

Claytor *et al.* (1990) reacted pre-analyzed, tritium-free palladium wire with deuterium gas in a sealed system. A current was conducted through the wire, thereby driving off the deuterium along with tritium. Figure 5 shows the measured tritium concentration in the gas as a function of time at various heating currents. Although only certain batches of palladium produced tritium, contamination was eliminated as an explanation.

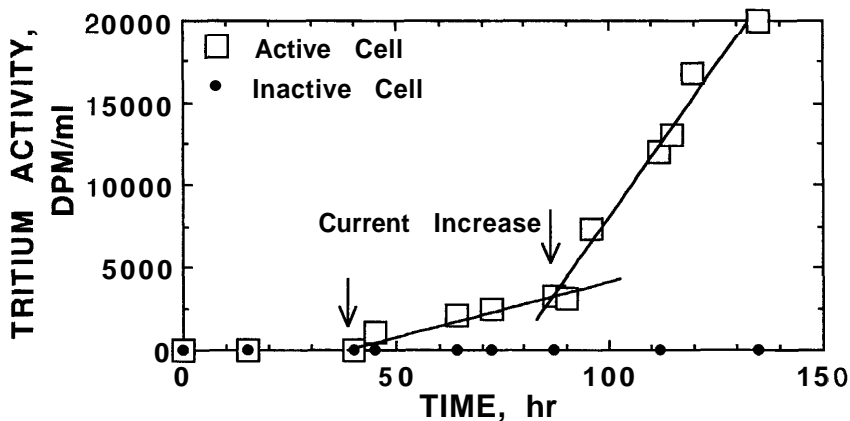


Fig. 4. Tritium concentration as a function of time at three different cell currents. Results are also shown for a dead cell studied at the same time.

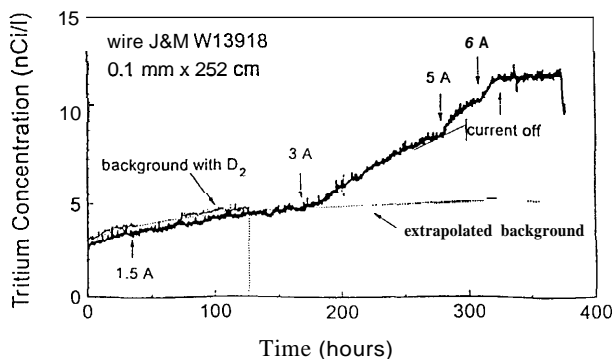


Fig. 5. Tritium evolution at various heating currents.

This is only one of three techniques used by these authors to successfully produce tritium. The first technique consisted of alternating layers of pre-analyzed palladium and silicon through which a pulsed current was passed. The surrounding deuterium gas was pumped through a detector sensitive to β emission which occasionally showed the presence of significant tritium. A technique presently being explored involves the use of pulsed, electric discharge in low-pressure deuterium. A palladium plate is the anode and a palladium wire is the cathode. As before, the surrounding gas is passed through a β detector in a sealed, stainless steel system. Tritium production is monitored in real time during the discharge. Both methods have produced similar tritium levels.

Discussion. Tritium, when present as contamination, will show certain unique characteristics. Consequently, when tritium is detected, its possible origin as contamination can be easily demonstrated. Attempts to dismiss the appearance of tritium must take these behaviors into account. In addition, no tritium has been found in commercial palladium. Because recent studies have used various prepurification methods and detection techniques before the palladium was studied, the possibility of using unexpectedly contaminated palladium is eliminated. In addition, the various environments have been combined with different detection methods so that a common measurement error or a common source of contamination can not explain all claims. Clearly, the challenge to find an overlooked, nonnuclear explanation has increased to almost impossible levels. A cavalier rejection based on "lack of convincing evidence" is no longer sufficient unless a plausible, overlooked explanation is offered as well.

At no time has the tritium production rate been large enough to generate detectable power. Indeed, its presence is seldom seen in energy producing cells. Therefore, an explanation for energy production must look elsewhere. How-

ever, its production level is much too large to be explained by conventional theory.

III.3. Helium

III.3.1. Background. Helium is the third possible fusion product as well as a product resulting from several other conceivable nuclear reactions. When this product occurs from fusion in high-energy plasma, a gamma-ray is emitted. Absence of gamma emission when helium is claimed in a "cold fusion" environment has been used as a reason to reject the claim. Another reason is based on the possibility that the detected helium came from the construction materials or by diffusion into the cell from the atmosphere, so-called contamination.

When detected, a higher concentration is found in the gas rather than in the palladium where it is proposed to originate. This observation raises a red flag because helium placed in palladium by other methods is not easily removed. Why does "cold fusion" helium apparently leave so easily? This question will be addressed in a later section after the various studies are described.

