COLD FUSION:
An Objective Assessment

Edmund Storms
Energy K. Systems
Santa Fe, NM 87501
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Many people still believe that cold fusion is the result of bad science. In contrast, numerous laboratories in at least 10 countries have now claimed production of anomalous energy using a variety of methods, many of which are now reproducible. This energy is proposed to result from nuclear reactions initiated within a special periodic array of atoms at modest temperatures (energy). Evidence for nuclear reactions involving fusion of deuterium, transmutation involving both light and heavy hydrogen, and nuclear interaction between heavy nuclei has been published. The claims, if true, reveal a new method to release nuclear energy without harmful radiation and without the radioactivity associated with conventional methods. This paper examines published evidence describing this new phenomenon in order to test its reality and to extend an understanding of the process.

1. INTRODUCTION

In 1989, Pons and Fleischmann [1] (P-F) caused a media storm by claiming to cause fusion to take place in an ordinary electrolytic cell containing D_2O. This process was first named "Cold Fusion" by Steven Jones - an especially poor description. The names "Chemically Assisted Nuclear Reactions" (CANR) and "Low Energy Nuclear Reactions" (LENR) more correctly describe the phenomenon. Over 21 papers by P-F describe their work in more detail, a few of the more important ones are noted here. [2-5] Their claim was soon rejected because it could not be easily replicated and it could not be explained using information available at the time. From six months after the announcement until now, the subject has been ignored by the scientific community and is considered by many to be pathological science. In spite of this general rejection, some work continued, initially in ten countries and now in six countries, with official government support in most cases. These studies have provided a large number of observations and have answered most of the questions posed by skeptics. Even though the results defy conventional explanation, it is time for this information to be known by the general scientific community, regardless of its interpretation. If true, the observations reveal a completely new method to initiate nuclear reactions within an atomic structure. On the other hand, if these claims are false, as many people believe, a large number of highly trained scientists, using well understood equipment, can not be trusted to obtain accurate data, thereby calling into question conclusions reached in other fields based on the same techniques.

The phenomenon is claimed to produce fusion as well as a complex mixture of transmutation reactions. Twelve different methods, listed in Table 1, have been reported to produce anomalous energy (AE) and/or nuclear products (NP), some with good reproducibility and some with difficulty. Most of these methods produce many of the same effects using both hydrogen and deuterium. Consequently, light water can not be used as a null (blank) test of the method as some people have suggested. Naturally, theoreticians have been busy trying to structure these observations into a model. Over 500 models have been suggested with perhaps a dozen giving useful insight. A few of these ideas will be discussed later in the paper. Regardless of the explanation du jour, more energy appears to be produced than is being applied, thereby violating basic thermodynamic expectations. The important question is, “Why”?

TABLE 1
METHODS CLAIMED TO PRODUCE CANR

1. Electrolysis of D_2O (H_2O)-based electrolyte using a Pd, Pt, Ti, or Ni cathode; (This is the original P-F method, which has been duplicated hundreds of times to produce claimed AE and NP in every country where the method has been studied.)
2. Electrolysis of KCl-LiCl-LiD (fused salt) electrolyte using a Pd anode; (This method has been difficult to duplicate.)
3. Electrolysis of various solid compounds in D_2 (Proton conduction); (This method has been duplicated in the US, Japan and France to produce AE.)
4. Gas discharge (low energy ions) using Pd electrodes in D_2 (H_2); (Variations on this method have reported AE and NP in the US, Russia and Japan.)
5. Ion bombardment (high energy ions) of various metals by D+; (Variations on this method have reported NP in Russia and Japan.)
6. Gas reaction (H_2) with Ni under special conditions; (Replicated independently several times in Italy to produce NP and AE.)
7. Cavitation reaction involving D_2O and various metals using an acoustic field. (This method has been replicated in the US to produce NP and AE.)
8. Cavitation reaction in H_2O using microbubble formation; (Several attempts to duplicate variations on the method have failed.)
9. Reaction of finely divided palladium with pressurized deuterium gas; (Variations on this method have produced NP and AE in the US and Japan.)
10. Plasma discharge under D_2O or H_2O; (Variations on this method have produced AP and NP in the US, Italy and Japan.)
11. Phase change or a chemical reaction, both involving compounds of deuterium; (NP production has been reported in the US and in Russia)
12. Biological Systems based on living cultures; (NP has been reported in Japan, Russia and France.)

