REVIEW OF EXPERIMENTAL OBSERVATIONS ABOUT THE COLD FUSION EFFECT

COLD FUSION

KEYWORDS: *cold fusion, review, experimental*

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The experimental literature describing the cold fusion phenomenon is reviewed. The number and variety of careful experimental measurements of heat, tritium, neutron, and helium production strongly support the occurrence of nuclear reactions in a metal lattice near room temperature as proposed by Pons and Fleischmann and independently by Jones.

I. INTRODUCTION

Since the first proposals that nuclear fusion reactions might occur in a metal deuteride,[1,2] a considerable accumulation of supporting and nonsupporting information, both quantitative as well as anecdotal, has become available in refereed journals, reports, and conference proceedings. Earlier reviews were prepared by Bockris et al.,[3] Hurtak,[4] Rabinowitz,[5] Tsarev,[5] Schultze et al.,[5] and Srinivasan.[6] Books have been published by Peat,[7] Mallove,[8] and Close.[9] Dehn[10] and Huggins[11] provided a discussion of the electrochemistry of cold fusion cells and hydrogen/metal interaction, respectively. A summary of theoretical approaches was given by Miley et al.[12] and by Preparata.[12] A selective annotated bibliography was prepared by Braun.[13] Tsarev and Worledge[14] prepared overviews of the two conferences held in Utah, one in March 1990 and the other in October 1990.

Because the field is growing so rapidly, much work is still unavailable except in reports, preprints, and word of mouth.[15,a] Such information is not used in this review to a significant extent because it cannot be examined by those who may wish to make their own analysis of this controversial subject. This review includes only those published papers I have been able to personally review. My intent is to reduce duplication of effort in the field by bringing together most of the major published studies, to demonstrate that important patterns have been observed that cannot be explained adequately by chance or error, and to help focus future work in more productive directions while giving optimism for success. I, for one, am amazed to find so many excellent papers, especially in view of the very negative reporting by the press.[9,16–21] I apologize to those authors who do not find their work cited herein. Such omissions are due only to limitations on my part.

At the present time, understanding of the field is divided between those who do not believe there is suf-

[a]A great deal of up-to-date information, insight, and opinion can be obtained from *Fusion Facts*, published by the Fusion Information Center, P.O. Box 58639, Salt Lake City, Utah, 84158.

Copies of the conference proceedings cited herein can be obtained as follows:

Proc. 1st Annual Conf. Cold Fusion
National Cold Fusion Institute
390 Wakara Way
Salt Lake City, Utah 84108 ($55.00)

Anomalous Nuclear Effects in Deuterium/Solid Systems
Prof. S. E. Jones
Brigham Young University
Physics Department
Provo, Utah 84602 ($68.00 to S. & J. Scientific Company)

Cold Fusion Symp., 8th World Hydrogen Energy Conf.
University of Hawaii
Hawaii Natural Energy Institute
2450 Dole Street, Holmes Hall 246
Honolulu, Hawaii 96822 ($15.00).

ficient information to require a re-evaluation of conventional beliefs about atomic fusion and those who believe that the data, although incomplete, strongly suggest the possibility of unusual nuclear reactions in a metal lattice. An approach that would do justice to both viewpoints is difficult to contain in one review. Therefore, I adopt the more probable viewpoint by assuming that a real phenomenon has been discovered and try to show patterns of behavior that would give some understanding of its characteristics. In a few cases, I attempt to show how the proposed errors have been reduced or eliminated and how various conventional explanations do not apply. Hopefully, those who do not believe that any one study is sufficiently complete to change their minds might be impressed by the consistent patterns of behavior among various studies and the considerable background information that is now available. This review is not intended as a substitute for reading the original papers.

I suggest that the lack of reproducibility or easy explanation can no longer be used to dismiss positive results as misinterpretation of normal behavior, however tempting this might be. Nevertheless, this lack of reproducibility does justify some frustration, and it does slow progress. In any other field, this frustration would stimulate a redoubling of efforts to discover the implications of the negative observations. One would think this would be especially true in a field having such importance to nuclear physics and a potential for clean, unlimited energy. This positive approach is being taken in Japan, India, and the USSR in contrast to most other countries.[b]

A growing literature giving explanations for cold fusion is available but is not discussed in this review. Although some theories offer important insight, it is still too early to make a proper assessment. It is worth noting that conventional theories have been extended in an attempt to explain at least low-level neutron production.[12,24–101] Only a few of these attempts conclude that cold fusion is possible, but many more do not reach this conclusion. General failure of the conventional approach has inspired many new models.[95,102–122] The issue is no longer the limitations perceived by some[9,16–18,123–135] to exist in early work nor the perceived conflict with conventional theories of fusion. The problem now is to properly explain a growing body of increasingly sophisticated data being generated by competent scientists in many countries.

Many "negative" studies have been reported for heat,[126,130,136–151] tritium,[139,140,149,152–157] protons (Refs. 153, 156, and 158–167), ^{3}He (Refs. 153, 168, and 169), electromagnetic radiation (Refs. 140, 142, 145, 148, 151, 153, 164, and 170–183), and neutrons (Refs. 130, 139–142, 145, 147–149, 151–156, 164, 170–173, and 178–211). This negative work can give valuable information about conditions that prohibit the cold fusion effect and an understanding that can help bound the conditions in which the effect operates. It does not demonstrate that the effect is not real. In many cases, no nuclear products were observed because conditions were present that are now known to be unsuitable for cold fusion to occur. In other cases, it is not clear why the conditions failed to produce positive results. Many people who report positive observations also have many occasions when negative results are found. Clearly, this incredible phenomenon is not going to be easy to understand. However, it is unfortunate that so many excellent detection techniques and talented scientists have been assembled in one place during several of the better experiments only to have nothing to measure.

An equally large number of positive observations for heat,[1,155,212–234] tritium,[1,3,219,223,232,233,235–252] and neutron production[2,217,219,224,229,235,236,239,243,246–282] have been published. Recently, two unconventional approaches have given excess heat: a fused salt cell[222] and a cell using ion discharge.[224] In addition, a new particle (the iton) is claimed to have been detected.[283] Of course, these positive results are not all equally credible. Less well studied during confirmed fusion is the emission of electromagnetic radiation (from visible to gamma rays).[217,233,255,256,264,272] Emission of energetic nucleons from the deuteride surface[168,283–287] and ^{4}He formation[115,169,220,228] have been examined. Excess heat, tritium, and neutrons have not only been produced but have also been detected using a variety of techniques. This demonstrates that the positive observations are not caused by a particular method of production or detection.

Success depends on giving the deuterium atoms some additional energy, required to achieve high deuterium-to-metal ratios and to overcome the fusion barrier by an as yet unknown process. A variety of methods have been used to impart this energy. Examples are listed in the order of increased energy.

1. Direct Gas Reaction: In these experiments (Refs. 147, 168, 170, 172, 180, 188, 193, 200, 207, 210, 235, 244, 249, 252, 259, 264, 266, 269, 272, 274, 276, and 280), titanium or palladium is placed in D_2 gas at pressures from <1 bar to megabars with the usual pressure between 40 and 60 bar. Energy is proposed to be imparted to the deuterium atoms by phase changes or microcracking initiated by temperature or pressure cycling. Neutron emission has been detected, especially when titanium is used. No reaction is seen when all of the titanium is reacted with deuterium, after multiple temperature cycles, or if normal hydrogen is used

[b]Two percent of the hot fusion budget is devoted to cold fusion in Japan according to J. Bockris.[3] According to P. K. Iyengar,[22] chairman of the Indian Atomic Energy Commission, broadly based work is continuing in India. According to D. Worledge,[23] 15 million rubles will be allocated to 20 laboratories over the next 4 years for cold fusion research in the USSR.

instead of deuterium. Tritium has been detected in the gas and metal after neutrons were produced on a few occasions.

2. Conventional Wet Electrolytic Approach: Typically, a palladium or titanium cathode and a nickel or platinum anode are placed in an electrolyte consisting of a mixture of D_2O containing LiOD, NaOD, or Li_2SO_4 alone or combined with other salts. The container is designed to prevent atmospheric contamination but with a vent to allow escape of generated gas. This arrangement is called an "open" cell and is drawn to show the simplest configuration in Fig. 1. When a catalyst is placed in the assembly to recombine the generated gases, the cell can be completely sealed, and a "closed" cell is created. Direct current of various magnitudes is passed between the electrodes so that D_2 is formed at the cathode and O_2 is produced at the anode. Because of the applied voltage, very high effective pressures can be generated within the metal,[c] and the ions are given a modest energy. This very chemically active deuterium reacts with the palladium or titanium cathode to form a hydride having a high but variable stoichiometry that depends on a complex set of circumstances. The stoichiometry that is achieved in localized regions appears to play a role in making the effect occur. Many variations on this basic design have been reported. Excess heat, neutrons, protons, and tritium have been detected using this method, although not all at the same time. A sudden change in charging current seems to trigger the cold fusion effect. However, initiation also has been observed without this abrupt change.

3. Electric Current in Gas-Containing Cells: In these experiments,[224,235,240,288] a voltage sufficient to produce gas discharge is applied to electrodes in low-pressure deuterium gas. This process gives the deuterium ions more energy than they can achieve in an electrolytic cell. Both palladium and titanium have been used as the cathode. Unexpectedly large amounts of neutrons, tritium, and excess heat have been detected but not all in the same experiment. One study has achieved tritium and neutron production by passing pulsed current through alternating layers of palladium and silicon disks[240] in high-pressure D_2 gas. This is a combination of gas discharge and direct gas reaction.

4. Ion Bombardment and Implantation: In these experiments,[165–167,178,187,199,236,266,267,284,289,290] ions and molecules are accelerated to various energies and impacted on various target materials. This technique not only implants deuterium into the metal lattice to give a very high deuterium-to-metal ratio, but it can also produce ion energies that approach those used in hot fusion. Neutrons, tritons, and protons have been detected that, in some cases, were in greater quantity than expected. Implantation of hydrogen in metals has been reviewed by Myers et al.[291]

Typically, all of the conditions listed above produce bursts of nuclear products sometimes superimposed on a relatively steady lower production rate. This behavior implies a nonequilibrium state (Refs. 33, 256, 267, and 292–294) and/or two independent processes. Apparently, suitable conditions can be imposed by changing the environment or are produced as a natural consequence of electrolytic action. Note that electrolysis may appear steady in a macro sense, but the conditions are nonequilibrium when viewed on a micro level. Bubble formation produces chaotic regions in which the electrolytic reaction is turned off and on, thereby rapidly changing the chemical environment of the surface. Erratic formation of bubbles, microcracks, and dislocations make the interior of the metal very complex. These factors, by themselves, would make the phenomenon very difficult to reproduce. Indeed, most normal physical and chemical processes involving palladium are frequently difficult to reproduce.

Apparently, the creation of some types of special condition are essential if the nuclear effect is to occur at all. Reproduction of these special conditions is the primary problem in making a general study of the nuclear processes possible. Although many workers who have continued to study the cold fusion effect have been rewarded by increased reproducibility within their own laboratories, a universal recipe does not seem to

[c]The magnitude of the pressure can be calculated using the Nernst equation. However, the very nonideal nature of the solution must be taken into account to obtain the correct pressure.

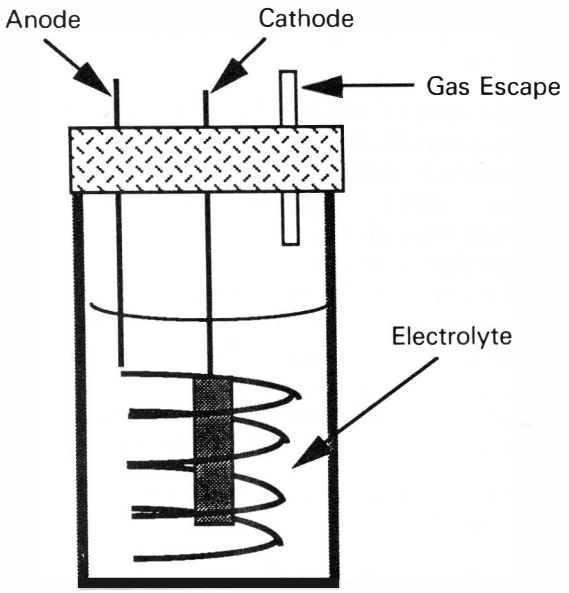

Fig. 1. A simple electrolytic cell.

exist. Just too many unknown and, therefore, uncontrollable variables are present. However, there are quite a number of conditions that are now known not to produce positive results. Some of these insights are examined.

An important special condition that must exist for any of the nuclear reactions to be initiated is the presence of high, local concentrations of deuterium, as previously suggested.[1,295] This view is widely accepted. Such high concentrations have been proposed to be associated with regions of stress,[264,296] to be enhanced by surface or bulk impurities, and to be associated with phase changes.[118] On the other hand, the deuterium concentration can be reduced by excessive microcracking or by normal hydrogen in the metal.[297] Generally, these high concentrations are expected to occur at or near the surface, especially during electrolytic charging or ion bombardment. These considerations as well as many observations suggest that tritium production occurs mainly at the surface for both titanium and palladium. Heat and neutron production are not so easily located in this respect. Nevertheless, many workers still propose that the heat reaction occurs within the entire volume of the electrode. Consequently, they report heat production as energy per cubic centimetre or energy per mole. This gives the impression of much greater energy release than has actually occurred from the small cathode volume used in the cell. This approach also underestimates energy density within the few active regions.

From the first, the deuterium-deuterium (D-D) fusion reaction was thought to be the most likely source of nuclear products, although other possibilities have been proposed. This reaction has two branches that have been measured at high energies, yielding an almost equal probability. These branches are

$$D + D = {}^3He\ (0.82\ MeV) + n\ (2.45\ MeV)$$

and

$$D + D = H\ (3.02\ MeV) + t\ (1.01\ MeV)\ .$$

A third branch,

$$D + D = {}^4He + \gamma\ (23.5\ MeV)\ ,$$

is possible, but it has a very low probability in plasma reactions. Considerable confusion and disbelief has been created by the lack of neutrons, consistent with detected tritium and heat. Data now clearly show the following:

1. No experiment has detected sufficient neutrons or tritium to account for the reported heat.[298] Although neither tritium nor neutrons are usually detected during heat production, there is evidence that ^4He is produced.[169,222,228]

2. While there is a clear relationship between neutron and tritium production, occasionally neutrons are produced without any tritium being found.

In order for these and other apparently conflicting observations to be explained, even to a limited extent, an important hypothesis is proposed. At least three nuclear reactions are proposed to occur within a metal deuteride lattice. One reaction produces the major source of heat, the second produces mainly tritium with a few neutrons giving a neutron-to-^3H ($n/^3H$) ratio near 10^{-9}, and the third appears to produce mainly neutrons. Which of these operates at any time depends on the special conditions that exist at that time. Of course, more than one of these reactions could occur at the same time but at different locations in the metal. Additional reactions have been suggested, but the evidence is less compelling. Detailed experimental justification for this suggestion and a model that combines the various mechanisms and nuclear reactions is developed in this review. The experimental studies for heat, tritium, neutron, gamma-ray and ^4He production are discussed.