A double-blind analysis of various unused, helium implanted, and electrolyzed palladium was done early in the field's history. (Morrey *et al.*, 1990) The as-received palladium contained $4.3 \pm 3.3 \times 10^9$ atoms/mg. An electrolyzed palladium cathode, supplied by Pons and Fleischmann after producing 1.4×10^{11} ergs of heat, showed $26 \pm 16 \times 10^9$ atoms/mg, but only within 25 μm of the surface. This amount is too small to account for the heat by a factor of 36. A clear conclusion is compromised because the as-received palladium contained much more helium than normally seen in such material, making the nature of the electrolyzed sample uncertain. For these reasons, the work was generally rejected. Subsequent studies are more convincing.

The first measurement of helium in the evolved gas was provided by Miles *et al.* (1991). Eight gas samples taken in Pyrex flasks during heat production contained helium while six control cells showed no helium above background. Because glass was used to contain the gas, the results might have resulted from diffusion of helium through the glass. In response to these concerns, the investigators measured the diffusion rate of helium through glass. When corrections were made, excess helium remained in the flasks. Another study (1994a) was launched using metal flasks. These results are shown in Figure 6. Although the errors are large, the measured helium is close to that expected from the $d + d = {}^4\text{He}$ fusion reaction and well above measurements made using H_2O -based electrolyte in a control study.

Gozzi *et al.* (1994) studied several cells using in-line helium measurement. One cell (#10) revealed a time delay between heat production and helium release, as can be seen in Figure 7. Total energy and accumulated helium (plotted as power from the d-d fusion reaction) are compared as a function of time in Figure 8. Because a slight air leak might have occurred after 900 hr, the final helium rise may not be significant.

Bockris *et al.* (1993) detected helium in palladium used in an electrolytic

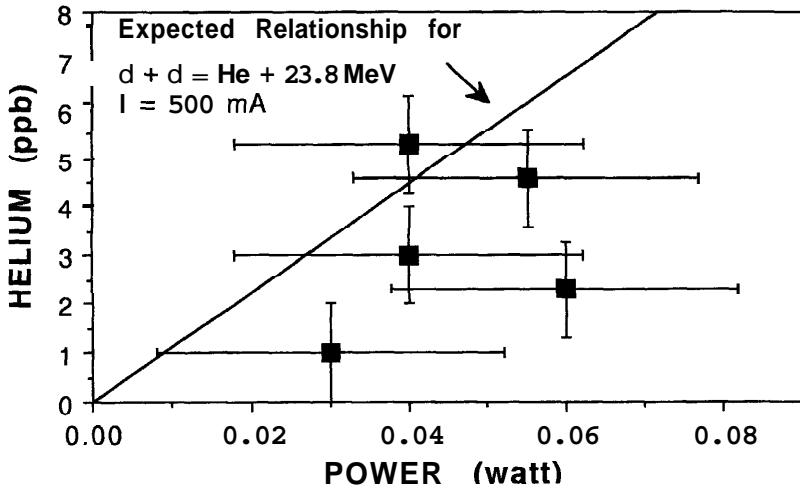


Fig. 6. A comparison between excess power and excess helium. The line shows the relationship expected if helium and power are produced by the reaction $d + d = {}^4\text{He} + 23.8 \text{ MeV}$. Helium is collected at a fixed current and time.

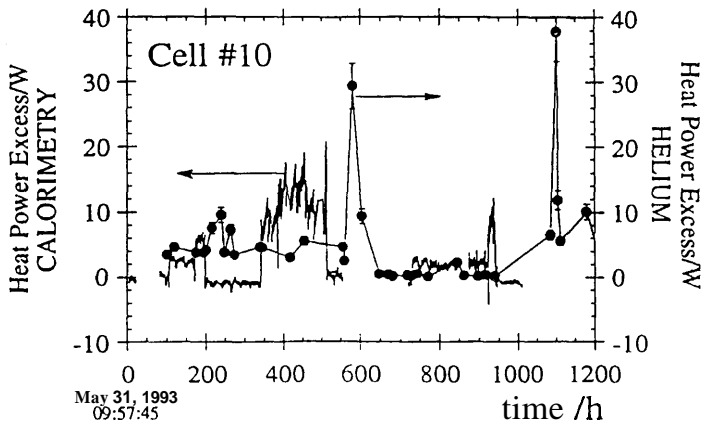


Fig. 7. Excess power and resulting helium compared as a function of time.

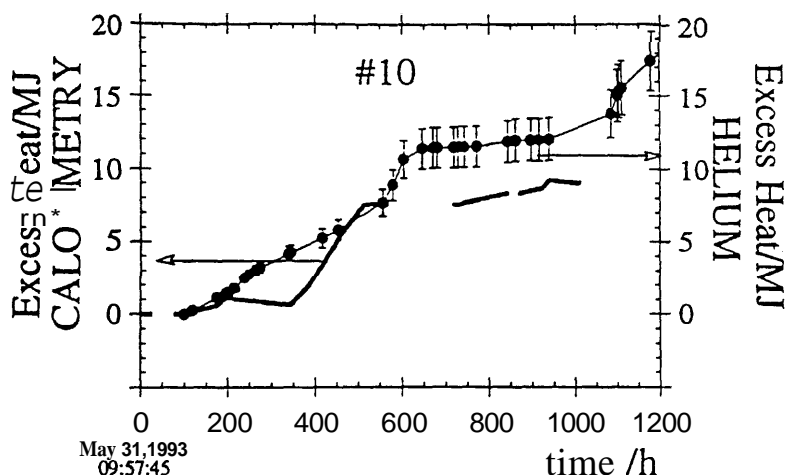


Fig. 8. Total Energy and total helium compared as a function of time.

cell after tritium was produced. Heat production was not measured. Various samples were cut from the electrode at different places and the results are compared in Figure 9. Clearly, the helium content is very nonuniform in this material but well above background.