The literature of the field now contains over 3000 publications on the subject with about 1000 being important to an understanding, only a fraction of which are discussed here. Unfortunately, much of this information is not available in “normal” scientific journals to which a reader has easy access. Easily available, peer reviewed journals will be cited when possible even though this will result in much useful information being ignored. A few of the references in this paper are to conference proceedings because the data are available only from this source. Listings of available references and the hard-to-find publications are available to serious students and can be obtained from several sources. [6-9]

This paper has three major objectives: to give a general overview of the field so that interested scientists can understand the individual observations, to answer some of the major challenges raised by skeptics, and to suggest several new ideas for future study. The method used by Pons and Fleischmann will be the primary focus of the discussion because this is the most thoroughly studied method. A few other methods are introduced briefly to show that the effect can be produced in several different ways to give similar patterns of behavior. Hopefully, this effort will reawaken interest in this fascinating subject.

2. DISCUSSION

Several basic questions must be answered before the claims can be believed.

1. Have the claims been replicated?

2. Can prosaic errors or processes explain the effect?

3. Are reproducible patterns of behavior observed?

4. Can the effect be produced using various methods?

5. Why has the effect been so hard to replicate?

6. Does the anomalous energy have a nuclear source?

7. Can these claims be explained?

These questions were asked in 1989 and only now, 12 years later, can suitable answers be provided. While the answers given here may not satisfy everyone, hopefully they will lessen doubt about the phenomenon being real and encourage more people to study the effect.

QUESTION #1. HAS ANOMALOUS ENERGY BEEN REPLICATED?

As noted in Table 1, many of the methods have been successfully replicated. Because, the P-F method has been given the greatest attention, this method will be used to answer Question #1. A few other methods will be examined briefly as an answer to Question #4. Please note that some of these methods use little or no applied power to produce the AE.

First, the nature of the so-called anomalous energy produced by the P-F method needs to be understood. Claimed anomalous energy (AE) is detected as heat and measured using a calorimeter. Anomalous power (AP) is defined as the difference between the amount of heat (watts) being removed from the calorimeter, based on a previous calibration, and the amount being applied as electrical power, which is calculated as voltage across the cell times current through the cell. Anomalous energy is the product of anomalous power and time. Table 2 shows a partial listing of AP using the P-F method. These results were obtained by different laboratories, at different times, using different calorimeters. Notice, for these examples, the amount of AP is always well above the claimed uncertainty. In addition, many of these studies report finding numerous active samples even though only the most active one is listed in the table. Many other studies either failed to detect AP or the results were marginal. The wide range of values might indicate systematic error, but they also are consistent with a variable amount of active material being involved in the process. Do these facts have any meaning other than that everyone is making the same mistake? An answer must come from an understanding of how the studies were done, as discussed in Questions #2 and #3.

QUESTION #2: CAN PROSAIC ERROR OR PROCESSES EXPLAIN THE EFFECT?

An answer requires all possible errors be identified, something that is not always possible to do. The major errors will be evaluated first. All calorimeters need to be calibrated and various methods are used to do this. A Joule (resistive) heater can be placed within the cell and a known amount of electrical energy applied. A better method is to apply electrolytic power while using an inert cathode. This method is sometimes possible while using a palladium cathode because bulk palladium frequently takes many days before AE is detected. This delay provides an opportunity to calibrate the calorimeter by applying various amounts of electrolytic power to the cell before AP starts. The calibration method used is very important when evaluating potential errors. Several of the listed studies used more than one method.