II. EXCESS HEAT PRODUCTION

Four major logic levels are associated with understanding the source of excess heat. The first level asks the question

1. Is the excess heat caused by errors in the measurement?

This possibility is discussed in Sec. II.A.

Should the answer be "no," the question at the next level is

2. What is the reaction that produces excess heat?

As the amount of observed excess energy increases beyond a certain level, the probability for a nuclear origin increases as well. At some level, there is no possibility of evoking a chemical source without major conflict with basic chemical experience. This experience shows that there is an upper limit to the energy that can be obtained from a chemical bond. Thus, there is an upper limit to the energy that can be obtained from the limited quantity of chemicals that exist in a cell. This assertion is discussed in Sec. II.B.

If the amount of heat is sufficiently large and nuclear products are found, the question becomes

3. What nuclear reaction produces the excess energy?

Conventional fusion theory predicts a trivial fusion rate at room temperature. Consequently, if a significant fusion rate does occur, it must be caused by an

unexpected phenomenon involving special conditions that exist in a periodic array of metal atoms. Several theories have addressed this aspect but are not discussed in this review.

The question at the next logic level is

4. What is the new phenomenon, how can it be initiated in the lattice, and what nuclear reactions are influenced by the phenomenon?

At this level of acceptance, we are dealing with an approach normally applied to a mature science. As yet, the cold fusion field has not reached this level in some people's minds.

Efforts to attribute the heat to a chemical source have taken three forms

1. The calorimeter has a positive bias because energy accounting has not been properly made.
2. Energy is accumulated in some chemical form during the initial charging and released later.
3. An unknown reaction releases the energy. The latter source is proposed to be either mechanical or chemical.

II.A. Errors in Calorimetric Measurements

One needs to appreciate that the technique of calorimetry is very highly developed, and has been used with increasing accuracy for >100 yr. While an individual may make a mistake or an apparatus may fail in some respect, these problems are not common within the field of expertise. Nevertheless, all measurements contain some error. Error analysis depends on the type and design of the calorimeter used. However, in all cases, the errors can be divided into two groups: (a) random errors that relate to the precision of the various individual physical measurements needed to arrive at the excess heat and (b) systematic errors that occur because some energy has been ignored in the calculation due to design defects or unknown chemical reactions. Both types of errors are normally revealed by studying cells containing H_2O as the electrolyte, using platinum as the cathode instead of palladium, or inactive cells containing both D_2O and palladium. If such cells show no excess heat above that which can be accounted for by considering all energy entering and leaving the cell, the calorimeter is generally considered to be accurate to the degree that input power equals measured power.

The most important systematic errors involve energy that leaves the cell. When gases escape, there is an uncertainty in the chemical energy carried away by the resulting hydrogen and oxygen because of possible partial recombination within the cell. However, all of the workers reporting excess heat are aware of this problem, and, when tested, recombination is found to be negligible at currents >30 mA/cm^2 (Ref. 299) and as long as the electrodes are kept below the fluid surface.[139,143,144] Dissolved hydrogen and oxygen can be recombined on the anode, but the rate is trivial.[300] Furthermore, many workers now place a recombiner within the cell so that no gas need leave, and all of the chemical energy remains in the cell. An additional factor is the transport of D_2O vapor out of the cell with the gases.[139,212] Heat associated with this loss is small when the cell temperature and current are low but become significant when both are large. This quantity needs to be included in the heat calculations when the highest accuracy is desired. Some LiOD + $D_2O(l)$ mixture is also carried away as an aerosol within the gas stream. This effect increases as the current is increased but is small under most conditions. Of course, none of these processes is important when a closed cell is used.

Energy deposited within a cell is in the form of an electric current and is calculated by multiplying the current passing through the cell by the voltage measured between the electrodes. This energy can be determined with very high precision provided both current and voltage are measured as a function of time. Once the cell is assembled and turned on, energy flow is monitored, and any subsequent energy entering the cell will be detected within limits determined by known errors. Although some workers have charged the palladium at low current without monitoring the energy during this time, most excess heat has been found after a complete accounting was made from the time the cell was first turned on.

Besides the electric current, chemical reactions and physical strain may add energy to the cell.

II.B. Chemical Sources of Excess Heat

Typical cells contain a very limited number of elements and amount of material. Therefore, the total possible excess mechanical or chemical energy contained in these materials or produced by interaction also must be equally limited. Only energy above the lowest possible energy states of the *initial* constituents of the cell is available to be added to energy that is generated within the cell. The only additional substance that is normally added is D_2O to replace that which is lost by electrolysis from an open, unsealed cell. Deuterium oxide is generally acknowledged as being in its lowest chemical state under these conditions. Furthermore, all of the construction materials are chemically inert to each other when allowed to remain in contact over a long time. Therefore, for a chemical reaction to occur, some form of energy must be supplied from the outside. In this case, this energy is supplied by the electric current.

Only three current-induced chemical reactions are known to have the potential to affect the energy balance to a significant extent. These are the formation of

D_2 and O_2 gases from the heavy water (see Sec. II.E.3), formation of PdD_x at the cathode with the release of O_2 gas, and formation of Pd-Li alloy at the cathode by reaction with lithium ions. Peroxide formation has been proposed but not detected.

The formation of β-PdD by a reaction between palladium metal and deuterium gas[34,301,302] and chemisorption on internal cracks[303] gives off heat. This source of heat is discussed in detail by Godshall et al.[141] An observed increase in cathode temperature during the initial reaction to form PdD and a decrease during removal of deuterium is consistent with expectations.[219,229] An initial cooling of the cell has also been reported[149,216,219] that is not caused by the Peltier effect.[148] However, as the palladium cathode becomes saturated with deuterium, this relatively small energy perturbation decreases, and the temperature of the cell returns to a baseline value.

Elemental palladium and lithium form an alloy with heat release. However, the reaction in a cell is between palladium and Li^+ ions in solution. This reaction requires energy that, again, is supplied by the flowing current. Consequently, a slight temperature reduction would result to the extent that such an alloy formed. This temperature reduction is not observed because the rate of formation is limited by the diffusion rate of lithium in palladium, a very small number.

In summary, any chemical reaction that requires additional Gibbs energy supplied by the flowing current to occur will appear as a loss of energy from the cell. Should such a normally unstable compound be formed but go unnoticed, a heat effect would occur when the cell current was subsequently decreased or stopped, thereby allowing the compound to decompose. Only one such heat effect has been reported,[213] but at a level much too small to suggest this effect could be the cause of significant excess heat. Thus, critiques that explain the excess heat as being due to the formation of hypothetical compounds are not consistent with observation.[128,304] An analysis of possible chemical reactions was developed soon after the first announcement of the cold fusion effect and should be consulted for more detail.[3,305]

The palladium can contain some strain energy that would be released during hydriding.[306] While the amount of this energy is difficult to quantify, it is expected to be small,[307] and it would be released and measured only during the initial hydriding process. Excess heat lasting weeks has been detected even when fully annealed, strain-free palladium was used. Should strain energy be introduced and subsequently released during hydriding, no excess heat would be seen because the energy would be part of the measured heat balance within the calorimeter. Consequently, the proposed behavior of strain energy, either initial or induced, is not consistent with observation.

Another approach can be taken to put the chemical-mechanical source of heat in perspective. The amount of excess energy reported can be compared to various chemical and physical processes. As much as 50 MJ/cm^3 of palladium[d] has been reported to be released during the life of a cell.[212] This amount of energy is sufficient to melt 641 cm^3 or 7690 g or 72 mol of palladium at 1825 K (Ref. 308), and its production would require 1700 g of hydrogen to be burned. If released during a short time, this energy would raise a typical cell (<1 kg of glass and heavy water) to >12 000 K. Of course, only a few cells have achieved this much excess energy production, and, fortunately, it occurred over many weeks. Nevertheless, these examples of common chemical and physical processes show how difficult it is to attribute this amount of excess energy to a nonnuclear process. The only other alternative is to argue that a large positive and variable bias exists in all calorimetry measurements giving positive results. This suggestion is not supported by any other behavior pattern in the measurements.

II.C. Examples of Experimental Results for Excess Heat Production

Table I compares the various reported heat measurements, both positive and negative, and lists the accuracy for the calorimeter when a value is reported. Each entry generally represents several examples of positive and/or negative results. The presence of excess heat was usually not claimed until the accuracy limit was exceeded. On average, the calorimeters that produced negative results have lower accuracy than those that gave evidence of excess heat. Nevertheless, they should have been sufficiently sensitive to see heat if it had been produced. The absence of heat is proposed to be caused by unfavorable conditions that existed in the palladium cathode. This aspect is discussed in Sec. II.E.2.

Although all of these results have potential importance, a few studies need to be examined in detail because they are unique. In general, the heat production rate reported in these studies is so large that dismissing the results as being caused by calorimeter errors is not reasonable. Furthermore, the heat was made under a variety of conditions so that if it is caused by a chemical effect, a variety of very energetic chemical reactions must be assumed. Such an assumption is very difficult to justify.

[d]This reported value assumes that energy production is proportional to the volume of the electrode. This assumption may not be correct. It is not clear from the paper just how much total energy was produced in this experiment. If the smallest reported electrode volume of 0.01 cm^3 is assumed, the total energy would be ~0.5 MJ. When this quantity is used, subsequent calculated values need to be reduced by a factor of 100. In spite of this uncertainty, chemical sources of energy are still very unlikely.

TABLE I

Summary of Calorimetry Studies

Reference	Cathode[a]	Treatment[b]	Type[c]	Open or Closed[d]	Blank[e]	Accuracy[f]
No Excess Heat Reported						
Albagli et al.[142]	1-mm wire	725°C, vacuum	Isothermal	Open	Yes	≈5%
Armstrong et al.[150]	Sheet	?	Flow	Open	Yes	<4%
Bosch et al.[151]		Melted	Heat loss	Open	No	5%
Chemla et al.[146]	1-mm wire	?	Heat loss	Open	Yes	3 to 5%
Fleming et al.[175]	0.5- to 3-mm, melt cast, hot pressed	Anodized, vacuum	Seebeck	Open, closed	Yes	2%
Godshall et al.[141]	Cast	900°C, vacuum	Vapor	Open	?	2%
Hayden et al.[136]	Investment bar	600°C, vacuum	Flow	Closed	Yes	0.3%
Iyengar et al.[235]	Tube	Sanded	Adiabatic	Open	Yes	?
Jow et al.[138]	1 and 0.5 mm	1140°C, vacuum	Seebeck	Open	Yes	2%
Keesing et al.[148]	1-mm wire	≈1400°C	Substitution	Open	No	1%
Kreysa et al.[130]	Sheet, 1-cm rod	?	Heat loss	Open	No	5%
Lewis et al.[140]	0.25- to 3.9-mm wire	Sanded, melted	Isothermal	Open	Yes	<6%
Longhurst et al.[145]	51-μm foil, 1-mm wire	?	Heat loss	Open	Yes	5%
McCracken et al.[147]	Sheet, rod, tube, titanium sponge	600°C, vacuum	Flow	Closed	Yes	1%
Miskelly et al.[126]	2.2- and 3.9-mm wire	?	Heat loss	Open	Yes	5%
Redey et al.[143]	6.3-mm wire	650°C air and 600°C vacuum	Heat loss	Open	No	0.3 W
Ritley et al.[157]	6-mm wire	Variety	Heat loss	Open, closed	Yes	0.4 W
Stilwell et al.[144]	1.4-mm wire	245°C	Heat loss	Open	Yes	5 to 10%
Wiesmann[139]	Rod, sheet	300°C, vacuum	Heat loss	Open	Yes	≈0.5 W
Williams et al.[149]	1- to 6-mm wire, bar, cast, ribbon	Variety	Heat loss, isothermal	Open, closed	Yes	5 to 10%
Excess Heat Reported						
Appleby et al.[214]	0.5- and 1-mm wire	None	Seebeck	Open	Yes	<1%
Arata and Zhang[229]	2-cm rod	?	Cathode temperature	Open	Yes	Not applicable
Droege and Droege[218]	2-mm wire	?	Isothermal	Closed	Yes	≈0.5%
Eagleton and Bush[309]	Investment bar	Aqua regia, 200°C, air	Heat loss	Closed	Yes	0.3 W
Gozzi et al.[219]	Powder	Sintered	Cathode temperature	Open	No	Not applicable
Guruswamy and Wadsworth[232]	Palladium, titanium, zirconium	600°C, argon	Heat loss	Open	?	?
Huang et al.[234]	Coin	Arc-melted	Flow	Open	No	0.05
Hutchinson et al.[215]	6.3 mm, 1.3 cm	900°C, vacuum and 200°C vacuum	Heat loss	Open	No	?
Kainthla et al.[220]	1- and 3-mm wire	Electro	Heat loss	Open, closed	No	3%
Karabut et al.[224]	Disk	?	Heat loss	Gas	Yes	?
Lewis and Sköld[230]	3-mm bar	900°C	Flow	Open	Yes	0.2 W
Liaw et al.[222]	Wire	Torch melted	Heat loss, fused salt	Open	Yes	?
McKubre et al.[213]	Rod	Melted, 800°C, vacuum	Flow	Closed	Yes	0.2 W
Miles et al.[231]	6.3-mm wire	?	Heat loss	Open	Yes	5%
Noninski and Noninski[225]	0.5-mm wire	?	Adiabatic	Open	No	0.1%
Oriani et al.[226]	1-mm wire	None	Seebeck	Open	Yes	0.3%

See footnotes at the end of the table.

(Continued)

TABLE I (Continued)

Reference	Cathode[a]	Treatment[b]	Type[c]	Open or Closed[d]	Blank[e]	Accuracy[f]
Excess Heat Reported (Continued)						
Pons and Fleischmann[1,212]	1, 2, 4, and 8 mm	None	Heat loss	Open	Yes	<1%
Santhanam et al.[227]	Titanium and palladium	?	Substitution	Open	No	?
Schreiber et al.[216]	Old crucible	Melted, hammered	Heat loss	Open, closed	Yes	<1%
Scott et al.[217]	5.6 and 2.8 mm	900°C, vacuum	Flow	Open, closed	Yes	1 to 3%
Szpak et al.[233]	Electrodeposited palladium	None	Heat loss	Open	Yes	?
Yang et al.[223]	6, 3.5, and 2.2 mm	600°C, argon	Heat loss	Open	?	?
Zahm et al.[155]	4-mm wire	?	Heat loss	Open	No	?

[a]All cathodes are palladium except when noted. A few examples of size are given even though cathodes of various length, mass, and area were frequently used.

[b]Lack of space limits the details that can be listed in this category. In many cases, the cathode was heated in vacuum at the indicated temperature. Other treatments might have proceeded this anneal. In some cases, other treatments might have been used instead of an anneal.

[c]A variety of calorimeter types have been pressed into service, each having its own sensitivity and absolute error. They are as follows:

1. Adiabatic: Energy is measured by noting the rate of temperature change. This generally occurs so rapidly that little energy is lost to the surroundings.