Liaw *et al.* (1993) also determined helium in a palladium electrode. In this case, the metal was used in a molten salt cell containing a KCl-LiCl(D) electrolyte heated to 450 °C. The helium contents of used and unused palladium, shown in Figure 10, have slightly different averages but the difference is not statistically significant. Indeed, the relative absence of helium in palladium heated to such high temperatures is not surprising.

Savvatimova (1994) analyzed palladium that had been exposed to deuterium ion bombardment. This treatment resulted in heat production as well as emission of various nuclear products as described in other sections. Figure 11 compares the helium contents of unused palladium with parts of the target shielded from the ions and parts exposed to bombardment.

Yamaguchi and Nishioka (1990) reacted specially prepared palladium with D₂ gas and observed heat and helium production when the deuterium was rapidly removed in vacuum. Helium was released to the gas only when the palladium reached 200 °C. No helium was produced when H₂ was used.

Zhang *et al.* (1993) electrolyzed titanium in D₂O-based electrolyte and detected helium in that part of the rod within the electrolyte. No helium was found in the rod above the electrolyte.

Stringham and George (1993) produced heat and helium during acoustic

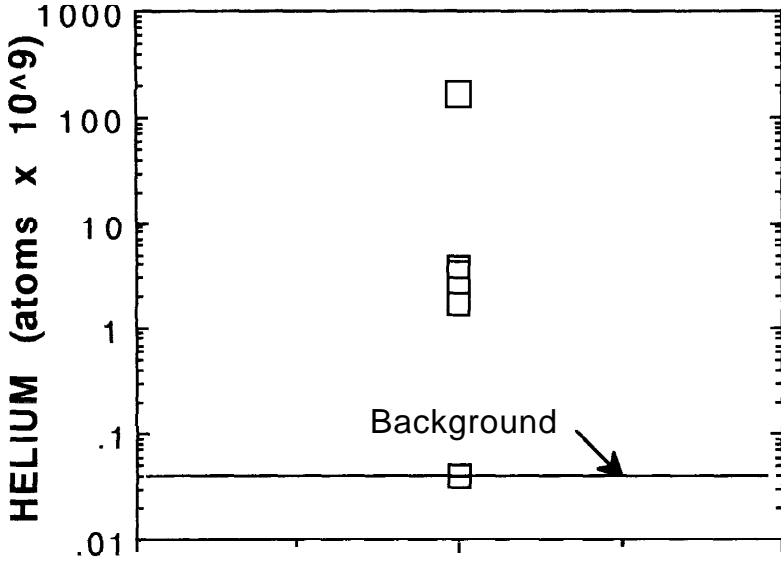


Fig. 9. Number of helium atoms in various samples taken from a palladium.

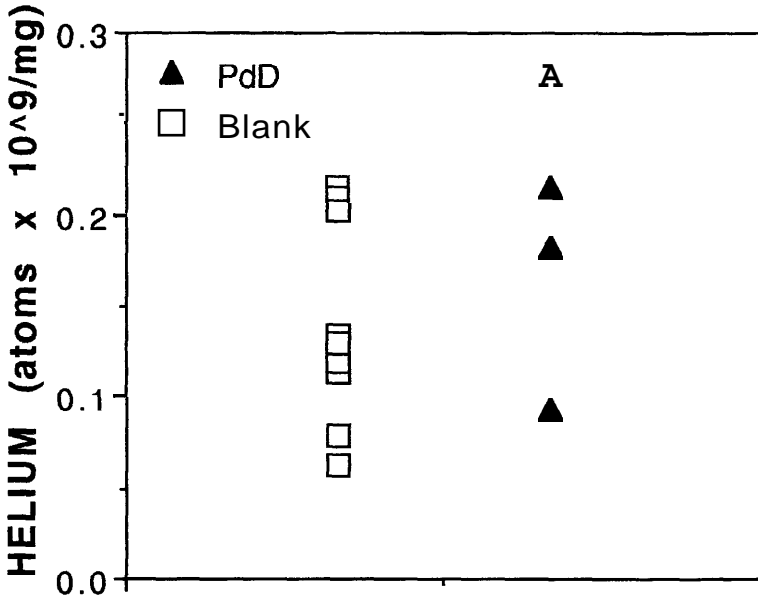


Fig. 10. Comparison between helium contents of unused and used palladium after heat production in a molten salt cell.