Each calorimeter design has its own set of potential errors. These errors can be evaluated in several different ways provided sufficient information is given in the publication, a condition that is seldom met. One method uses statistics by assuming all errors are random. However, most error is not random, but instead results from overlooked deficiencies within the apparatus producing a bias or off-set. The difference being that random error produces an error band in which any change in energy is hidden, while an off-set results in apparent energy that may be anomalous or may be caused by error in the measurement resulting from a prosaic process. A few such problems associated with the electrolytic method have been identified [10-16]. Especially important are uncertain recombination[17] of D_2 and O_2 gases being generated within the cell, unrecognized temperature gradients [18, 19], and a variable thermal conductivity of the cell wall [20], each of which is described below in more detail.

Many errors are completely avoided by using a flow-type, Seebeck-type, or the double-wall isoperibolic-type calorimeter containing a recombination catalyst. These improved techniques do not suffer from errors attributed to early studies. Rather than causing the anomalous effects to disappear, these improved methods are found to produce the same behavior as obtained using less sophisticated calorimetry, as can be seen in Table 2. Consequently, the effects have not gone away when better equipment is used, a condition that must be met before the popular concept of pathological science can be applied. [21]

TABLE 2

List of Studies Reporting Anomalous Energy Using the Pons-Fleischmann Method

AUTHOR	DATE	TYPE(a)	CLOSED/ OPEN(a)	PRECISION W	MAXIMUM AP(b) W, mA/cm^2
Huang et al. [1]	1989	Flow-type(c)	open	±0.05	2.3, 450
Kainthla et al. [2]	1989	Isoperibolic(d)	open	±0.05	1.08, 468
Samthanam et al. [3]	1989	Isoperibolic(e)	open	?	1.54, 63
Appleby et al. [4]	1990	Seebeck(e)	open	±0.000001	0.0457, 600
Beizner et al. [5]	1990	DW Isoperibolic (d)	open	~0.1	~1, ~500
Eagleton and Bush [6]	1991	Isoperibolic(d,f)	closed	±0.3	6.0, 450
Scott et al. [7]	1990	Flow-type(c)	open and closed	±0.2	2.0, 600
Fleischmann et al. [8]	1990	Isoperibolic(d)	open	<±0.01	2.8, 1024
Hutchinson[9]	1990	DW Isoperibolic	open	±1.0	4, 250
Zahn[10]	1990	Double cell comparison	open	?	~2, 124
Miles et al. [11]	1990	DW Isoperibolic(d)	open	±0.05	0.3, 100
Oriani et al. [12]	1990	Seebeck(d)	open	±0.2	3.2, >1000
Yang et al, [13]	1990	A primative flow-type	open	~±5	9.1, ?
Zhang[14]	1990	Seebeck	open	±0.00001	0.15, ~15
Bertalot et al.[15]	1991	Seebeck	open	±0.005	0.08, 650
Bush et al. [16]	1991	Isoperibolic	open	~±0.05	0.52, 227
McKubre et al. [17]	1991	Flow-type(d)	closed	±0.05	0.5, 660
Noninski[18]	1991	Isoperibolic	open	?	2.6, 80
Yun et al. [19]	1991	Seebeck(e)	Open and closed	±0.01	0.24, 500
Bertalot et al.	1992	Flow-type	open	±0.025	3.0, 190