2. Heat loss: Energy production causes the temperature of the cell to increase until energy loss equals energy gain. The achieved temperature is used to determine the energy production rate. Several variations on this design have been used as well as various methods of calibration. A detailed analysis of this calorimeter type is given by Pons and Fleischmann.[212]

3. Isothermal: A source of known energy is applied to the cell, and this energy is adjusted so as to keep a constant temperature as other sources of energy change. A resistor is usually used to add this known energy. However, Droege and Droege[218] used a thermopile.

4. Vapor: The cell is kept in a Freon bath that is boiling at a known rate. Changes in the boil-off rate are used to determine the energy added by the cell.

5. Seebeck: Heat is allowed to exit the cell through a thermopile, and the generated voltage is used to determine heat flow.

6. Flow: Heat is carried away by flowing water. Energy change is determined by measuring the temperature difference between water entering and leaving the calorimeter. This quantity is used in combination with the flow rate and the heat capacity of water.

7. Substitution: A quantity of known energy is used to bring the cell to the same temperature that was achieved during electrolysis. The difference between the net energy supplied to the cell during electrolysis and the known energy is considered to be excess.

8. Cathode temperature: On a few occasions, excess heat was determined by measuring the temperature increase of the cathode. While being sensitive to heat production, this method cannot give a quantitative value.

[d]Calorimeters without internal recombination of the gases are considered to be open even though they may be isolated from the atmosphere. Closed cells recombined the D_2 and O_2, thereby allowing no gas to escape. One study, designated "gas," used ion discharge in D_2 gas.

[e]Some calorimeters were run using a platinum cathode or H_2O in the electrolyte. This gives a baseline for zero excess heat production and a measure of the accuracy. A "Yes" is noted if such blanks were studied and "No" if not. Very often, however, cells that were expected to produce excess heat did not. During this time, a blank baseline could be obtained in spite of not running a formal blank.

[f]Frequently, but not always, a value for the accuracy is noted in the paper. Generally, the sensitivity was less than this value. No excess heat was claimed by the authors unless the accuracy limit was exceeded by an arbitrary amount.

1. Williams et al.[149] (United Kingdom Atomic Energy Authority, Harwell, England): This is a very broad study using palladium and titanium from a variety of sources and several calorimeter designs. However, no evidence of excess heat, neutron, gamma-ray, ^3He, ^4He, or tritium production was reported. The calorimeters were sufficiently sensitive and the current range was sufficiently broad ($\leq$600 mA/cm^2) that the

excess heat should have been detected had fusion occurred. This negative result has produced considerable skepticism about the cold fusion effect.

2. McKubre et al.[213] (SRI International): A high-pressure cell (60 atm D_2) was electrolyzed under conditions that prevented oxygen formation. The palladium was vacuum melted, machined, etched with aqua regia, vacuum annealed at 800°C, and cooled in D_2. Excess power between 1.5 and 2 W with bursts was reported. In addition, autoradiography found radioactivity[e] in the cathode even though no evidence of tritium was found in the electrolyte or in D_2 removed from the electrode. No ^{3}He or ^{4}He was detected. However, detection sensitivity may not have been sufficient to see the amount of helium associated with the small total energy production. Surface analysis found no change in the normal isotopic ratio and no elements that might be associated with a fusion reaction. Loading near a deuterium-to-palladium ratio (D/Pd) of 1, based on resistivity change, was claimed, but not all electrodes so loaded produced heat. Deuterium loss produced heat in one case. A deuterium gradient is suggested to be important.

3. Appleby et al.[214] (Texas A&M University): A very sensitive microcalorimeter was used to study small samples. Normal LiOD as well as material enriched in either ^{6}Li (98.67%) or ^{7}Li (99.8%) was used in the electrolyte without producing a significant difference in excess heat production rate. However, when the LiOD was replaced by NaOD, energy production decreased to zero over ~10 h. Subsequent replacement of the NaOD by LiOD caused excess heat to return. When the current was interrupted, excess heat production did not stop immediately but decreased rapidly at first, then more slowly over several hours.

4. Santhanam et al.[227] (Tata Institute, India): Excess heat is claimed using 1 *M* NaCl as the electrolyte and palladium or titanium as cathodes. Palladium gave the larger production rate. This rather incompletely described work is the only claim for excess heat using sodium in the electrolyte.

5. Bush and Eagleton[221] (California State Polytechnic University): An investment bar of palladium (Englehard Industries) was used. By carefully studying excess energy production as a function of charging current in several cells, a fine structure was found in the relationship. This structure is explained by the authors using a resonance theory. Kainthla et al.[220] (Texas A&M University) measured heat production over the same current range with similar detail and reported no such structure.

6. Liaw et al.[222] (University of Hawaii): This is the first study using a fused salt of KCl + LiCl in which LiD is dissolved. Excess heat was obtained between 400 and 460°C using palladium or titanium as the active electrode (anode). Only palladium that had been flame melted, which gave a porous surface, produced heat. Palladium gave a power production rate equal to 1512% excess at 692 mA/cm^2 and 460°C, a net gain of 25.4 W from 0.498 g of palladium. Excess ^{4}He was detected in the electrode but not enough to account for the heat. Titanium also produced excess heat but at a much lower rate. While lithium is present in the solution, it reacts with the aluminum cathode rather than with the anode. Apparently lithium does not need to be present with the deuterium for excess energy to be produced.

7. Karabut et al.[224] ("Lutch," USSR): Heat and neutrons were produced by using electric discharge in D_2 gas with a palladium cathode. Although this work is not reported in detail, 120 to 150% excess heat over the electrical input is claimed. The effect did not occur when the palladium was oxidized and when its temperature exceeded 500 K. The maximum neutron flux was $\sim 10^7$ n/s, which, it is claimed, corresponds roughly to the heat production rate if a branching ratio ($n/^3$H) of 10^{-8} to 10^{-9} is assumed.

8. Bush et al.[228] (University of Texas and the Naval Weapons Center): Helium-4 was found in the effluent gas (100× detection limit) while excess heat (0.14 to 0.52 W) was being produced in Pd/LiOD-D_2O cells. The amount of helium was consistent with the amount of heat. No ^{4}He was found when heat was not produced. This work confirms that ^{4}He is the nuclear product of heat production, and it shows that the reaction occurs on the surface. In addition, dental X-ray film located on the outer surface of the cells showed the presence of radiation. Normal water containing cells showed neither ^{4}He nor radiation, although some unexplained excess heat was reported. No ^{3}He was detected.

9. Droege[218] (Environmental Optics Corporation): When D_2O was replaced by H_2O, the heat continued for ~35 h, then abruptly dropped to zero. Scott et al.[217] [Oak Ridge National Laboratory (ORNL)] found that after the electrolyte was replaced by one containing normal water, excess heat, neutron, and gamma-ray production took >100 h to disappear. Huang et al.[234,311] (University of Hawaii) also found that 20 to 40 h were needed to eliminate excess heat after adding normal water. Belzner et al.[216] (Stanford University) reported loss of heat when the electrolyte was exposed to the atmosphere. In this case, the effect

[e]Blanks showed no such effect. Miles and Miles[310] have calculated some possible radioactive species that might be present.

could have been caused by CO_2 as well as by water pickup.

10. Arata and Zhang[229] (Kinki University and Osaka University, Japan): The temperature of a large palladium cathode (2 × 5 cm) was measured while deuterium was caused to repeatedly enter and leave the metal by switching the cell current off and on. Production of heat during charging and cooling during discharging were clearly observed. In addition, large bursts of heat were seen occasionally as the palladium temperature rose and fell (70 to 110°C) while the current was constant. The magnitude of this energy is far higher than can be explained by the deuterium absorption reaction, in contrast to the conclusion reached by the authors.[f]

11. Lewis and Sköld[230] (Uppsala University, Sweden): A bar (3 × 3 × 55 mm) of palladium was electrolyzed, and it produced excess heat while neutron and tritium measurements were being made. In one cell, excess heat showed bursts to 155%, and there were occasional neutron bursts associated with turning the cell off and on as well as just before excess power production ceased. Onset of power production seem to be associated with D_2O additions. No excess tritium was found in the electrolyte. Another cell gave bursts of excess heat to 39%, but neutron bursts were seen only after heat production had largely ceased.

II.D. Relationship Between Heat Production and Cell Current

When the steady component of heat production as watts per square centimetre is compared to the total cell current as milliamperes per square centimetre, a broad relationship is found,[g] as shown in Fig. 2. As first suggested by Pons and Fleischmann,[212] there is a marked increase in excess power as the current density is increased at low current density. When measurements based on a variety of cathode volumes and areas are compared, there is a suggestion that an upper limit to heat production exists at each current and that this limit approaches a constant value as current is increased. When plotted on a linear scale in contrast to the log scale shown in Fig. 2, the upper limit for an aqueous cell is described by the equation,

$$W\ (\mathrm{W/cm^2}) = 3.6I\ (\mathrm{A/cm^2})$$

to at least 0.7 A/cm^2. The solid line in the figure shows values obtained from this equation. There is an indication in the data that the process may saturate at higher currents and the large scatter indicates that current density is not the only important variable.[h] Typically, large bursts lasting several minutes superimpose on the steady heat production. Fleischmann and Pons state that tritium is produced during these episodes, but the details are still lacking and confirmation by other studies is mixed. Some bursts appear to produce tritium and some do not. At much higher temperatures, in a fused salt cell, Liaw et al.[222] have produced a much larger steady power with a similar sensitivity to current density and a similar tendency for burst formation.

It is hard to support an argument that all of these measurements, based on many different calorimeter designs, suffer from errors that can conspire to produce this relationship. Nevertheless, there are a number of factors that need to be considered when interpreting this behavior. The following partial list also gives an example of the difficulty in sorting out variables so that reproducibility can be achieved. As the current is increased,

1. Bubble coverage will increase, thereby shielding a greater average fraction of the surface from the current and producing greater local fluctuation in deuterium content as bubbles are made and released.

2. The voltage across the surface layer will increase.

3. The temperature of the cathode will increase.

4. The concentration of deuterium in the surface region of the cathode will increase.

5. The deposition rate of impurities will increase.[312]

The order of importance that should be assigned to these variables is not clear at the present time. However, a comparison between the aqueous cells at 25 to 50°C and the fused salt cell at 400 to 460°C strongly suggests that temperature is a major variable.

[f]The authors[229] conclude that the measured temperature increase of the cathode was due to a reaction with deuterium. This cannot be correct for the following reasons: The palladium was found to increase from 70 to 112°C over 1.5 min. If no energy were lost to the electrolyte, this temperature change would require 460 cal, based on the sample weight and the heat capacity of palladium. At the maximum cell current of 500 mA, 4.7×10^{-4} mol of deuterium would have been available to react with the palladium during the 1.5-min temperature increase. This would have generated ~4 cal if all had reacted. Thus, the energy generated is at least 100 times greater than the energy available from the hydriding reaction.

[g]Unfortunately, not all the positive results could be compared because certain details are lacking in the papers.

[h]The large scatter at low current densities may be partly due to temperature errors caused by poor mixing because of the small amount of evolving gas.[142] This is not a problem at high current, where bubble generation produces good mixing.

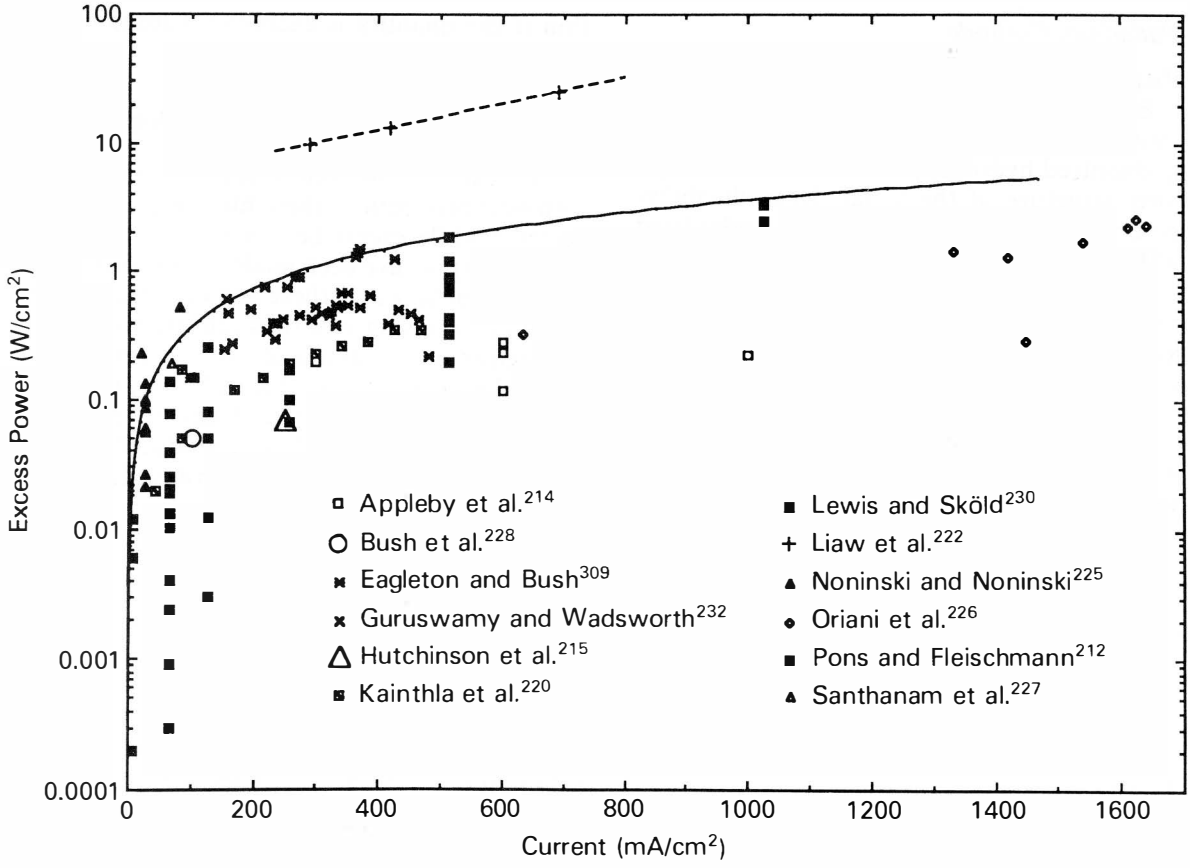

Fig. 2. Effect of total current density on excess power per square centimetre. All values are from D_2O-containing cells except those for Liaw et al.[222]

II.E. Factors Affecting Heat Production

Although there are clearly many important variables that have not yet been revealed, a few can be suggested based on both negative and positive observations.

II.E.1. Electrolyte

Electrolytes containing LiOD, LiOH, LiOD + Li_2SO_4, Li_2SO_4, LiOD + NaCN, or NaCl all have given excess heat on occasion. However, when LiOD was used at very high concentration in glass containers, excess heat was not observed, perhaps because glass components deposited on the cathode surface.[143] Nevertheless, glass or stainless steel cells have been used successfully at the usual 0.1 *M* concentration.