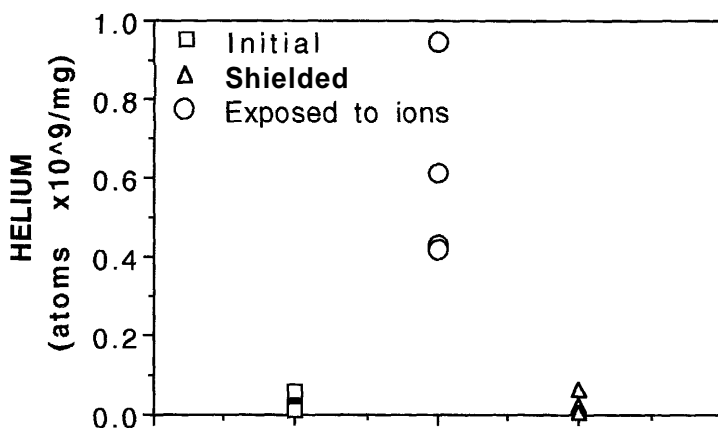


Fig. 11. Helium contents of unused palladium, and palladium exposed to ion bombardment and shielded from the ions.

loading of palladium in D_2O contained in a sealed stainless steel system. A blank run for ≈ 20 hrs give 0.5 ppm 4He in the gas while an active study produced 552 ppm during the same time. This amount of helium is far in excess of any possible contamination. Unfortunately, this work is not yet described in sufficient detail to make an evaluation possible.

Hoffman (1995) provides detailed data for helium measurements using palladium obtained from a variety of studies as well as from gas samples provided by Miles.

Discussion. Contamination is the only experimental reason for rejecting helium as a nuclear product. If present, this helium must be either in the initial palladium or result from an air leak.

The helium content of virgin palladium is found to be much too small to account for the helium found after several recent "cold fusion" experiments. Air leaks are expected to produce random amounts of helium with an upper limit equal to the concentration in air.⁷

The reported results do not show this random nature and are, on a few occasions, above the air-concentration value. Furthermore, absence of helium when a H_2O -based electrolyte is used demonstrates a low probability for air leaks during the study. Although better data are desired, a good case has been made relating helium and energy. Whether helium production is the only energy source is still not known. In addition the nature of the helium producing reaction is still unknown.

How can the proposed helium leave the metal so easily? Several explanations can be suggested, The "cold fusion" reaction occurs very near the surface. Consequently, the diffusion distance would be very small, possibly only

⁷The usual helium concentration in air is 6 ppm. A leak capable of introducing even a small fraction of this concentration would also add easily detectable amounts of other elements contained in air.

a few microns. Localized heating produced by the nuclear reaction could increase the diffusion rate. Finally, the diffusion rate of helium through the unique lattice structure in which the nuclear reaction is proposed to occur may be greater than through normal β -PdD. A combination of these possibilities could account for the loss of helium from the palladium.

Detection of α -particles, as described in the next section, adds additional evidence for helium producing reactions.

III.4. Charged Particle Emission

III.4.1 Background. Very energetic emissions of $^1\text{H}^+(\text{p})$, $^3\text{H}^+(\text{t})$, $^4\text{He}^{++}(\alpha)$ and $^3\text{He}^{++}$ are expected from a fusion reaction. Indeed, some of these particles have been detected using CR-39 plastic and silicon surface barrier (SSB) detectors. The results are listed in Table 10.

CR-39 plastic forms tracks within its structure where a charged particle passes. These tracks are revealed by a development technique and are visible under

TABLE 10
Charged Particle Emission

Investigation	Detection Method	Energy MeV	Particle	Environment
Aiello <i>et al.</i> (1990)	SSB	≈ 3	P	Pd heated and cooled in D_2 .
Cecil <i>et al.</i> (1990)	SSB	≈ 4.5	t, He or α	TiD warmed in vacuum.
Chambers <i>et al.</i> (1990)	SSB	3.5	t	Ti bombarded with 350–1000 eVD ⁺ . Emission occurred from backside.
Dong <i>et al.</i> (1991)	CR-39	many tracks	α ?	Pd reacted with D_2 (9 atm) followed by heating and cooling. H_2 produced no charged particles. Results sensitive to palladium source and pretreatment.
Iida <i>et al.</i> (1993)	SSD	3–5, 8	? + α	Pd or Ti implanted with 240 keV D ⁺ . Emission detected after beam turned off. Al_2O_3 layer required.
Jin <i>et al.</i> (1994)	CR-39	many tracks		During vacuum loss of D_2 from PdD_x . H_2 produced no emission.
	CR-39	many tracks		$\text{YBa}_2\text{O}_{7-x}$ reacted with D.

TABLE 10 (continued)
Charged particle emission

Investigation	Detection Method	Energy MeV	Particle	Environment
Karabut <i>et al.</i> (1992, 1995)	SSB CR-39	3.5 1-16 many tracks	<i>a</i>	Low-voltage discharge in D ₂ with Pd electrode. Emission detected after discharge was turned off.
Kamada (1994)	CR-39	1-2 0.6	<i>a</i> <i>p</i>	Aluminum implantation with H ⁺ or D ₂ ⁺ and exposed to 200 or 400 electrons.
Kasagi <i>et al.</i> (1993)	SSB	12.5-16.5	<i>p</i>	TiD _{>1,2} bombarded with 150 keV D ⁺ .
Mo <i>et al.</i> (1993)	SSB	5		Ti or Pd reacted with D ₂ and temperature cycled.
Taniguchi (1994)	SSB	4, 7, 9		Pd electrolyzed on one side in LiOD-D ₂ O.
Yamaguchi and Nishioka (1993)	SSB	3 4.5-6	<i>p</i> ³ He or <i>a</i>	Pd coated with MnO _x on one side, reacted with D ₂ , and coated with Au on the other side. Emission produced during explosive release of D ₂ in vacuum

a microscope. Rough information about type and energy of the particle can be obtained from the track size.