[20]					
Gozzi et al. [21]	1992	Isoperibolic(g)	open	±0.63	9.0, ?
Hasegawa et al. [22]	1992	Temperature of cathode	closed	~±0.1	~0.7, ?
McKubre et al. [23]	1992	Flow-type(d)	closed	±0.1	1.2, 440
Ota et al. [24]	1992	Flow-type	closed	~±0.1	1.0, ?
Storms[25]	1993	Isoperibolic(g)	closed	±1.0	7.5, 700
Okamoto et al. [26]	1994	Flow-type	open	±3.5	6.0, 66
Storms[27]	1994	Isoperibolic(d,f)	closed	±0.5	2.0, 600
Bertalot et al. [28]	1995	Flow-type(e)	open	?	11, 2000
Takahashi et al. [29]	1995	Double cell comparison(f)	open	±0.65	3.5, ?
Kamimura et al. [30]	1996	Isoperibolic(g)	closed	±0.25	0.700, 800
Yasuda et al. [31]	1996	Flow-type	closed	±0.05	5, ?
Ota, et al. [32]	1996	Flow-type(d)	closed	±0.075	0.29, 750
Szpak et al. [33]	1999	Isoperibolic	open	±0.01	0.4, 133
Storms [34]	2001	Flow-type(d)	closed	±0.03	0.8, 0.75

(a) * With a flow-type calorimeter, power is measured by flowing water through a jacket that surrounds the cell, or a coil inside the cell, and recording the flow rate and the temperature change of the water stream. Although this is an absolute method, it must be calibrated because the water can not capture all of the heat.
*The isoperibolic calorimeter determines power production by measuring the temperature drop across the cell wall. The device must be calibrated and is accurate only when the measured temperature represents the average ΔT.
*The double-wall (DW) isoperibolic calorimeter uses an additional thermal barrier outside of the cell across which the temperature drop is measured. The device must be calibrated, but is independent of any temperature variation within the cell.
*The Seebeck calorimeter determines power production by measuring a voltage generated by the temperature difference between the inside and outside of its walls. In this device, all walls are sensitive to this temperature difference, hence any energy that escapes the enclosure will generate a voltage proportional to the amount of power being lost. The device must be calibrated and is independent of the cell temperature.

* Double cell comparison uses two nearly identical cells, one of which is active and the other is assumed to make no AP. Heat production is based on the temperature difference between the two cells and accuracy depends on the two cells remaining identical in their properties.

*An open cell allows the generated gases to escape. A closed cell causes the gases to be converted back to water.

(b) Although only one value is given, frequently several different samples of palladium were reported to produce anomalous power (AP). The amount of anomalous energy (AE) is highly variable, depending on how long the active sample was studied.

(c) Calibration could have been unstable.

(d) Calibrated with internal heater and checked with Pt cathode and/or H_2O based electrolyte

(e) Calibrated only with internal heater

(f) Mechanical stirring used

(g) Calibrated using only an inert cathode.

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Because P-F started the field, their work has been subjected to especially sharp analysis [11, 14, 22-31]. Their study is no longer the only source of support for their claims because the effect has been duplicated many times using much better equipment, as described in a later section. Nevertheless, the most recent evaluation concludes that their claims for AE are justified[32] based solely on their work.

The following prosaic explanations for the claimed AE have been suggested.

Release of hydrogen gas[33]
Gas, as it is released by the palladium, is proposed to carry away heat, thereby cooling the cathode and depositing this energy in the electrolyte where it might be mistaken for excess energy. In addition, energy is then proposed to leak into the cell through the cooled cathode lead from the warmer outside.

Because all electrolytic cells are thermodynamically closed systems, energy used to compress the hydrogen (deuterium) within the cathode will exactly equal energy produced by its release. No net energy will be generated under this condition. In any case, an inert cathode would exhibit the same effect during calibration, thereby canceling the effect, should it be real.

Production of hydrogen gas [34]
Release of atomic hydrogen from the Pd lattice is proposed to produce bursts of heat as it combines to form H_2 gas and as it reacts with any surface oxide.

This explanation is not possible because under steady-state conditions hydrogen enters the palladium as fast as it leaves. At most, this effect could only explain small bursts of energy, not steady production normally reported. Also, no surface oxide remains on a Pd surface once electrolysis starts.

Recombination [17, 35]
The importance of recombination was recognized by everyone in the field since 1989. Although recombining catalysts were not used at first, care was taken to measure the amount of D_2O leaving the cell as D_2 and O_2 gas. Most studies, including P-F, found this effect to be less than 1 percent. In addition, subsequent studies have shown that recombination is only a problem when a very low applied current (below 100 mA) is used.[32, 36-38] In any case, most studies reporting AE now use an internal catalyst to convert all D_2 and O_2 back to D_2O.