The effect of enriched lithium has been studied to determine whether lithium-deuterium fusion was occurring. Stilwell et al.[144] found no excess heat when normal lithium was used. On the other hand, Appleby et al.[214] produced excess heat, and the amount was insensitive to whether ^6Li, ^7Li, or normal lithium was used. When the lithium-containing electrolyte was replaced by one containing sodium, the heat effect stopped.[214] Nevertheless, heat has been produced in a fused salt cell, in which lithium does not enter the palladium, and heat has been reported[227] using an electrolyte containing NaCl. In addition, tritium has been produced on many occasions using a sodium-containing electrolyte.[235] Apparently, lithium is not essential to the production of tritium and perhaps not to the production of heat as well.

Any impurity in the electrolyte such as normal water, impurities released by chemical reactions with cell components or added with the lithium, CO_2 picked up from the air,[218] or impurities[i] present in the D_2O may affect the reaction or introduce errors in the heat measurement. The presence of copper or solder in contact with the electrolyte results in impurity deposition on the cathode.[238] Impurities in the platinum anode are slowly leached out and deposited along with the platinum. All of these factors affect reproducibility.

[i]Solids at 16 ppm were detected in a bottle of D_2O supplied by Aldrich Chemical Company and 9 ppm in a bottle supplied by MSD Isotopes.[313]

II.E.2. Palladium Cathode

Purification by vacuum annealing is a common practice. Excess heat has been obtained from both vacuum-annealed as well as "as-received" metal. While removing dissolved hydrogen, annealing also changes the physical structure of the metal. Reproducibility cannot be expected until the structure is standardized to that which allows the effect to occur. On the other hand, heating palladium in air removes carbon from the near-surface region, thereby removing one of the components that may help the cold fusion effect in an aqueous cell.[238] Heating and melting the metal with a propane torch seemed to have no detrimental effect when the metal was used in a fused salt cell.[222,j] Cleaning palladium with acids containing chlorine may not be advisable because this element is a strong poison that inhibits reaction with hydrogen. Commercial palladium contains a variety of impurities. Some of these (rhodium and silver) migrate to and concentrate at the surface during electrolysis.[314] Until the effect of these impurities is known, only the purest palladium should be used.

II.E.3. Correction for Electrochemical Energy Loss

An open electrolytic cell loses energy when the D_2 and O_2 gases leave. The amount of this energy can be subtracted from that entering the cell in various ways. The most common is to multiply the thermoneutral potential[k] by the cell current and subtract the resulting energy term from the electrical energy flowing into the cell. Minor variations in the thermoneutral potential have been used in the various studies (1.526 to 1.540 V). The recommended value is 1.527 V, −70.46 kcal/mol, or −294.6 kJ/mol (Ref. 315). To the extent that a value higher than the recommendation is used, the reported heat will overestimate the actual excess energy, especially at higher cell currents. This quantity is accurate as long as only D_2O is being electrolyzed. In practice, some H_2O is present in the heavy water, and this is electrolyzed preferentially. Therefore, the actual neutral potential will be slightly smaller than the mentioned value, depending on the amount of normal water present. This error also will cause an overreporting of the excess heat. The normal water concentration in heavy water cannot be based solely on the amount claimed by the manufacturer because new bottles can differ from this claim, and normal water can be picked up during the experiment. Furthermore, hydrogen from normal water will enter the palladium preferentially[143,297,316] and reduce or stop excess heat production if the quantity is excessive. Closed cells do not suffer from this problem.

[j]It is not certain whether this treatment would add or remove carbon.

[k]The thermoneutral potential is the enthalpy for the formation of D_2O expressed in volts (1 faraday = 96 489 C).

II.F. Nuclear Products Associated with Heat Production

To learn whether neutrons or tritium are associated with heat production, these nuclear products must be detected while excess heat is being generated. Many measurements have been made in the absence of excess heat production and these are discussed in Sec. III. Attempts to detect neutrons and tritium during heat production have had mixed success. Tritium has been detected in cells while producing heat by Gozzi et al.,[219] Fleischmann and Pons,[1] and Bockris et al.[3] During the latter study, heat had been produced for ~10 days before bursts of tritium were observed. In no case is the detected tritium sufficient to account for the observed excess heat. On the other hand, Miles et al.,[231] Lewis and Sköld,[230] Zahm et al.,[155] Scott et al.,[217] and McKubre et al.[213] did not detect tritium in their cells after heat production even though it was sought.

Scott et al.[217] reported low-level neutron and gamma-ray emission from a cell making excess heat. Lewis and Sköld[230] reported neutron bursts both during and after heat production. On the other hand, Salamon et al.[164] did not detect neutrons or gamma rays from cells being studied by Pons and Fleischmann. It is not clear whether these cells were actually producing excess heat during the examination although, based on other work, this may not be a critical point. Zahm et al.[155] detected neither neutrons nor gamma rays while excess heat was being observed.

The only detected nuclear product that is clearly associated with heat production is ^4He. These studies gave the following general results:

1. Morrey et al.[169] (group effort): Various pieces of palladium supplied by Fleischmann and Pons, both used and unused, were analyzed for ^4He and ^3He. The work established that once helium enters the lattice, even by alpha-particle bombardment, it is retained. Surface helium can be removed by etching. Unfortunately, there was sufficient ^4He in the unused palladium that production in the used metal could not be established. No ^3He was detected.

2. Liaw et al.[222] (University of Hawaii): Electrodes used in a fused salt cell were analyzed for ^4He. One of four samples showed ^4He at 14σ above background. The other three samples were only slightly above background. The amount of ^4He detected was not sufficient to account for the observed excess heat.

3. Bush et al.[228] (University of Texas and the Naval Weapons Center): Sufficient ^4He was detected in the evolving gas to account for the observed excess heat within a factor of 10. Blank cells showed no ^4He. No ^3He was detected. Helium retained by the electrode was not determined.

III. TRITIUM, NEUTRON, AND RADIATION PRODUCTION

Attempts have been made to detect neutrons, tritium, gamma rays, protons, ^{3}He, and ^{4}He as likely nuclear products. Of these, neutron detection has been given the greatest effort although it is the more difficult measurement because of the generally low emission rate. In addition, shifts in the ^{6}Li/^{7}Li ratio and the palladium isotopic ratio have been sought.[314] Techniques such as particle track[153,168,287,317] and autoradiography[213,235] have been used to detect high-energy particles, but these techniques cannot be used for identification.

If tritium and neutrons are actually produced in a metal lattice, the existence of at least two nuclear reactions cannot be doubted. The only issues are (a) whether tritium is produced in the cell rather than entering from an outside source as contamination and (b) whether the neutrons actually are emitted from the fusion cell rather than from cosmic-ray showers, electrical noise, or other external sources. Each of these issues is addressed later. However, the detection by different laboratories of both neutrons and tritium at the same time to give an internally consistent ratio largely eliminates the possibility of chance or contamination as an explanation.

III.A. Neutron/Tritium Ratio

Most workers do not have facilities available for the routine detection of both tritium and neutrons. Consequently, only a few measurements of the relative production rates have been reported. Values for the $n/^3$H ratio and the cell conditions are listed in Table II. These data are plotted as the log (number of tritium atoms) versus log (number of neutrons) in Fig. 3. Clearly, the ratio is significantly less than unity, with a lower limit near 10^{-9}, and it has a range of values. Indeed, low-level neutron emission has been observed without the presence of tritium being detected even

TABLE II

Reported Tritium Production and $n/^3$H Ratio

Reference	$n/^3$H	Tritium (μCi)[a]	Cell Design
Wolf et al.[252,b]	10^{-7}	≈7	Palladium in LiOD
Claytor et al.[240]	2.7×10^{-9}	0.17	Palladium + silicon (SiO_2) in D_2
	$0.8(\pm 1) \times 10^{-9}$	0.32	Palladium + silicon (SiO_2) in D_2
	$2.4(\pm 4) \times 10^{-9}$	0.044	Palladium + silicon (SiO_2) in D_2
Iyengar et al.[235]			
1[c]	10^{-7}	7	Titanium (rod) in NaOD
2	10^{-8}	380	Pd-Ag (tube) in NaOD
3	10^{-9}	190	Pd-Ag (disk) in NaOD
4	8×10^{-9}	1.9	Palladium (tube) in LiOD
5	1.7×10^{-6}	0.03	Palladium (cube) in LiOD
6	1×10^{-6}	0.21	Palladium (pellet) in LiOD
7	9×10^{-4}	0.009[d]	Palladium (ring) in LiOD
8	3.2×10^{-4}	0.0009	Palladium (coil) in Li_2SO_4
9	7×10^{-7}	0.17	Palladium (button) in LiOD
Sona et al.[248]	2×10^{-6} to 10^{-7}	?	Palladium (sheet) in LiOD
Gozzi et al.[219,247]	3.4×10^{-6}	0.01	Palladium (rod) in LiOD
Packham et al.[237]		0.08 to 340	Palladium (wire) in LiOD + NaCN
Storms and Talcott[238]		0.01 to 0.06	Palladium (wire) in LiOD
Chêne and Brass[250]		0.0005	Palladium (wire) in LiOD
Sánchez et al.[256]		≈0.03	Titanium (sheet) in Li_2SO_4
Iyengar et al.[235] (p. 57)		56.3	Palladium (tube) in LiOD
Iyengar et al.[235] (p. 84)		0.007 to 0.03	Titanium in D_2 at 900°C
		0.07	Pd-Ag in D_2 at 600°C
Kaushik et al.[246]		≈30	Titanium in D_2 cycled
Chien and Huang[241]		≈40	Palladium in LiOD

[a] 1 μCi = 2.2×10^6 disintegration/min = 3.4×10^{-11} mol = 2.1×10^{13} atoms = 3.7×10^4 Bq.
[b] First report of $n/^3$H ratio but tritium value has since been repudiated.[318]
[c] Numbers for points shown in Fig. 3.
[d] This value, obtained from a table (p. 34), is inconsistent with 16.25 μCi given in the text[235] (p. 52).

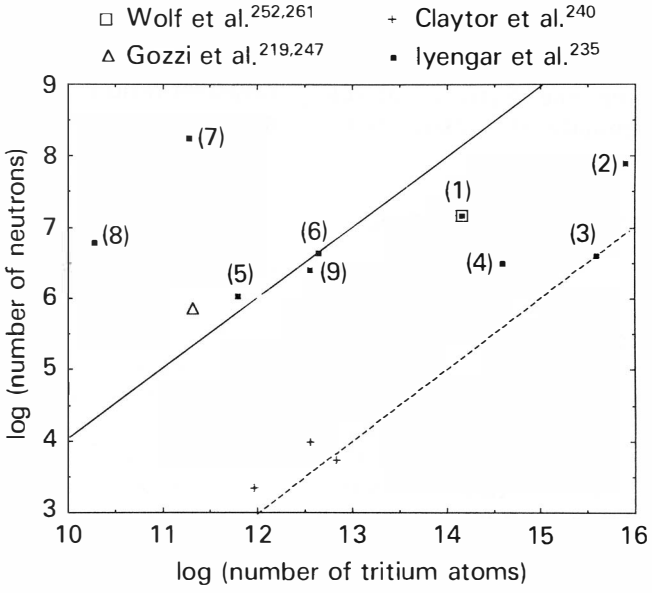

Fig. 3. Relationship between the number of tritium atoms and the number of neutrons produced in electrolytic cells. The "+" symbol describes results from a dry electrolytic cell. A dashed line shows a constant $n/^3H$ ratio of 10^{-9}, and the solid line shows a constant ratio of 10^{-6}. These lines do not imply a fit to the data points. Numbered points correspond to the numbering in Table II.

though it was sought.[217,230,259,274,278] This experience suggests two neutron-producing reactions. One reaction produces mainly neutrons and the other is associated with tritium production with a branching ratio near 10^{-9}. Conditions might conspire to produce a mixture of these reactions in most cells. Regardless of the interpretation, the $n/^3H$ ratio is clearly much less than unity, falling between 10^{-4} and 10^{-9} for a variety of cell conditions.[319] Although the $n/^3H$ ratio falls in a rather wide range, it seems likely to me at least that a much wider range would result if these two reactions were not coupled in some way.

III.B Tritium Production

Tritium has been detected after using at least six different methods of production. These include

1. wet D_2O electrolytic cells containing palladium
2. dry SiO_2 electrolytic cells containing palladium
3. thermal cycling of titanium in D_2
4. high-voltage discharge of D_2 with a titanium cathode
5. ion bombardment using D_2 on palladium or titanium
6. codeposition of palladium and deuterium onto nickel.

At least six different methods for tritium detection have been used. Each has been successful in demonstrating the presence of tritium on some occasion. These include

1. liquid scintillator
2. proportional counting of beta emission
3. autoradiography
4. beta-excited K_α X ray from titanium
5. mass spectrometer[l]
6. silicon surface-barrier particle detection of ejected triton.

III.B.1. Comparison of Reported Results

Table II lists the various reports of tritium production. The amount of tritium listed is a crude estimate in some cases because insufficient detail was provided.

The rate of tritium production cannot be determined because tritium is produced in a series of bursts during the active life of a cell and the result is accumulated in the electrolyte. Most measurements are made at time intervals that are long compared to the burst interval.

Tritium production appears to occur during neutron bursts. Several of the more extensive studies of tritium production are worth examining in more detail:

1. Iyengar et al.[235] [Bhabha Atomic Research Centre (BARC), India] report a very extensive study in which tritium and neutrons were produced by electrolytic cells of various designs containing various electrolytes using titanium, palladium or Pd-Ag alloy cathodes. Tritium was also produced by gas loading titanium and palladium under various conditions. Using autoradiographs as well as other techniques, this tritium was found to occupy isolated locations on the titanium surface but is more uniformly distributed in palladium. When made by gas loading, the resulting tritium was contained mostly in the metal rather than in the deuterium gas. Tritium was detected in old Ti-D samples (10 to 20 yr), using various techniques, at levels between 9 and 4000 μCi. However, the history of these samples is uncertain.

2. Storms and Talcott[238] [Los Alamos National Laboratory (LANL)] studied a variety of surface poisons and palladium alloys in an effort to find the best conditions for tritium production. Although only a small amount of tritium was made, it was done in cells that allowed for complete inventory of tritium entering and leaving the cell. All produced tritium was found only in the electrolyte.

[l]Kay et al.[320] have pointed out the pitfalls of this technique.

3. Claytor et al.[240] (LANL) produced tritium in D_2 gas (0.001 to 0.32 μCi) by applying a pulsed voltage (1200 to 2500 V, $\geq$150 μs), through alternating layers of palladium and silicon disks surrounded by the gas under pressure. In 8 cells out of 30, excess tritium $>3\sigma$ was observed. Recent cells have shown a reproducible production rate of 0.5 nCi/h with no production in control cells. Various techniques were used to verify that the tritium was being produced within the cell.