A SSB produces a current pulse proportional to the particle energy. Barriers placed between the source and the SSB, with proper calibration, can be used to identify the particle type. Generally this method has a low background so that high sensitivity can be achieved.

In addition to these conventional methods and detected particles, Matsumoto (1991a), using nuclear emulsions, has seen evidence for several unusual particles. These observations and the proposed model need to be further explored.

Discussion. Charged particle emission has been detected at levels many orders of magnitude above background. In addition, charged particles have been detected when three different methods have been used to initiate the effect within several chemical environments. A complex effect involving, perhaps, several nuclear reactions is revealed by the variety of particle types and energy. Although the exact nature of the reactions is uncertain, their occurrence is not.

Nuclear reactions produced under "cold fusion" conditions are thought to couple their energy directly into the general lattice rather than into individual

particles. If this process occurs, why are charged particles seen at all? Two mechanisms can be proposed.

The fusion reaction occurs at a surface where the resulting energy release can not couple effectively. The resulting high-energy particles are emitted and detected. Particles created at a depth sufficient to couple their energy will not be detected because they will not retain sufficient energy to escape. Consequently, the energy spectrum should have a cut off at low-energies. In this model, the magnitude of the detected signal is unrelated to the total nuclear reaction rate because most reaction products are proposed to remain in the lattice.

The other possibility involves fractofusion. Crack generation and the resulting charge separation might generate a brief "hot" fusion reaction within a crack. The resulting ions could escape and be detected if the crack formed sufficiently close to the outer surface. Such a reaction should also produce 2.5 MeV neutrons and a fewer number of 14 MeV neutrons resulting from the energetic triton. Only 2.5 MeV neutrons have been detected.

III.5. Gamma Emission from Radioactive Isotopes

Radioactivity found in previously nonradioactive material is clear proof for a nuclear reaction. Of the various radioactive emissions, gamma radiation is one of the easier to detect and to separate from background radiation. In addition, the half-life of a gamma source and the emitted energy can be used to identify the radioactive isotope. Consequently, claims for gamma emission produced by "cold fusion" studies provide significant proof for anomalous nuclear reactions.

Bush and Eagleton (1994a) detected gamma emission from a nickel cathode after it had been electrolyzed in a $\text{Rb}_2\text{CO}_3\text{-H}_2\text{O}$ electrolyte for about 2 months. An average half-life of 3.8 days was measured over a 30 day period. Evidence for the presence of several emitting isotopes with different half-lives is given. Unfortunately, the gamma-ray energy was not determined. A semi-log plot of the total count rate is shown in Figure 12 as a function of time.

Karabut *et al.* (1992) subjected palladium sheet to bombardment by 100-500 eV deuterium ions. Gamma radiation was detected using a germanium detector and X-ray film. Gamma radiation of ~ 200 keV was emitted in beams while the apparatus was operating. Gamma energies corresponding to various isotopes of rhodium and X-rays were emitted from the palladium target after the study. Normal rhodium was present in the palladium at <7 ppm, a concentration too small to be involved directly in the apparent nuclear activation process. Autoradiography of the target showed irregular regions of radioactivity that may have been tritium. Further details can be found in papers by Savvatimova and Karabut (1995) and Karabut *et al.* (1995)

III.6. Nonradioactive Isotope Production. Increased concentration of a nonradioactive element is a difficult proof for a nuclear reaction because cont-

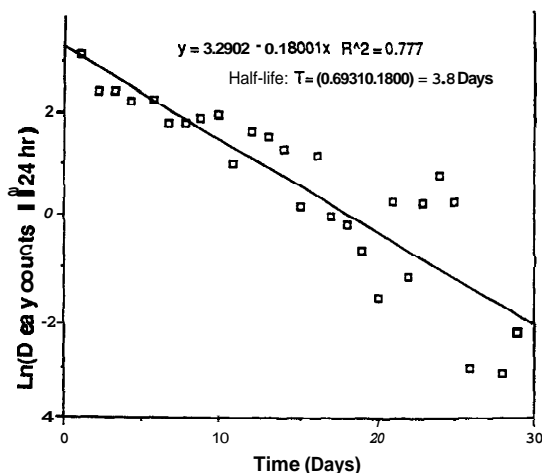


Fig. 12. Semi-log plot of gamma count rate vs time for all emitting species within the sample. This radioactivity was produced in a $\text{Rb}_2\text{CO}_3\text{-H}_2\text{O}$ electrolytic cell.

amination is always a real possibility. On the other hand, a change in isotopic ratio is a much better indicator. Such a change is independent of contamination and the ratio can be determined very accurately by mass spectrometry if the amount detected is sufficiently above background levels.