Release of stored stress [39-42]
Most samples of Pd have been annealed before their use, hence contain very little stress. Stress is introduced into palladium when it reacts with hydrogen. While this stress might be released suddenly by crack formation, thereby producing a burst of energy, such release can not account for the observed large, continuous production of AE under steady-state conditions. Some studies have reported an amount of AE greater than an equivalent weight of TNT, an energy well outside of any possible energy storage mechanism.

Current fluctuations [43]
Bubble action is proposed to cause high frequency fluctuations in both current and voltage. Because DC measurements are made, these AC components could be missed by the data acquisition system. As a result, the amount of power applied to the cell would be too small compared to the amount being measured by the calorimeter, hence excess power would be proposed.

Such spikes on the applied DC voltage have been measured using a high frequency scope while AP was being produced and found to be less than 50 mV.[44] In addition, the same missing power would occur when the cell is calibrated using a dead cathode or the Pd cathode before AP is generated. As a result, the effect would cancel out. Also, people who have calibrated using both an internal heater, which does not produce this AC component, and a dead cathode report excellent agreement between the resulting calibration constants, thereby suggesting this error is not present, as Holst-Hansen and Britz concluded.

Peltier Effect [45]
A difference in Peltier coefficients between the metals used as cathode and anode is proposed to cause pumping of energy into the cell by applied current.

Two problems exist in this model. The proposed mathematical formula leads to an unrealistic conclusion, i.e. that an infinite amount of heat can be introduced into the cell when the temperature difference between interior and exterior approaches zero. The other problem is that the effect, if real, only becomes important when unrealistic differences in Peltier coefficients are proposed. In any case, use of electrolytic calibration would subtract such heat from the final result, thereby canceling any effect.

Chemical reactions [46]
Excess heat is proposed to result from the formation of chemical compounds within the electrolyte caused by the electrolytic current.

The chemicals used in a typical electrolytic cell are all stable and do not interact chemically unless a current is applied. This current can initiate various chemical reactions including reaction of D_2 with the cathode to form PdD, reaction of O_2 with the Pt anode to form PtO, reaction of Li with the cathode to form an alloy, and the rare formation of D_2O_2. These reactions are very slow, involve very little energy, and are endothermic. Such a chemical product would have to be more stable than the most stable compound known to exist in order to account for the observed energy. No chemical product even close to this requirement has ever been found within an active cell.

Temperature gradients [14]
Temperature gradients are proposed to exist within the electrolyte, which causes the recorded temperature to be unstable. As a result, EP based on this temperature would be unstable and potentially wrong.

Any cell design that uses the interior temperature to determine the loss-rate of heat is susceptible to this problem. Normally, bubble action reduces this gradient to insignificant values during electrolysis.[20, 47, 48] However, calibration using an internal heater can lead to unexpected error because no bubble action would be present to reduce the temperature gradient. Therefore, all studies using only this method of calibration are suspect unless electrolytic current is applied during heater calibration, as was done in some studies including those of P-F.

Variable thermal conductivity of the wall [20]
A stagnant layer of fluid exists next to the cell wall and this layer affects the apparent thermal conductivity of the wall. Because a single-wall isoperibolic calorimeter is sensitive to the thermal conductivity of the wall, changes in this stagnant layer, caused by mechanical stirring or convection currents produced by bubble action, change the calibration constant. Fortunately, the calorimeter used by P-F lost most of its energy by radiation through the wall and by conduction through the lid. Therefore, their values were not affected by this problem. Some other studies have not been so fortunate.

Jahn-Teller effect [49]
Energy is proposed to be generated by D atoms dissolving in PdD, combining to form D_2 molecules within a new structure, and then leaving as D_2 gas. To quote the author, "excess heat of cold fusion appears to be nothing more than the storage and release of the latent vaporization heat of heavy water".