4. Packham et al.[237] (Texas A&M University) studied a variety of cells in an attempt to produce tritium. Levels between 0.08 and 340 μCi in the electrolyte were seen in 14 out of 28 open cells. One cell that was producing heat showed two bursts of tritium in the gas. Because this tritium was recombined and returned to the cell, the amount of tritium going only into the electrolyte is not known.

5. Kaushik et al.[246] (BARC, India) cycled the temperature of titanium chips in D_2 gas and found that only 4 out of >1000 chips examined showed the presence of tritium at the $\approx$30-μCi level.

6. Adzic et al.[243] (Case Western Reserve University) studied open and closed cells from which tritium production up to 49 times the starting concentration was observed. Very low charging currents were proposed to improve the probability of success.

7. Szpak et al.[233] (Naval Ocean Systems Center) electrodeposited palladium deuteride onto copper in an open cell. Heat, tritium (×10), and X rays were detected. These effects were not seen in control studies. An image was recorded on X-ray film within the cell that showed the presence of low-energy radiation.

8. Taniguchi et al.[286] (Osaka Radiation Research Institute, Japan) did not look for tritium but did detect what appeared to be the high-energy proton that accompanies tritium production. A very thin palladium cathode (10 to 18 μm) was electrolyzed using LiOD or LiCl in the electrolyte. A silicon barrier detector on the outside of the cell measured counts up to 100 times background for which the energy was determined. The energy spectrum was consistent with, although not identified as, 3-MeV protons with a lower energy component, as if they had been produced on the surface next to the electrolyte. If, as argued later, the reaction occurred on promontories, some of the protons would have had to pass through the electrolyte to reach the detector, thereby further reducing their energy.

III.B.2. Possible Errors in Claiming Tritium Production

Tritium can be present as contamination in cell materials or in the environment; various chemical reactions in the scintillator fluid can mimic the presence of tritium; and tritium can accumulate in the electrolyte as a consequence of electrolysis. Each of these possible errors is discussed starting with the problem of contamination.

Tritium can enter a cell with the construction materials and through the cell walls from room air. Both methods of contamination have been studied. Because tritium has a very low concentration in the normal environment, significant contamination from room air or from commercial materials has a very low probability. Indeed, workers at Texas A&M University[237] made a rather thorough analysis of common construction materials associated with their cells, including a number of palladium samples. They found no evidence for tritium contamination. A study of normal water-containing cells provides a method to detect tritium contamination from all sources. Excess tritium has not been reported when normal water cells are studied.[m]

A study of a cell operating in a high-tritium environment has been made.[322] As expected, tritium pickup is nearly linear with time starting at time zero. This is in contrast to the behavior of an active cold fusion cell that typically shows an initial delay followed by burst formation of tritium.[237,238,241,256] Figure 4

[m]However, neutron production has been reported from a light water cell.[321]

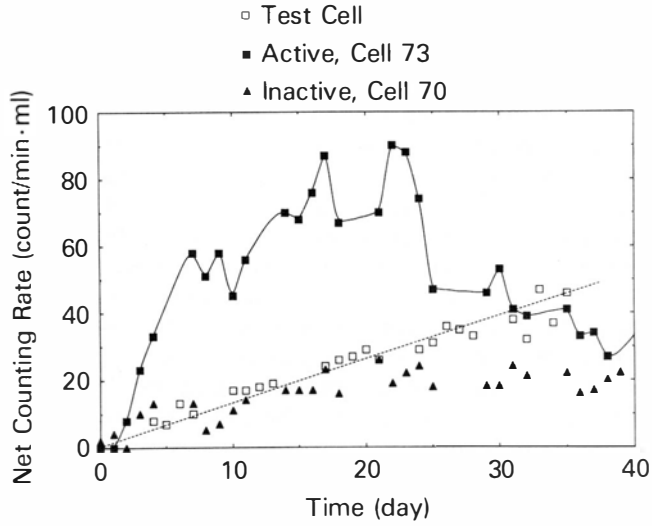

Fig. 4. Comparison between the net counting rate in an active cell, an inactive cell, and a cell stored in a high-tritium environment as a function of time from the onset of the respective studies. The net counting rate was obtained by subtracting the counting rate of the solution before the studies were started. Cells 70 and 73 were in series, and the increase in tritium content of cell 70 was due to enrichment that should affect cell 73 as well. The environment in which the test cell was placed contained $\approx$50 times more tritium than the environment of cells 70 and 73.

compares the concentration of tritium as a function of time in an active and an inactive cold fusion cell to an identical cell stored in a high-tritium environment. The patterns of tritium increase in the cells are completely different. While other cell designs are expected to have different pickup rates should environmental tritium be present, a smooth, nearly linear increase is expected for all designs as tritium in the room diffuses through the cell walls or enters when the cells are opened for sampling.

The tritium might be present in the palladium electrode, although the method of manufacture largely rules out this possibility.[323] Of the hydrogen isotopes, tritium has the least tendency to remain in palladium[324] when it is heated to temperatures used for processing, forming, or annealing. Nevertheless, Wolf[318] reports finding tritium in two pieces of unused palladium wire as well as in an annealed electrode after it was used in a normal water cold fusion cell.[n] This contrasts with a very complete study[325] using 45 samples of palladium from a variety of sources, including the source used by Wolf. This work did not find any evidence (±3 dpm/ml, 99% confidence = ±12% of background) for tritium contamination in the examined palladium but did find that certain conditions during the analytical procedure would cause an *apparent* presence of tritium. Even if tritium were present in the palladium cathode, it would quickly leave the metal[o] and appear in the evolving D_2 gas (>95%) during electrolysis.[297] This behavior is in sharp contrast to its delayed production[p] and subsequent retention in the electrolyte during most successful cold fusion experiments.

These considerations indicate that the tritium reported to have been made by cold fusion is very unlikely to have been caused by contamination of the cell or the palladium. Of course, it is impossible to "prove" that the observed excess tritium is not caused by contamination. However, when a number of laboratories make sufficient tritium by a variety of techniques using a variety of materials with a similar pattern of production, the argument for contamination as the source of tritium becomes increasingly difficult to justify.

Tritium can also accumulate within the electrolyte during electrolysis because the evolving D_2 and O_2 gases contain approximately one-half as much tritium as does the electrolyte.[q] Consequently, the tritium content of the electrolyte in an open cell will nearly double after extended electrolysis. Equations describing this tritium increase have been published (Refs. 3, 145, 149, 235, 238, 248, 326, and 327). Of course, closed cells containing a gas recombiner will not show this effect.

Chemiluminescence is caused by the presence of certain impurities in the scintillator fluid used to detect tritium. Some scintillator fluids are more sensitive to this effect than others. Because the effect generally decreases with time after the sample is mixed with the fluid, the effect can be separated from the true presence of tritium. Nevertheless, this is an area where care needs to be taken. However, this effect cannot be used to dismiss all claims for tritium production because most workers take the effect into account, and tritium has been detected using other techniques not subject to this problem. Further discussion about tritium measurement can be found in Ref. 328.

III.C. Neutron Production

Of the various aspects of the cold fusion effect, the production of neutrons has been studied the most thoroughly (see Table III). Neutrons have been produced after using at least eight different techniques. These include

1. thermal cycling of titanium, palladium, and $YBa_2Cu_3O_7$ in D_2
2. pulsed electrolysis
3. wet (D_2O) electrolytic cells containing palladium or titanium
4. dry (SiO_2 or Al_2O_3) electrolytic cells containing palladium
5. ion bombardment over a range of energies (50 eV to 60 keV)
6. sudden release of deuterium from palladium
7. chemical reactions in D_2O (Ref. 329)
8. physical breakup of deuterided $YBa_2Cu_3O_7$ (Ref. 267), LiD, and titanium with deuterium-containing substances (see Tsarev[5]).

Neutrons have been detected using at least seven techniques:

1. ^3He detector
2. BF_3 detector
3. detection of (n,γ) reactions in water
4. ^6Li glass combined with a scintillator
5. photon recoil scintillation spectrometer
6. fission track detector using film containing uranium
7. neutron activation of silver.

Each of these production and detection techniques has been successful in demonstrating the presence of neutrons on some occasion. When the energy of the

[n] No tritium was detected in the electrolyte of this cell.
[o] The loss is a first-order reaction with a half-life between 12 and 24 h, depending on the charging current and the condition of the palladium.[297]
[p] Wolf et al.[252] reported a delay of several weeks before tritium was observed in certain cells.
[q] This ratio applies to palladium cathodes in alkaline solutions.[238,326,327]

emitted neutrons is measured, values near 2.45 MeV (Refs. 2, 252, 257, 258, and 267) as well as peaks near 4 and 6 MeV (Ref. 258) are found. Neither neutron emission nor tritium was detected when Pd-D and Ti-D were bombarded with muons.[195,198,202] Most positive results are not consistent with radon decay.[135]

Errors in neutron measurement involve the detection of extra neutrons caused by cosmic-ray showers and electrical noise in the detector circuits. Most people who have studied the cold fusion effect are aware of both problems. However, when the counting rate is low, it is hard to be sure that neither of these problems is occurring[170] unless extra precautions are taken, including

1. keep the mass low around the detector to avoid cosmic-ray spallation events
2. compare the results to an identical but inert cell,
3. measure the background while the cold fusion cell is being studied
4. use a cosmic-ray–sensitive veto counter
5. make the measurements underground
6. use multiple counters
7. use anticoincidence noise rejection
8. use a sensitive detector (>10%) and determine the sensitivity using a standard source.

A number of studies have now given positive results during which all of these precautions were employed. High count rates and especially a count rate that is correlated with another measurement are easier to believe than a single, low-level experience. Such correlations have been observed.

Two regimes of neutron production are observed: (a) average rates <1 n/s over a relatively long time with burst behavior and (b) rates near 10^6 n/s for a short time. The large difference in these rates suggests either two separate nuclear reactions or an occasional high concentration of the special condition. A very high D/Pd ratio, by itself, does not seem to be sufficient to cause neutron production. Low-level neutron emission from thermal cycled titanium in pressurized D_2 has been duplicated by at least five independent, carefully done studies. Numerous studies showing how neutron emission is coupled to various parameters are discussed in detail as follows:

1. Jones et al.[2] (Brigham Young University) produced low-level neutron emission at 2.5 MeV by electrolyzing palladium in an electrolyte containing a complex mixture of metal salts. Bertin et al.[257] (University of Bologna, Italy) used titanium as the cathode instead of palladium and obtained essentially the same result.

2. De Ninno et al.[244] (Frascati Research Centre, Italy) cooled titanium chips in high-pressure D_2 to liquid nitrogen temperature. Neutron bursts were observed when the assembly was warmed to room temperature. This is the first report of this phenomenon. Menlove et al.[259] (LANL) repeated the procedure and observed that bursts of neutrons had a high probability of emission (3 to 12σ) near −30°C. No effect was found when normal hydrogen or palladium was used in place of titanium. This effect was also seen by Izumida et al.[274] (Hitachi, Japan), who found a >3σ increase in count rate between −53 and 0°C. Iyengar et al.[235] (BARC, India) also observed neutron emission (up to 200 n/s) when titanium was held in D_2 (10 atm) at 77 K and warmed during evacuation. Jorne[112] (University of Rochester) placed palladium in D_2 gas at 90 atm and −80°C. When warmed slowly, neutron and gamma-ray bursts occurred as the temperature changed between ≈500 and 600 K. No effect has been found in any of these studies when normal hydrogen was used. Jianyu et al.[282] (China Institute of Atomic Energy, People's Republic of China) thermal cycled titanium and palladium in pressurized deuterium gas using an underground laboratory. Seven out of 10 assemblies gave bursts of neutrons (3 to 75 times background) between −100°C and room temperature using titanium, but not when palladium was used.

3. Sona et al.[248] (CISE SpA, Italy) charged a palladium sheet from one side using a palladium anode in an electrolytic cell. The neutron signal started increasing when the current was started, and this steady increase lasted for 400 min and reached 4 times background. Over the next 400 min, the signal dropped and reached background where it remained for 41 h after the current had been stopped.

4. Granada et al.[263] (Centro Atomico Bariloche, Argentina) subjected an electrolytic cell with a palladium cathode to alternating current on-current off conditions (≈2-min cycle). Neutron production was highest at about the center of the current-on time and near the center of the current-off part of the cycle. Repeated cycles reduced the effect. Neutron production was ~0.3 n/s. Takahashi et al.[258] (Osaka University, Japan) also produced neutrons from palladium (0.017 n/s, 1.4 times background) using the pulsed-current technique (19-min cycle). They found the best LiOD concentration to be 0.6 *M*. Perfetti et al.[270] (Frascati Research Centre, Italy) found neutron emission from both palladium and titanium cathodes when a 1-h-on/1-h-off cycle was used. Mathews et al.[277] (Indira Gandhi Centre, India) found a current increase to cause increased neutron production in a cell containing a titanium cathode with palladium and nickel salts in a D_2O electrolyte. Arata and Zhang[229] (Kinki University and Osaka University, Japan) were able to produce bursts at average rates exceeding 10^8 n/s by cycling the current off and on. In this case, the cathode consisted of a 2-cm-diam palladium rod attached to a

TABLE III

Summary of Neutron Measurements

Reference	Metal[a]	Method[b]	Detector[c]	Efficiency[d] (%)	Background[e] (count/s)	Excess[f]
Negative Results						
Aberdam et al.[193]	Palladium, titanium	Electro	^{6}Li scintillator	2.3	2×10^{-5}	0
	Titanium	60 atm				0
	Ti_4Ni_2O	60 atm				0
Abriola et al.[181]	Palladium	Electro	Germanium, BF_3	?	?	<13
Albagli et al.[142]	Palladium	Electro	BF_3, NaI	0.02 to 0.03	0.7	0
Alber et al.[186]	Palladium	Electro	NE-213, BF_3	?	0.02	0
Aleksan et al.[192]	Palladium, titanium	Electro	^{6}Li scintillator	12.5	7×10^{-4}	<0.014
Baurichter et al.[182]	Palladium	Electro	Germanium, scintillator		?	<20
Barwick et al.[168]	Palladium, titanium	15 atm	CR-39	Not applicable	Not applicable	0
Behrisch et al.[167]	Titanium	Implantation	Surface barrier			0
Besenbacher et al.[199]	Palladium, titanium	Bombardment	Scintillator			0
Blagus et al.[201]	Palladium	Electro	^{6}Li scintillator	0.5	?	<0.2
Blencoe et al.[276]	Palladium	<38 atm	BF_3	6	0.16	0
	Titanium	<38 atm	BF_3		0.148	0.164?
Broer et al.[190]	Palladium	Electro	NaI	1.5	1	0
Brudanin et al.[210]	Palladium, titanium	Electro, gas	BF_3, germanium	0.3	$10^{-3,-5}$	0
Brudanin et al.[287]	Palladium	Electro	CR39, silicon			0
Bruschi et al.[207]	Titanium	<1 atm	NE-213	1.3	?	0
Butler et al.[185]	Palladium, titanium	Electro	^{3}He	9.2	0.0028	0
	?	Gas	^{3}He	9.2 to 15		0
Campbell and Perkins[204]	TiD	Infrared heat	NE-213	?	?	0
Davies et al.[198]	Palladium, titanium	Muon	NE-213			0
Deakin et al.[176]	Palladium	Electro	X ray	0.0039	0.0003	0
Dignan et al.[178]	Pd-Ir	Implantation	NaI	0.0004		0
Ehrlich et al.[194]	Palladium	Electro	Boron proportional counter	2.6	0.016	0
Faller et al.[154]	Palladium	Electro	Germanium		40 (gamma only)	0
Gottesfeld et al.[170]	Palladium	Electro	^{3}He, NE-213	16	0.005	0
	Titanium	53 atm				0
Guilinger et al.[152]	Palladium, titanium tritide	Electro	^{3}He	1.3 to 4	0.0017	0
Hajdas et al.[172]	Palladium	Electro	NE-213, BF_3,	0.006	0.0001	0
	$LaNi_5$	12 atm	NaI, NE-102			0
Henderson et al.[179]	Palladium, titanium	Electro	NE-213, NaI	?	0.1 to 0.7	0
Hill et al.[180]	Palladium	Electro	Germanium, BF_3	0.35	0.01	0
	Titanium	50 atm		0.28	0.01	0
Ilić et al.[153]	Palladium	Electro	^{3}He, CaF_2 CR39, germanium	0.14	?	0
Kamm et al.[200]	Titanium	12 to 62 atm	Boron proportional counter	0.123	0.029	0