III.6.1. Calcium, Strontium, Iron and Other Elements. Bush (1992) proposed that energy generation in $\text{H}_2\text{O-Ni}$ cells is caused by nuclear transmutation reactions. To support this idea, Bush and Eagleton (1993), as well as No-toya and Enyo (1993), presented evidence for increased calcium concentration in cells using $\text{K}_2\text{CO}_3\text{-H}_2\text{O}$ as the electrolyte. The reported amounts are very near background levels, hence easy to reject.

To eliminate the contamination problem, Bush and Eagleton (1994a) electrolyzed $\text{Rb}_2\text{CO}_3\text{-H}_2\text{O}$ and looked for strontium, a much less abundant element compared to calcium. After removing all rubidium from the sample, the $^{86}\text{Sr}/^{88}\text{Sr}$ isotopic ratio was determined using a mass spectrometer. The normal ratio of 0.12 was found to have changed to 2.6. Because the normal $^{85}\text{Rb}/^{87}\text{Rb}$ ratio is also 2.6, the change in the strontium ratio is proposed to result from proton addition to each of the two rubidium isotopes.

Karabut *et al.* (1992), as described above, bombarded palladium with deuterium ions and observed an increase in the concentration of many elements by 10 to 10^4 times, as well as changes in isotopic ratio of some elements. For example, the zirconium content increased from <0.05 ppm to 1200 ppm and the $^{90}\text{Zr}/^{91}\text{Zr}$ ratio changed by a factor of twenty. These changes were only produced in material located very near the bombarded surface. Attempts at replication are underway at several laboratories.

Singh *et al.* (1994) and Sundaresan and Bockris (1994) claim the production

of iron by sparking very pure graphite electrodes in ultra-pure water. A prosaic explanation can be proposed wherein undetectable levels of iron in the bulk material are concentrated at the electrode tip. The authors have tried to eliminate this possibility by using very pure materials. In addition, this explanation is made more complicated because the process does not occur when oxygen dissolved in the water is replaced by nitrogen. No nuclear evidence has been reported and no plausible nuclear reaction has been suggested.

III.6.2. Gold. Gold production from base elements was the dream of ancient Alchemists and a claim certain to raise the emotional temperature of modern scientists. Into this maelstrom has stepped Champion (1994) with a book describing just how this transformation might be accomplished. A variety of methods including thermal combustion, electrolysis, and sparking are described and these are claimed to produce both normal and radioactive isotopes by various nuclear processes. A theory is also proposed. Unfortunately, the controversial nature of his claim has prevented an objective analysis or proper sharing of available information.

III.6.3. Biological. Of the various claims for nuclear transmutation, the biological method is one of the more difficult for modern science to accept. Living systems, both plant and animal, are said to combine certain nuclei in order to make elements that are missing in their diet. Even more amazing, the transmuted product is always the nonradioactive isotope of the required element. Louis Kervran (1970) focused attention on this phenomenon in a series of articles and books beginning in 1960. Since then, many scientists, including compostors and farmers, have shared personal experiences supporting the claims. Recent studies of molds and yeasts by Komaki (1993) have produced additional quantitative evidence.

Rejection of these claims is based on the proposed use of faulty analytical methods. If this explanation is correct, measurements using standard techniques must be in error by as much as a factor of 10 in some cases, with the error always giving a result supporting the claims.

IV. Present Status of the Field

Seven international conferences have been held and several professional societies* have included sessions about cold fusion in recent years. The literature on the subject has grown to over 1300 publications, many peer reviewed. Clearly a lot more is known than many people realize. A magazine called "Infinite Energy" and several newsletters are being published. Regular informa-

*This list includes the American Physical Society, The American Nuclear Society, The American Chemical Society, The American Society of Mechanical Engineers and The Electrochemical Society.

tion can be obtained from "Fusion Facts".⁹ Many informative articles appear in 21st Century Science & Technology. Occasionally, the print and TV media have shown interest, sometimes with objectivity, sometimes not.

A few governments and a growing number of companies are funding work in the field. Support in Japan has been recently raised to at least \$100M/yr and to involve university, industrial, and government laboratories. The work is supported at high government levels. (Matsui, 1993; Asami, 1995) Clearly, Japan is intent on understanding and eventually using this new phenomenon. Support is growing in Italy, India, China, France, and, in spite of serious problems, in Russia.

On the other hand, the U.S. government has shown little interest even though several government laboratories have obtained evidence for the effect. The U.S. patent office has not issued patents using the term "cold fusion" even though over 250 applications have been received. Ironically, at least two patents (Patterson, 1994) describing one aspect of the phenomenon have been granted when this term was not used. A few companies have supported work, the most notable being the Electric Power Research Institute (EPRI)¹⁰ and recently ENECO¹¹.