This process ignores the fact that the same amount of energy would be used to place D within PdD as would be released when the D_2 leaves. In a closed system, under steady state conditions, energy can not be generated unless a permanent change takes place in either the chemical or physical structure. For this explanation to apply, D_2O in the electrolyte would have to change its properties by losing energy. After sufficient time, this energy would be exhausted and the remaining D_2O would have much different properties compared to fresh D_2O. No evidence for this change has ever been seen. If this energy were stored during initial loading of the palladium cathode, the process would be seen as an endothermic reaction having a value equal to the amount of energy released later. No such storage and release process has been seen in any study.

Errors in Calibration Constants [50]
The calibration constant of a flow calorimeter, or any type of calorimeter for that matter, is proposed to fluctuate such that periodic EP can be observed when a fixed value for the calibration constant is used. This variation can take two forms. If a calorimeter is stable, the constant will show random fluctuations around a mean, generated by minor variations in the measurement of temperature and applied power. When a calorimeter is unstable, the constant will show a steady drift with time. The assertion made here is that the actual sensitivity of a calorimeter will fluctuate even though the calorimeter appears to be stable, thereby generating periodic bursts of apparent EP.

This assertion has been applied to only one unique study [51] in which EP was found to result when the applied current was increased in steps over a range and then decreased in the same manner. Presumably, changes in the calibration constant occurred at the exact moment each of the seven such current scans were started and this change always resulted in similar behavior, i.e. a rising and then a falling EP. While such coincidence can not be totally ruled out, the proposed error can not be applied to the many studies that report EP lasting for hours and days, with periodic calibrations being made during this time.

Although these processes apply only to the P-F method, no prosaic process has provided a satisfactory explanation for all positive results using the other methods (Table 1), especially when AE and NP are produced in the absence of applied power. This does not mean such an explanation is not possible. It only means that the probability of finding a prosaic explanation has been significantly reduced. To make the challenge still more difficult, AE has now been detected under a wide range of conditions using many different calorimeters, all of which gave the same basic behavior. This effectively rules out a single prosaic process. We are now left with a situation such that several errors must occur, each giving the same apparent basic behavior regardless of the apparatus or method being used. This is a very weak basis for believing error is the only cause of the observations.

QUESTION 3: ARE REPRODUCIBLE PATTERNS OF BEHAVIOR OBSERVED?

Presence of reproducible patterns within the data sets are as important as achieving reproducibility of the phenomenon its self. Such patterns are based on AE being produced only under certain unique conditions by all studies. For example, a pattern can be claimed if AE is only detected when the D/Pd ratio is above a critical value, or if nuclear products are always found after AE production, regardless of the method used. Production of nuclear products will be discussed in Question #6.

Lack of space prevents each method listed in Table 1 from being described in detail. Instead, only a few especially compelling investigations will be examined. First, the P-F method will be described below, followed by a few other methods as answers to Question #4.

The work at SRI, lead by Dr. McKubre, studied the phenomena, first with $6M provided by EPRI (Electric Power Research Institute). After this program was terminated, work was continued by IMRA (Japan) at nearly the same level. A very small effort is now being funded by the US government. Over the course of this work, several designs of flow-type calorimeters were used that share the following characteristics:

1. The cells are sealed and contain a recombiner. As a result, no gas leaves the cell. Therefore, uncertainty in the amount of recombination is not an issue. Successful action by the recombiner is monitored using different methods including change in gas pressure.
2. The cells contain a heater, which maintains a constant inner temperature. Power to this heater can be adjusted to compensate for any change in temperature caused by electrolysis or by anomalous processes. This heater is also used to determine whether the power measurement, based on the flow rate and temperature change of a cooling fluid, is accurate. Sensitivity better than ±0.01 W (±0.1%) is claimed.
3. The electrolytic cell, its surrounding heater, and the cooling-fluid channels are all contained within a silvered, evacuated Dewar in order to isolate them from the environment.
4. The whole assembly is immersed in a fluid bath, which maintains a constant environment of 30±0.003°C. This bath is also the source of cooling fluid. Consequently, most studies are done at a temperature above 30°C.
5. A constant flow pump is used to circulate cooling fluid. Flow rate is checked periodically by weighing the fluid passing through the calorimeter. Better than 98% of power produced within the cell is captured in this fluid.
6. All aspects of the measurement are under computer control, which provides continuous monitoring, and redundant RTD sensors are used for temperature measurement.
7. The deuterium content of the palladium cathode is determined by measuring its change in resistance.