Kashy et al.[197]	Palladium, titanium	Electro	NE-213 (2.5 MeV)	1	?	0
Kocsis et al.[211]	Palladium, titanium	Electro	^{3}He	6.3	0.002	0
Kuzmann et al.[208]	Fe-Zr	Electro	BF_3, NE-213	?	?	0
Lewis et al.[140]	Palladium	Electro	^{3}He, germanium	14 to 20	0.2	0
McCracken et al.[147]	Palladium	Electro	^{3}He, BF_3, NaI	1.6	0.0083	0
	Titanium	40 atm			0.0083	0
Myers et al.[166]	Palladium, titanium, zirconium	Implantation	Particle detector			0
Porter et al.[156]	Palladium	Electro	Germanium, ^{3}He, NE-213	1.3	0.058	0
Rehm et al.[158]	Palladium	Electro	Particle	28	0.001	0
Salamon et al.[164]	Palladium	Electro				0
Schirber et al.[188]	Palladium, titanium	<2.4 kbar	^{3}He	≈9.2	0.0028	0
	$Ti_{0.8}Pd_{0.2}$	50 atm			0.0028	0
	Zirconium, vanadium	50 atm			0.0028	0
Schrieder et al.[159]	Palladium	Electro	Particle detector			0
Silvera and Moshary[171]	Palladium	105 kbar	BF_3	0.09	0.0006	0
Southon et al.[184]	Titanium tritide	Electro	NE-213 (14 MeV)	2.5	0.0006	0
Vielstich et al.[209]	Palladium	Electro	NE-213 (2.5 MeV)	43	0.0012	0
Werle et al.[189]	Titanium	50 atm	^{3}He	10	0.8	0
Ziegler et al.[162]	Palladium	Electro	Particle detector	≈100	5×10^{-5}	0
Positive Results						
Bertin et al.[257]	Titanium	Electro	NE-213 (2.5 MeV)	4	0.055	0.3 times background
Celani et al.[255]	Palladium	Electro	^{3}He, NaI	1		4 to 16 times background
Claytor et al.[240]	Palladium	Electrodischarge	^{3}He	1.3	0.2	3 to 8σ
De Ninno et al.[244]	Titanium	50 atm	BF_3	0.005	0.00064	35 times background
Fleischmann and Pons[1]	Palladium	Electro	BF_3	0.024	?	3 times background
Govorov et al.[280]	Pd-Sm	1 atm	^{3}He	10.5	?	1.9 times background
	Pd-Ru					
Gozzi et al.[219]	Palladium	Electro	NaI(γ)	0.005	0.0008	180 times background
Granada et al.[263]	Palladium	Electro	^{3}He	17.5	0.001	6σ
Gu et al.[266]	Palladium	Bombardment	BF_3	?	0.033	10 times background
Harb et al.[275]	Palladium	Electro	^{6}Li scintillator	0.53	0.002	2 times background
Iyengar et al.[235]	Palladium, titanium	Electro, gas discharge	BF_3, ^{3}He		Variety	
Izumida et al.[274]	Titanium	20 to 50 atm	^{3}He	0.5	1.7×10^{-2}	>3σ
			BF_3	0.02	2.8×10^{-4}	>3σ
Jianyu et al.[282]	Titanium	Gas	^{3}He	20	0.005	<75 times background
Jorne[264]	Palladium	60 atm	NE-213	1	0.03	2 times background
Jones et al.[267]	Palladium	Electro	^{6}Li scintillator (2.2.5 MeV)		0.001	3.5 times background

See footnotes at the end of the table.

(Continued)

TABLE III (Continued)

Reference	Metal[a]	Method[b]	Detector[c]	Efficiency[d] (%)	Background[e] (count/s)	Excess[f]
Positive Results (Continued)						
Karabut et al.[224]	Palladium	Discharge	^{3}He	5	0.1 to 0.01	10^8 times background
Lewis et al.[230]	Palladium	Electro	^{3}He	8	0.2	2 to 10 times background
Li et al.[317]	Palladium	9 atm	CR-37, CaF_2	Not applicable	Not applicable	Tracks
Lin and Liu[273]	Palladium	Electro	^{3}He, BF_3, germanium	?		≈30 times background
Lipson et al.[278]	Titanium	D_2O (mill)	?		0.05	6 times background
Menlove et al.[259]	Titanium	1 to 40 atm	^{3}He	21 to 44	0.2 to 0.03	3 to 9σ
	Palladium, titanium, vanadium	Electro				3σ
Miljanić et al.[249]	Palladium	Electro	NE-213, LiI	0.04	0.0077	3 times background
	Titanium	25 atm	BF_3	0.01	0.00055	5 times background
Perfetti et al.[270]	Palladium, titanium	Electro	^{3}He	1	0.03	4 times background
Prelas et al.[268]	Palladium	Bombardment	BF_3, scintillator			2 to 4 times background
Rout et al.[236]	Titanium	Discharge	Silver activation		Not applicable	10^6 to 10^8
Sánchez et al.[256]	Titanium	Electro	BF_3, NaI	?	0.00056	$\leq 2 \times 10^4$
Sato et al.[265]	Palladium	Electro	^{3}He	7	0.025	3 times background
Scott et al.[217]	Palladium	Electro	NE-213, NaI	0.146	0.0009	3 times background
Seeliger et al.[271]	Palladium	Electro	NE-213, 2.5 MeV			5 times background
Sinha et al.[281]	Palladium, titanium	Electro	^{3}He, NaI	?	0.003	4 to 6 times background
Sona et al.[248]	Palladium	Electro	^{3}He, BF_3	0.02	0.0013	<3.3 times background
Shani et al.[272]	Palladium	3 kg/cm^2	NE-213			
Takahashi et al.[258]	Palladium	Electro	^{3}He, NE-213	0.17	0.019	≈70 times background
	Pd-Ag	Electro	^{3}He, NE-213		0.04	1.4 times background
Wolf et al.[252]	Titanium	67 atm	NE-213 (2.5 MeV)			0
	Palladium, titanium	Electro		5	0.013	3.8 times background
Yagi et al.[269]	Titanium	Gas	NE-213	0.13	0.003	3σ
	SiO_2	Gas	NE-213	0.13	0.003	3σ
Yamaguchi and Nishioka[254]	Palladium	Gas	BF_3			≈10^5 times background

[a]The elements, alloys, or compounds are listed.

[b]Material studied in an aqueous electrolysis cell is indicated by "Electro" and a dry electrolytic cell by "electrodischarge"; gas loading is generally designated by the pressure of the D_2 gas; and "discharge" and "bombardment" designate the use of high-voltage discharge in low-pressure D_2 and bombardment by high-energy ions, respectively. When in D_2 gas, the material was generally cycled with respect to pressure and/or temperature.

[c]Frequently, variations in the listed detectors were used. In addition to neutron detection, many workers made provisions to find gamma rays by using the listed detector. The ^{3}He and BF_3 detectors are sensitive only to near-thermal neutrons while the various scintillators such as NE-213 and ^{6}Li combined with NE-213 can be used to determine the energy of both neutrons and gamma rays within a wide energy range. Pulse-height measurement is used to distinguish between neutron and gamma emission. Detectors made from germanium or NaI are sensitive to gamma and X rays. CR39 is a track detector that is sensitive to high-energy particles. Frequently, two detectors are used to eliminate the possibility of spurious counts in one detector being interpreted incorrectly.

[d]The stated value for neutrons per count, expressed as percent, is listed. The value is only for the neutron detector. Occasionally, several configurations were studied, giving multiple values for the efficiency. The smaller the value, the more likely small emission rates would be missed.

[e]The background is given as counts per second only for neutron detection. In some cases, a variety of values were observed depending on the configuration. This value as well as the listed efficiency can only be used as a rough guide to the sensitivity of the detection system. The original paper needs to be consulted for more detail.

[f]Excess neutron detection rate is expressed as a multiple of background or sigma above background. Generally, a range of values was reported, depending on the particular experiment.

gold-plated bar of titanium.[r] On the other hand, neither Blagus et al.[201] (Ruder Boskovic Institute, Yugoslavia), using much shorter cycles (2 Hz, 2.2 mHz, and 0.56 mHz), nor Aiello et al.[205] (Universita di Catania, Italy), using loading and unloading in D_2 gas, produced neutrons.

5. Iyengar et al.[235] (BARC, India) reported a large variety of observations during which neutrons were detected from palladium, Pd-Ag, titanium, and Ni-Ti electrodes using LiOD or NaOD in the electrolyte. Steady production as well as large bursts were measured. Neutron production was correlated with gamma-ray and tritium production. Pulsing the current between 1 and 2 A during part of a cell history seemed to encourage production of nuclear products.

6. Gozzi et al.[219] (University of Rome, Italy) correlated a sudden increase in cathode (sintered palladium powder) temperature (>120°C) with a burst of neutrons (7.2×10^5). In this case, it is not known whether the heat rise caused conditions that produce neutrons or, on the other hand, a nuclear event produced neutrons and caused a temperature rise.

7. Yamaguchi and Nishioka[254] (NTT Basic Research Laboratory, Japan) coated a sheet of palladium (1 mm thick) on one side with Mn-O and on the other with gold. After being held for a day in 0.5 atm D_2 at room temperature, the sample was placed in vacuum. Within ~3 h, an explosive release of deuterium occurred that was associated with a burst of neutrons (1 to 2×10^6 n/s). Sudden heating caused alloying between the gold and palladium. Repeated cycles using the same sample produced similar neutron bursts but after a shorter time in vacuum. Neutron production and heat were not observed while using normal hydrogen. This heat cannot be caused simply by loss of the small amount of contained D_2 gas because this reaction is endothermic.

8. Bém et al.[330] (Institute of Nuclear Physics, Czechoslovakia) found that a thin layer of titanium (1.4 to 1.7 mg/cm^2 on molybdenum) that had been reacted with tritium showed low-level neutron production at 14 MeV when it was used as a cathode in an electrolytic cell. On the other hand, Guilinger et al.[152] [Sandia National Laboratories (SNL)] failed to find evidence of fusion using a thin film of titanium tritide on copper in an electrolytic cell, and Southon et al.[184] (McMaster University, Canada) detected no neutrons after a larger piece of titanium had been heated in T_2 gas and electrolyzed. However, there were other major differences between these studies besides the thickness of titanium that could account for the different results.

9. Sánchez et al.[256] (Universidad Autonoma Cantoblanco, Spain) electrolyzed titanium in a cell containing Li_2SO_4 in D_2O. Bursts of neutrons (up to 4×10^4 times background) were correlated with changes in cell current, gamma-ray detection (2 to 2.3 MeV), and tritium production. The neutron rate dropped in a linear manner after the cell current was turned off.

10. Lipson et al.[278] (Institute of Physical Chemistry, USSR) found that ball milling titanium with D_2O or deuterated polypropylene caused neutron emission (0.3 to 0.4 count/s) during the process, for a short time (8 to 10 min) afterward, and when the material was cooled in liquid nitrogen. Repeated cycles caused the effect to disappear.

11. Silvera and Moshary[171] (Harvard University) reported an important negative study done at very high pressures (105 kbar) using thin palladium (97 μm thick × 208-μm diameter) in D_2 gas. A D/Pd ratio of 1.34 ± 0.1 was claimed. This is much higher than any other reported value. However, the palladium had been pressure bonded to rhenium, an operation that would have severely disrupted the periodic array of atoms within the lattice. Detection sensitivity was not sufficient or stable enough to be able to conclude that energy was being produced although there was a slight indication of excess heat (<2.3 mW). No neutrons were observed above the 1.86 ± 0.3 count/h background, and no effort was made to detect tritium. Fractofusion[s] is not possible under these conditions, although heat and/or tritium production might have been possible but their production was inconclusive.

12. Shani et al.[272] (Ben Gurion University and Hebrew University, Israel) made studies of gas-loaded palladium and high-pressure D_2 that suggest that the emission of 2.5-MeV neutrons is enhanced by an external source of neutrons.

III.D Gamma-Ray and Other Emissions

Many workers have examined cells with gamma-ray detectors. However, only a few have detected gamma rays, and this was only while some other aspect of the cold fusion effect was occurring. Because normal water is usually present, some, if not all, of the gamma rays may result from neutron/proton interaction to give a 2.2-MeV signal. A calculated, idealized gamma spectrum produced by the 2.45-MeV neutron energy associated with D-D fusion has been published.[331]

1. Scott et al.[217] (ORNL) measured gamma rays while neutrons were being emitted and heat was being produced. Counts were seen between 2.61 and 3.14 MeV with no increase outside this range down to 2.12 MeV

[r]It is not clear which metal, the palladium or the titanium, caused the neutron burst.

[s]Fractofusion is fusion that is proposed to occur when cracks form in the metal hydride.

or above 5.2 MeV. Correlation between gamma-ray and neutron emission also has been reported by Celani et al.[255] (Frascati Research Centre, Italy) for gamma-ray energy between 100 and 500 keV, and >800 keV; Jorne[264] (University of Rochester) for gamma-ray energies >360 keV; and Sánchez et al.[256] (Universidad Autonoma Cantoblanco, Spain) for energies between 2 and 2.3 MeV. Iyengar et al.[235] (BARC, India) measured correlated neutron and gamma-ray emission (1.186 and >3 MeV) in a variety of cells. Bush et al.[228] (University of Texas and Naval Weapons Center) detected electromagnetic radiation while heat was being produced using X-ray film.

2. Matsumoto[283] (Hokkaido University, Japan) saw tracks in nuclear-sensitive film located on the outside of a cell containing a palladium cathode and an electrolyte of 3% NaCl in D_2O. The shape of the tracks was used to argue for a new particle called an "iton."