Several companies¹² have been formed in the U.S. to manufacture useful items and to develop unique ideas. Small, isolated efforts are underway in a few industrial, government, and university laboratories as well as in a few private homes. The total effort in the U.S. probably does not exceed \$1 M/yr. Because of general skepticism, the peer review system has effectively prevented publication in major journals and inhibited support for proposed funding.

⁹These publications can be obtained as follows:

- "Cold Fusion", 70 Route 202 North, Peterborough, NH, 03458-9872, (800) 677-8838.
- The Cold Fusion Newsletter, P. O. Box 60642, Palo Alto, CA 94306. (415) 493-4515.
- Cold Fusion Times, P. O. Box 81135, Welles Hills, MA 02181. (617) 239-8383.
- Infinite Energy, P.O. Box 2816, Concord, NM 03302 (603) 228-4516.
- Fusion Facts, P. O. Box 58639, Salt Lake City, UT, 84158, (800) 583-6232.
- 21st Century, P. O. Box 16285, Washington, D.C. 20041. (703) 771-1245

¹⁰Electric Power Research Institute, Nuclear Power Division, 3412 Hillview Ave., P.O. Box 10412, Palo Alto, CA 94303. (Thomas Passell, project manager)

¹¹ENECO, University of Utah Research Park, 391-B Chipeta Way, Salt Lake City, UT 84108. (Fred Jaeger, president)

- American Cold Fusion Engineering and Supply, P. O. Box 191394, Sacramento, CA 95819.
- Clean Energy Technology (CETI), 14332 Montfort, Suite 6302, Dallas, TX 75240.
- Clustron Sciences Corp., 1917 Upper Lake Drive, Reston, VA, 22091.
- Cold Fusion Research Advocates, 2060 Peachtree Industrial Court, Suite 313, Chamblee, GA 30341
- E-Quest Sciences, P.O. Box 60642, Palo Alto, CA, 94036.
- HydroCatalysis Power Corp., Greenfield Corporate Center, 1860 Charter Lane, Suite 208, Lancaster, PA 17601.
- Hydro Dynamics, 8 Redmond Court, Rome, GA 30165.
- Nova Resources Group, 1553 Platte Street, Suit 301, Denver, CO, 80202.
- The Cold Fusion Company, 7000 Boulevard East, Guttenberg, NJ, 07093.
- XCaliber Distribution Company, 8128 Mercury Point #B, San Diego, CA, 92111.

V. Conclusion

Production of various nuclear products (radioactive and stable), radiation of various types and energy, and heat energy from a nonchemical source all indicate the occurrence of novel nuclear reactions. These unexpected conclusions propose a whole new field of science, a field that studies chemically assisted nuclear reactions.

Neutrons and tritium, two expected fusion products, are produced, but at levels much too small to account for the anomalous energy. However, the levels are much too large to be consistent with conventional nuclear theory. In addition, the 14 MeV neutrons expected from deuteron-energetic tritium fusion are absent.

Production of energy and power levels too large for any conventional explanation have been demonstrated. The only nuclear product roughly consistent with energy production involving deuterium is helium, another possible fusion product. However, the expected gamma- and X-radiations are absent. Regardless of whether the observed helium accounts for all of the heat or is a side reaction, its presence is in conflict with theory.

Large amounts of anomalous energy have resulted from proposed nuclear reactions involving normal hydrogen when used as a gas or as H_2O in electrolytic cells. These observations suggest an even greater challenge to conventional theory.

Because of these threats to conventional theory, acceptance of a nuclear source has been slow in coming. Totally ignored is the more modest question, "Can the observed energy, from whatever source, be made useful"? It is surprising that this one simple question does not generate more interest.

Nevertheless, these strange and unexpected observations need an explanation. Skeptics base their rejection on unrecognized error or misinterpreted normal phenomenon. This approach is having an increasingly harder time making a credible case, as will be addressed later in the discussion. Another approach involves asking a simple question, "What novel processes are implied by the observations?" Two major requirements were realized from the start. First, for any of the nuclear reactions to occur at all, the coulomb barrier must be overcome by a more efficient process than is presently accepted. Second, the energy from the resulting nuclear reaction must be largely coupled to many atoms rather than to individual nuclear products. A third requirement recently appreciated is that the nature of the chemical environment determines which nuclear reaction will occur. These requirements flow directly from the evidence, however difficult they may be to believe. If these conclusions are rejected, other, equally novel suggestions must be substituted.

Numerous theories have been proposed, many of which do not require complete rejection of conventional theory. Because "cold fusion" operates in a crystal environment, the new explanations need not conflict with our present understanding of nuclear interactions based on a plasma or high-energy environments. Because different environments are involved, only an extension of

present theory is required. After all, Einstein did not require Newton to be abandoned.