3. Jones et al.[332] (Brigham Young University) detected charged-particle emission from deuterium-loaded palladium foils that showed clear energy peaks. Because the inferred energy depends on an uncertain knowledge of the type of particle, the absolute energy is unknown.

III.E. Nuclear Products from Bombardment or Implantation

Nuclear products have been produced by bombarding palladium or titanium with deuterium. Energy has been added to the atoms by using high voltage discharge, ion acceleration, or acceleration of D_2O or D_2 clusters. These techniques add energy to the deuterium atoms before they contact atoms residing in the metal lattice, resulting in what is called "lukewarm fusion" by some workers. Although some fusion is expected to be produced by such high energies, a large quantity of products, a low $n/^3H$ ratio, and sustained emission after bombardment has ceased have been observed and are not expected. On the other hand, some experiments did not produce unexpected results.

III.E.1. High-Voltage Discharge

Karabut et al.[224] (Scientific Industrial Association, USSR) produced heat and neutrons using discharge in D_2 gas with a palladium cathode. The purity of the surface was found to be important. A similar study by Besenbacher et al.[199] (University of Aarhus, Denmark), during which the palladium was covered by 50 Å of copper, failed to produce neutrons. Palladium, after being silver-soldered in air to copper, also failed to produce results in a discharge cell [Ruzic et al.[288] (University of Illinois)]. Prelas et al.[268] (University of Missouri) formed a microwave plasma in D_2 (0.5 to 10 eV) that was caused to impact on palladium metal. Evidence of low-level neutron and gamma-ray emission (2 to 10 times background) was obtained while the plasma was operating. A gamma-ray peak centering on 8.1 MeV was observed during one experiment after a lengthy discharge.

Rout et al.[236] (BARC, India) subjected titanium to plasma discharge of D_2 in a Mather plasma focus device[333] that produced ion energies in the 10- to 100-keV range. This technique produced significant amounts of tritium (up to 392 μCi) and a very low $n/^3H$ ratio ($<10^{-5}$).

III.E.2. Ion Bombardment

Chambers et al.[285] (Naval Research Laboratory), after several previously reported negative attempts, detected the emission of particles that were consistent with the presence of high-energy tritons ($\leq$5 MeV) after bombarding titanium with 300- to 1000-eV deuterons. The magnitude of the emission and its continuation for up to 6 min after the beam had been turned off are not consistent with expectation. Behrisch et al.[167] (Max-Planck-Institut für Plasmaphysik, Federal Republic of Germany) found that bombardment of titanium by 4.5-keV D_3^+ failed to produce detected reaction products.

Cecil et al.[284] (Colorado School of Mines) bombarded thin films of palladium (1 μm) deposited onto molybdenum (3 μm) using 95-keV D^+. Evidence of emitted 3-MeV photons and 1-MeV tritons was obtained during the bombardment. After the bombardment was stopped, when the foil had been sufficiently implanted with deuterium, a current was passed through the foil. Particle emission, assumed to be protons, was detected near 3 and 5 MeV. Later studies[283] using titanium implanted with deuterium followed by several thermal cycles produced large bursts of activity that were inferred to be 10-MeV tritons or ^3He. The presence of any emission during such a treatment, but especially its energy, is unexpected. Gu et al.[266] (Mississippi State University) observed neutron production (9 times background) while bombarding palladium with 1-keV D^+. Neutron production was also observed by Durocher et al.[187] (University of Manitoba, Canada) using 60-keV D^+. However, in the latter case, the flux was claimed to be consistent with known fusion theory. Further studies reported by McKee et al.[334] (University of Manitoba, Canada) showed neutron emission from palladium and titanium targets when loaded with deuterium using 60-keV D^+ and 30-keV D_2^+. Myers et al.[166] (SNL) detected nearly equal proton and triton emission while bombarding palladium, zirconium, and titanium with 10-keV D^+ but found no emission after the beam was turned off. Dignan et al.[178] (San Francisco State University) bombarded a thin film of palladium ($\approx$2000 Å) with 1-keV neutral deuterium and D_2 at 77 K and found no evidence of emitted neutrons or 23.8-MeV gamma rays.

III.E.3. Cluster Bombardment

Beuhler et al.[289] (Brookhaven National Laboratory) bombarded TiD, ZrD, and perdeuteriopolyethylene with clusters of D_2O containing 20 to 1500 molecules accelerated to 200 to 325 keV. A maximum in the resulting photon count rate occurred when the cluster size was near 200 D_2O molecules. The fusion rate was much larger than expected from conventional theory, and larger abundances of ^3H and ^1H were seen in the spectrum compared to ^3He, thereby giving an apparent branching ratio[t] of <0.88. Such studies fall in the transition region between hot fusion and cold fusion. This work has been discussed in detail by Rabinowitz et al. in a series of papers.[335]

Fallavier et al.[290] (Institut de Physique Nucléaire de Lyon, France) used clusters of frozen deuterium ions in the size range between $(200\ D)^+$ and $(300\ D)^+$. Bombardment of TiD and polyethylene targets using an energy of 100 to 150 keV produced no evidence of fusion.

IV. DISCUSSION

During the last 2 years, all of the observations made by the original discoverers of the cold fusion effect have been confirmed by numerous observations throughout the world. In addition, many new conditions have been discovered that cause the effect to occur. In spite of this effort, many people find a major problem in accepting the cold fusion effect because there is a lack of expected nuclear signatures, the magnitude of the effect is much larger than expected based on current theory, and there is still difficulty in replication. As a result, various arguments are proposed to attribute the heat to chemical processes, the tritium is explained as contamination or experimental error, and the neutrons are assumed to be caused by cosmic rays or instrument error. These explanations had reasonable basis during the early history of the field. Now, the variety of techniques and accuracy of the work make this approach much less tenable.

When *d-d* fusion occurs, the reaction products can be tritons (^3H), protons (hydrogen), helium (^3He), and neutrons. Based on considerable experience with "hot" fusion, these reaction products should be produced in negligible quantity, or at least in nearly equal amounts, and be accompanied by X radiation. To the extent that neutrons form, gamma radiation (2.22 MeV) should also be seen from *n-p* interaction with the surrounding water bath. The absence of significant neutrons as well as the absence of any expected nuclear product sufficient to cause the observed heat has added to the skepticism. In addition, the apparent absence of 14-MeV neutrons resulting from *t-d* (^3H-^2H) fusion is a concern to some. Because of these apparent conundrums, the field is still handicapped by considerable doubt and limited support in many countries.

Neutrons are now known to be produced as bursts ($\approx 10^3$ to 10^7 n/s) as well as at a steady but lower rate (<1 n/s). When measured, the expected energy for *d-d* fusion of 2.45 MeV is found along with neutrons near 3 and 7 MeV. Neutrons in unexpectedly large quantity have been found to issue from palladium, titanium, or several alloys after being loaded with deuterium by gas reaction, electrolysis, or ion bombardment. Nonequilibrium conditions, such as produced by temperature changes, increase the probability of production although an overt creation of nonequilibrium is not always a requirement. Physical commutation (ball milling) of titanium in a deuterium-containing media and chemical reactions involving deuterium-containing compounds also can result in neutrons. In some cases, neutrons seem to result from fracturing (fractofusion) of the material lattice. Although titanium is known to easily fracture when it hydrides, this effect is less obvious in palladium. Nevertheless, fissures are produced in palladium during electrolysis,[336,337] and each time it is cycled through the α-β transition.[297]

Values for the $n/^3H$ ratio fall, at the present time, between 4×10^{-4} and 10^{-9} using electrolytic cold fusion cells. Using conventional techniques, the expected branching ratio for *d-d* fusion is near unity for impact energies at least as low as 3 keV (Refs. 338, 339, and 340) and for muon fusion at even lower energy.[341,342] Ion impact studies by Beuhler et al.[289] near 100 eV indicate a slightly less than unity branching ratio. A variety of approaches have been used to explain this apparent conflict. Kim[97] argues that the muon fusion data are not applicable and suggests either that the branching ratio is nonlinear to give smaller $n/^3H$ values at lower energy or there is some resonance enhancement for tritium production in the low-energy region. Resonance between deuterium atoms has also been proposed by Zakowicz and Rafelski.[64] Mayer and Reitz[100] argue that a variety of resonance reactions are possible between deuterium and various impurity metals, and these reactions can result in preferential tritium production. On the other hand, Chatterjee[114] suggests that the branching ratio is very sensitive at low energies to the energy available in the final nuclear products after energy is drained off into the lattice electrons. This idea is extended by Hora et al.[96] using a proposed electron surface layer as the medium for screening and energy extraction. Collins et al.[111] suggest that a tunneling process in the lattice leads to an excited state of ^4He that decays primarily by the production of tritium, a proton, and energetic electrons. Handel[84] also suggests a tunneling process that involves neutron transfer. If a source of virtual neutrons were available in the system or real neutrons were

[t]This value is an upper limit because of an uncertain baseline for the ^3He peak caused by the residual X-ray background.

supplied from the outside, Kim[108] suggests that the $n + {}^6Li = {}^4He + T$ reaction might be the source of both tritium and helium without the production of neutrons. In a more novel model, Hagelstein[104] proposes that a virtual, coherent interaction between a deuteron and a proton occurs and that this not only makes tritium but also deposits the resulting energy into the lattice, thereby solving two problems. Finally, polarization of the two deuterium nucleons by the Oppenheimer-Phillips[343,u] process is proposed by several authors[29] to distort the reaction branches toward tritium production at very low approach energy. Using a statistical model, Bush[319] calculates a value of 1.64×10^{-9} for the $n/{}^3H$ ratio. This brief summary does not exhaust all of the published suggestions but is included to show that a variety of hypotheses have been proposed to explain the low $n/{}^3H$ ratio. Of course, there is no universal agreement as yet. On the other hand, there is general agreement that the fusion rate is extremely sensitive to the energy of approaching deuterons for the energies involved in the cold fusion process.[99] In addition, the two branches for D-D fusion may have different sensitivities to energy in this low-energy region if deuteron polarization is important. Therefore, when energy is added to the deuteron, the fusion rate will increase and the $n/{}^3H$ ratio may change. Proposed processes that add energy are fractofusion, energy amplification at the tips of dendrites on the surface, a high-energy tail to the Maxwell velocity distribution,[43] and phase changes[42,95] that add kinetic energy to the deuterons. These processes add a relatively small amount of energy and would be important only if the fusion process were very sensitive to the deuteron energy. Much more energy can be added outside the metal environment by gas discharge or ion bombardment. Whether these processes can add sufficient energy to explain the observations depends on the chosen nuclear model. In addition, the $n/{}^3H$ ratio may have a spectrum of values if the deuterons have a variable energy or if several different nuclear reactions occur simultaneously. A mainly tritium reaction is proposed when the least energy is added and a more neutron-rich product when the greatest energy is added.

The expected 14-MeV neutrons appear to be absent. These neutrons would result if fusion produces high-energy tritons that fuse with environmental deuterium. Even if energy measurements are lacking, the resulting neutrons should, nevertheless, add to the general neutron flux. Consequently, the $n/{}^3H$ ratio should be at least 10^{-5} even if no other neutrons were being made during tritium production. The absence of this neutron flux suggests that tritons are being made with insufficient energy to initiate *d-t* fusion. This energy reduction would result if the nuclear energy were coupled to the lattice in some way. In one case,[330] 14-MeV neutrons were measured after tritium was placed in a cell in advance of the cold fusion reaction. This unique positive result demonstrates that when correct conditions are present to allow fusion to take place, *d-t* fusion can occur, and the reaction produces neutrons of the expected energy. This result does not demonstrate that 14-MeV neutrons will result following *d-d* fusion.

Other types of radiation are expected and have been sought. High-energy particles, when passing through a metal lattice, must produce X rays. However, these X rays have very low energy and, consequently, are difficult to detect unless special provisions are made. Exposure of X-ray film located near the cathode has been reported in a few cases,[228,233] but a quantitative study made during X-ray emission has yet to be reported. However, there have been several unsuccessful attempts to detect X rays.

The initial skeptical reaction was to assume that tritium resulted from contamination. A great deal of effort has been devoted to showing that contamination is not an important factor and how contamination, if it should occur, would behave in an electrolytic cell. The tritium observed in a cold fusion cell does not act like tritium that is known to be present as contamination.[297] Tritium has now been made in electrolytic cells having a variety of electrolytes and cathode metals, by gas loading titanium, and by voltage discharge in low-pressure D_2 gas. It has been detected using scintillator fluid, proportional counting, K_α X-ray emission, and autoradiography. Amounts up to 380 μCi and $>10^5$ times background have been produced on several occasions. Although it is not possible to *prove* that contamination is not present, dismissal of all claimed tritium production based on contamination can no longer be supported by fact. If this assertion is to be made believable, it needs to be backed up by evidence rather than opinion.

Heat has been produced near 450°C at rates up to 25 W, which is >10 times the cell input energy rate. Typical cells at room temperature have excess energy production rates between 7 and 300%. In most cases, this rate is a factor of >10 above the sensitivity or uncertainty in the calorimeter measurements. Because of the care used in the design of more recent studies, dismissal of excess heat based on accumulated or absolute error is no longer tenable. The energy production rate shows a linear increases with cell current up to ~700 mA/cm^2 where it has a predicted production rate of 2.5 W/cm^2. An increase in temperature to ≈450°C results in a factor of 10 increase. Of course, the total amount of energy produced by a cell depends on how long the cell is run after excess energy production starts. Some cells stop production before the patience of the researcher has been exhausted. Other cells are

[u]Polarization of the deuteron was proposed to explain the unexpectedly high transmutation function during nuclear reactions between deuterium, and sodium, aluminum, silicon, and copper.[344]

reported to have produced a total energy >10 MJ. The energy production rate and the total energy obtained from a significant number of cells is far in excess of that produced by any conceivable chemical reaction. *Indeed, if this huge excess were produced by chemical reactions, the discovery would be as novel and important to the field of chemistry as nuclear reactions would be important to physics.* Recent detection of ^{4}He after two studies[222,228] of heat production adds support to the conclusion that excess heat is caused by a nuclear reaction.

The lack of reproducibility in the cold fusion effect is tied directly to a difficulty in creating the required conditions within the lattice or on the surface of the host metal. Regular success cannot be expected until many electrodes have been examined in detail to determine the conditions that both produce and do not produce the effect. In addition, a detailed understanding of the chemistry, metallurgy, and solid-state physics of many metal hydrides, not just palladium, is essential. Even palladium, which has been studied extensively for years,[345] still reveals new variables that affect its interaction with hydrogen.

IV.A. Do Nuclear Reactions Take Place on the Surface or in the Bulk?

A first step toward understanding the cold fusion effect is to determine where nuclear reactions occur. Is it a bulk or a surface effect? Perhaps a combination occurs, depending on the particular nuclear reaction and on the method used to add deuterium. The behavior of tritium can reveal the origin of the tritium-neutron reaction, and the behavior of helium can be used to understand the heat-producing reaction.

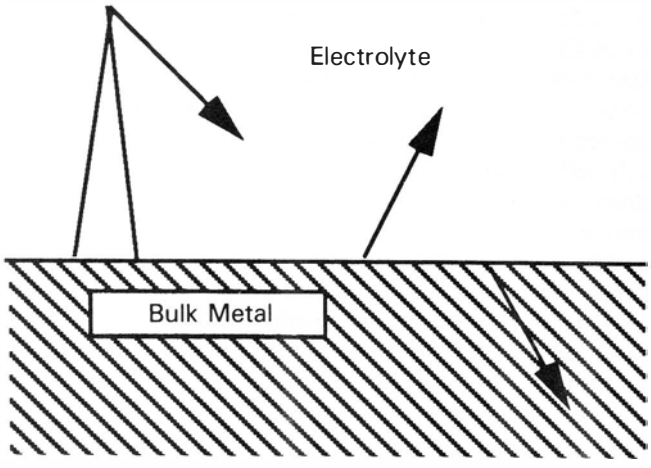

Fig. 5. Typical recoil paths of tritium from an idealized surface and dendrite.

IV.A.1. Tritium Production

Tritium that is located within bulk palladium will exit an electrolytic cell with the evolving gases.[297] Only tritium that forms on the surface can enter the electrolyte and then only if it is released by nuclear recoil energy. These conclusions are based on the behavior of tritium that was placed in a palladium cathode and then followed as it left an electrolytic cell. Because all observed tritium has been found in the electrolyte, except for one report,[3] it is reasonable to conclude that tritium is produced on the surface of the cathode. If this tritium is on the bulk surface, at least half will recoil toward the bulk material and subsequently appear in the evolving gases. The remainder will enter the electrolyte. This nearly 50/50 distribution between gas and electrolyte is not observed. Therefore, the tritium does not appear to form on the bulk surface. To be consistent with observation, we must conclude that tritium forms at the tips of dendrites[v] or promontories located above the surface, as first suggested by Lin et al.[347] supported by Rabinowitz and Worledge,[335] and developed further by Kim.[99] In this location, the solid angle toward the metal structure is sufficiently small so that most of the emitted tritons pass into the electrolyte rather than into the metal. Figure 5 shows typical recoil paths from an idealized surface and dendrite. Tritium has also been produced when Pd-D was electrodeposited,[233] a process that would be expected to produce a rich supply of dendrites.

Tritium production, as a surface reaction, is not expected to require a high average D/Pd ratio in the bulk material. General experience is consistent with this conclusion. However, a high deuterium-to-metal ratio is expected to exist in the dendrites where the fusion reaction is proposed to happen. Tritium production at this location is thought to occur because the deuterium atoms are given some additional energy by the applied cell voltage.[3,33,305,348] If tritium actually forms on the tips of dendrites, then the nuclear reaction does not take place in palladium but in a structure created by electrodeposited impurities. Unfortunately, this suggestion adds an overwhelming complexity to the problem because the surface impurity layer is very complex.[232,313,349–351] However, it does mean that a variety of metals may be useful as cathodes for tritium production, provided the correct impurities are present in the electrolyte.

To the extent that the nuclear energy is not coupled to the metal lattice during tritium production, bremsstrahlung X-radiation and 14-MeV neutrons should be observed. The apparent absence of 14-MeV neutrons suggests that tritium is produced with relatively little

[v]Electrodeposition of impurities is not the only way in which promontories can form on palladium. Stress relief during changes in hydrogen content can also cause variations in surface character.[346]

energy. If tritium forms on dendrite surfaces, methods that allow energy coupling to the metal lattice become a challenge to visualize.

When titanium or palladium are subjected to nonequilibrium conditions, such as temperature cycling after gas loading, tritium is formed even though no dendrites are present. Both metals are known to form cracks during this process. Although titanium and its alloys are more susceptible to cracking than palladium, fractofusion[235,306,342,351-354] is proposed to occur in both cases. During this process, deuterium atoms are given energy by the charge separation created when a crack is formed. Because the generated voltage gradient is high (> 10 keV/cm), the fusion rate and the $n/^3$H ratio would be more like that expected from high-temperature fusion. In addition, the initial formation of a crack may force the deuterium atoms very close together within slip planes, thereby increasing the probability for fusion[355] without additional energy being required. However, the reaction is very brief, the crack formation rate is limited, and the total number of cracks that can form is also limited. Therefore, this reaction is not expected to produce a significant amount of nuclear products. The small amount of tritium that is produced is expected to remain in the metal lattice during gas loading or be swept into the evolving gas during electrolysis. Bursts of neutrons and tritium would be expected if a large number of cracks should form at the same time. Because the resulting $n/^3$H ratio by this process is expected to be larger than by surface production, the relatively small amount of tritium would probably be missed by the usual detection methods. Consequently, this reaction would appear to produce mainly neutrons. However, there is no reason why this reaction and surface production could not occur simultaneously in an electrolytic cell, thereby giving a variable $n/^3$H ratio.

IV.A.2. Heat Production

Helium formation appears to be associated with heat production. A small fraction of the necessary helium has been detected within the metal,[222] but much more has been found in the evolving gas.[228] It is well known that once helium is captured[w] within a palladium lattice, it will not leave[356] except near the melting point. Therefore, for helium to be detected in the gas, it must have been produced sufficiently close to a surface so that recoil energy would allow it to be released from the lattice.[x] Nuclear recoil would direct some of the helium toward the bulk where it would remain. Consequently, some helium should be found in the bulk material, as has been the case. This heat-producing reaction is not expected to occur on the outer surface where tritium is thought to be produced because heat and tritium production are not initiated by the same conditions and seldom occur at the same time. In addition to the outer surface, there are internal environments that have contact with the evolving deuterium gas. Heat production, therefore, is proposed to occur in contact with the internal fracture system but near the outer surface where the D/Pd ratio would be sufficiently large. If this view is correct, thin films or foils of palladium should work better than bulk material because a greater fraction of the palladium would be involved in heat production and because thin films have a smaller tendency to relieve stress by crack formation. The presence of fewer cracks is proposed to result in a higher average D/Pd ratio and a higher fusion rate. In this case, most of the helium should be found within the metal film rather than in the gas.

The effect of dilution by normal water addition is more of a problem to understand. Studies have shown that heat continues for 20 to 100 h (see Sec. II.C) after normal water is added. Replacement of deuterium by protium in palladium produces some heat but hardly enough to account for the apparent excess. The deuterium replacement rate can be estimated by analogy to the tritium replacement rate. The half-life for tritium replacement by deuterium has been determined to be in the range of 12 to 24 h, depending on conditions.[297] Near-surface replacement would be completed first. Therefore, heat production should stop immediately. This apparent contradiction between helium behavior and water replacement behavior could be explained by some *p-d* fusion taking place or by assuming that isolated regions of high deuterium concentration remain in spite of normal hydrogen being present.

Heat production has been suggested to involve lithium that is located on the surface. This view was supported by a study showing that replacement of LiOD by NaOD caused a loss of excess heat with a somewhat faster rate than after addition of normal water.[214] In contrast to this experience, heat production was reported using NaCl in the electrolyte[227] and by a fused salt cell[222] that does not deposit lithium on the palladium. The fact that tritium can be produced in NaOD may not be relevant to heat production because the reaction environments appear to be different. At this time, lithium does not appear to be involved in the heat-producing nuclear reaction, although its presence does seem to improve the environment for heat production.

IV.B. Ion Bombardment

The tritium- and neutron-producing branches can also be enhanced by giving deuterium additional energy

[w]This includes helium that might be present as a contaminate. Therefore, the detected helium is not expected to result from helium that might have been contained in the palladium before the experiment started.

[x]This recoil energy is relatively small if the nuclear energy is coupled to the lattice as is apparently required for this reaction to occur at all.

using an ion beam or by gas discharge with the target being the cathode. This method should be much more neutron rich and fusion efficient than an electrolytic cell. Experience has shown that the target surface must be completely free of certain impurities if this technique is to succeed.[224] Consequently, the surface environment is important even when deuterium is given additional energy. Heat production has been reported on one occasion using the discharge technique, but helium was not sought.[224] Neutron production is said to have been sufficient to account for the observed heat if a small branching ratio is assumed. Because tritium and helium production were not reported, the true relationship between nuclear products and heat is still unknown in this case.

IV.C. Effect of Metal Environment

Because pure palladium was used successfully during the early work, it has been given particular attention. Later studies have shown that fusion can be obtained using palladium alloys as well as titanium. However, because fusion is apparently produced by more than one process, the results have been somewhat different between various metals. Titanium seems to be more likely to produce neutrons during thermal cycling than does palladium. On the other hand, palladium and especially Pd-Ag alloys seem more likely to give tritium and neutrons in an electrolytic cell. A variety of alloys, elements, and physical forms have been studied including palladium (both polycrystalline and single-crystal), Pd-Li, Pd-C, Pd-S, Pd-B, Pd-Be, Pd-Rh, and Pd-Rh-Li (Ref. 238); La-Ni (Ref. 172); Fe-Zr (Ref. 208); Ti-Pd, zirconium, and vanadium[188]; Pd-Sm and Pd-Ru (Ref. 280); Ti-Ni-O (Ref. 193); Pd-Ir (Ref. 178); Pd-Ag (Refs. 235 and 258); SiO_2 (Ref. 269); and vanadium (Ref. 259). Only SiO_2, titanium, palladium (drawn, rolled, hammered, annealed, and electrodeposited), Pd-Sm, Pd-Ru, and Pd-Ag have given evidence of a fusion reaction. Heat has been reported using titanium as well as palladium, although palladium appears to be the better choice for this aspect of the effect. The presence of large amounts of most elements that are normally present in palladium as low-level impurities, excluding silver, do not improve the reproducibility of tritium production. Therefore, at least one nuclear reaction involving these elements seems unlikely.

Rather special and difficult to reproduce conditions are an essential feature of the cold fusion effect. To the extent that nuclear reactions occur on the surface, the environment will be complex and not involve the base metal directly. Therefore, those variables that affect the surface and those impurities that reside on or are plated onto the surface need increased attention. On the other hand, heat production seems to be sensitive to the bulk properties of the metal.

Palladium has been found to show several unusual effects that might be relevant to heat production. In passing completely into the β-phase, excess volume is created.[297] This process continues without apparent limit each time the material is cycled between the α- and β-phases after being within the β-phase. Measurements of alternating current resistivity and capacitance of palladium cycled in this manner indicate that rifts or fractures are formed and these contain a significant amount of ionized[337] hydrogen under high pressure.[357,y] Detailed visual examination shows fractures of various sizes and shapes mainly associated with grain boundaries.[358,z] These fractures open and close depending on the charging or discharging conditions. During electrolytic charging, a flux of deuterium flows into the surface, through the metal and is exhausted from the electrode through that part of the fracture system connecting to the surface.[297] Thus, even under steady-state conditions, the metal hydride is not at equilibrium. Furthermore, the high-pressure, ionized deuterium gas present in the closed rifts is sensitive to current flowing through the palladium.[aa] This fracture system offers an additional environment, consistent with helium-loss experience,[bb] in which the heat-producing reaction might occur. This general behavior suggests that attention needs to be paid to the interior surfaces of palladium as well as to its outer surface.

IV.D. Proposed Nuclear Reactions

With very few exceptions, all of the effects attributed to cold fusion require the presence of deuterium. For a nuclear reaction to occur, either two deuterons must fuse together or a deuteron must fuse with some other nuclei such as a proton or a metal. A conclusion based on *d-p* fusion is made less likely because the presence of normal water eventually stops the reaction without producing an increase when the protium concentration in the palladium just begins to increase.[cc] Interaction with a metal nucleus may be possible but seems unlikely to be the main reaction because, except for palladium, other metals are present in very low and highly variable concentrations. When many of these impurities were added in higher concentration, no improvement in reproducibility was observed. In addition,

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[y] J. Dienes gives a theoretical analysis of formation conditions for internal fracture.[355]

[z] Matsumoto[358] proposes that this fracture system is partly caused by the fusion reaction, and the fusion reaction causes the size of the voids to grow. At the present time, there is no supporting evidence for this viewpoint.

[aa] It is worth noting that the addition of deuterium to the rift and dislocation system is expected to be slightly exothermic.[359]

[bb] For helium to be found in the evolving gas, it must be produced on or very near a surface that is in contact with the evolving gas.

[cc] After D_2O is replaced by H_2O, the H/D ratio in the palladium will slowly rise over several hours with the fastest change occurring in the near-surface region.

evidence for helium generation during heat production is starting to be accumulated. Consequently, *d-d* fusion remains the simplest explanation consistent with most experimental data. The observations of different combinations of heat, tritium, and neutron production are proposed to result from a different combination of the three branches for this fusion reaction. These branches are

1. $D(d,n)^3He$
2. $D(d,p)^3H$
3. $D(d,\text{energy})^4He$.

This explanation requires that each branch be sensitive to different conditions within or on the surface of a metal and that each branch couple most of the resulting nuclear energy to the lattice. While there is also some evidence for other reactions involving neutron transfer to the palladium and/or metallic impurity atoms, this does not seem to be the main source of heat or tritium. Nevertheless, these possibilities suggest that several nuclear reactions might be catalyzed by a metal lattice under special conditions.

V. CONCLUSION

It is easy to dismiss one or even a few observations of unexpected behavior that cannot be reproduced. This is done routinely by scientists during their work because most of such observations usually are caused by unknown errors. However, when many measurements, using a variety of techniques, are found to give similar results and begin to reveal patterns of behavior, the observations can no longer be ignored. This situation now exists in the cold fusion field. It is now far easier and more rational to begin the process of understanding cold fusion as a real phenomenon rather than finding ways to dismiss it. In spite of early difficulties, useful theoretical models are being constructed, and the work is gradually becoming reproducible. Unfortunately, the number of important variables is so large, the necessary diagnostic equipment is so expensive, and the general support is so minimal that a clear and convincing understanding will be very slow in coming.

At the present time, heat production equal to at least ten times the input energy has been achieved. This magnification is well above breakeven on a laboratory scale. The heat effect appears to involve mainly the near-surface rather than the entire bulk material, and it has a limited lifetime in present cells. Consequently, a possibility exists for considerable magnification of the effect should ways be found to involve a greater fraction of the metal for a longer time. This potential provides an important incentive for possible commercial application. The low availability and high cost of palladium may not be a limitation as first thought, provided the effect can be made to occur in thin films. If this phenomenon can be developed to the level of commercial usefulness, heat could be produced without the formation of significant undesirable products now associated with nuclear as well as combustion energy. Even "hot" fusion is not as benign nor as far above breakeven after years of study as is "cold" fusion. In addition, tritium might also be produced under different conditions without the large number of radioactive products that are a by-product of current methods. During this time of environmental concern, these possibilities are extremely important and should not be ignored.

A large fraction of the limited resource has been devoted to proving that cold fusion is real in contrast to understanding how it works. Except during the early euphoria, support has been minimal in many countries. As a result, many people have continued to do excellent work in spite of very little support from the scientific institutions or their peers, with a few exceptions. Although there are still many uncertainties, I suggest that the possible applications are so important and the present evidence for the reality of the effect is so strong that a more optimistic attitude and more support are warranted.

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