Available data can be summarized into several tentative conclusions. Because these conclusions are supported only by the kind of evidence normally available to a new field, they can not be considered proven. Nevertheless, more than enough evidence is available to justify further study and to guide theoretical understanding. These conclusion are:

1. Excess energy is generated without producing significant chemical products. Several studies claim power densities near $3 \text{ kW/cm}^3 \text{ Pd}$, total energies in excess of 200 MJ and power amplification over 1000 times. Evidence for local melting of palladium has been observed:
Therefore, energy can be produced at rates and in amounts well above the result of any conceivable chemical reaction or plausible error. This experience indicates that commercial application is highly probable.
2. Energy can be created by several methods, in at least nine different chemical environments:
Therefore, the effect is has a general nature and is not unique to palladium or to deuterium.
3. Significant helium (^4He) is found after anomalous heat is produced in environments containing deuterium:
Therefore, at least one heat-producing nuclear reaction is probably a complex and unusual form of d-d fusion. Evidence for other types of nuclear reaction has been obtained.
4. Neutrons and tritium are occasionally produced but in amounts too small to account for measurable energy:
Therefore, an explanation for excess energy must involve different products. In addition, commercial applications will not be handicapped by these hazardous products.
5. Largely absent are gamma-rays, X-rays, and radiation produced when energetic neutrons or tritons pass through matter:
Therefore, the released nuclear energy is at least partially coupled by some strange process to many atoms rather than to individual reaction products.
6. Emission of high-energy charged-particles and 2.5 MeV neutrons show that regions exist in which the nuclear reaction energy is not coupled to individual particles:
Therefore, nuclear products can leave the surface without coupling their energy to the atomic lattice. The coupling reaction is not a prerequisite to the LANR.

7. The neutron, tritium, helium, charged-particle, gamma-ray, and high-Z elements are produced under different conditions largely independent of each other:
Therefore, a variety of different environments can produce different nuclear reactions.
8. Presence of light water in the heavy-water stops energy production without producing ^3He :
Therefore, heat is not produced by d-p fusion in this environment.
9. Heat generation using D_2O is independent of whether ^6Li or ^7Li is used and is sometimes independent of whether lithium is present at all:
Therefore, lithium probably is not involved in the nuclear reaction involving D_2O .
10. Application of RF frequencies at certain values, but especially near 82 MHz, are said to enhance heat production in Pd- D_2O cells. Application of micropulses of very high current are also very successful:
Therefore, application of energy enhances the effect.
11. Tritium is produced in the electrolyte and helium is produced in the gas during electrolysis of palladium:
Therefore, both nuclear processes occur within the surface region of the metal, not within the bulk.

Arguments that the field has not followed normal scientific processes are true but not relevant. **Any** discovery having such unusual implications for theory and technology will naturally be treated in unique ways. Popular interest will cause the press to publish the results prematurely and uninformed peer reviewers will reject many manuscripts regardless of merit. Confusion and error will abound as the phenomenon is gradually understood. This process has taken longer than usual because of the great difficulty in reproducing the initial claims and the subsequent institutionalization of skeptical attitudes. Although large energy production rates are still difficult to achieve, many aspects of the effect can be easily reproduced when known procedures are used. A change in attitude only waits for skeptics to become aware of this new knowledge.

Recent studies have gone to great lengths to eliminate error, both real and imagined. If error is the correct explanation, it must be sufficiently large to account for power excesses well above 1 watt in calorimeters designed to measure much smaller values. Such error, if real, has significant implications for all fields of normal science. If recent calorimetry in this field is wrong, how can we trust thermodynamic values obtained in the past using similar techniques?

The observed effect has increased in magnitude as understanding has in-

creased. In addition, after a lull, the number of people involved in the work is increasing, especially in Japan. This experience is at odds with the concept (Langmuir, 1989) of "Pathological Science", a description frequently used by some people to reject the claims (Morrison, 1990; Huizenga, 1993).

Unfortunately, rejection of the phenomenon has not been based solely on logic and scientific arguments, methods even skeptics demand be applied to their own work. Instead, arbitrary restraints have been placed on publication and funding. As a result, many legitimate questions remain unanswered and technological application has been delayed. Although many good reasons can be visualized to reject some claims, a wise student of science always keeps an open mind because great changes happen regularly, are always at odds with current theory, and are never foreseen. Unfortunately, the level of arrogance demonstrated toward "cold fusion" shows how far some scientists have fallen from the accepted standards of their profession. We all need a reminder once in a while that our personal view of nature is not always correct. "Cold fusion" is a recent wakeup call. Others are just over the horizon.

Active skeptics need to consider another consequence of their intervention in normal scientific evolution. Any observer of modern times can recite a depressing list of problems brought on by our present energy sources and policies. These problems are now growing faster than any proposed solution and will become disastrous in the foreseeable future. Already, a few populations have suffered a taste of this prediction. If pollution-free, carbon dioxide-free and radioactive-free energy can be achieved using the "cold fusion" effect, or any other novel phenomena, should not such possibilities receive enthusiastic study regardless of conventional attitudes? The present course is too dangerous to risk missing a solution just because intellectual bias and economic advantage are being threatened.

Acknowledgments

I wish to apologize to the authors of the many excellent papers that could not be included in this review. We all are groping for the information that will give some sense to this amazing phenomenon. Each contribution helps. Unfortunately, not all studies make an important contribution to changing the skeptical attitudes that now stand in the way of further understanding.

Fred Jaeger (ENECO), by his support, helped make this effort possible. Charles Becker (TCC) has generously made copies of this paper available to the field before publication.

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