Nineteen samples of palladium were found to make AP with consistent results. One consistent behavior is shown in Figure 1 as the relationship between AP and average composition of the cathode. Figure 2 shows another pattern as the effect of applied current on AP. These two behaviors are found to be produced by all samples of palladium used in this work and by all samples reported in the literature when the necessary measurements were made. Variations in reported values are easily explained by the different shapes and sizes of the cathodes used, and by the amount of active material present on their surfaces. In addition, the following behaviors are also seen by everyone who has made suitable measurements.

1. The average D/Pd ratio must exceed a critical value. This value differs somewhat between studies because only the average composition can be determined and the value depends on the method used and the shape of the cathode. Typically, the value lies between D/Pd=0.85 and 0.90. Infrequently, compositions above this range are found to be dead for unknown reasons.
2. The current must be maintained for a critical time. This time is variable and presumably depends on how rapidly the surface can acquire the active structure. The time is zero for thin layers of Pd while it can be as long as months for bulk palladium. Failure to wait the necessary time is one reason some people have not seen the effect.
3. The current density must be above a critical value. Applied current determines the surface composition, hence the nature of the active structure. A value above 150 mA/cm^2 is usually found for bulk palladium. No critical value appears to be necessary for thin layers of palladium.
4. Inert palladium can sometimes be activated by addition of certain impurities to the electrolyte. These impurities are found to help the surface achieve a higher deuterium content.
5. The effect occurs in only a small fraction of samples, but more often in certain batches than in other ones. In fact, all physical properties of palladium are found to be batch specific, making this metal highly variable in its general behavior, even in conventional applications.

These patterns of behavior add evidence that the observations are a real behavior of nature and not caused by error.

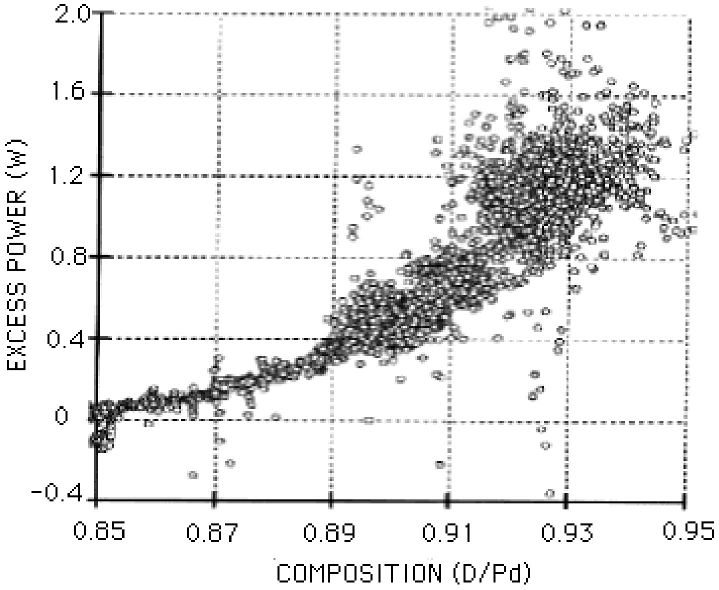

FIGURE 1. Relationship between average composition of PdD and the amount of anomalous (excess) power produced in a Pons-Fleischmann cell. This study was done at SRI.

QUESTION #4: CAN THE EFFECT BE PRODUCED USING VARIOUS METHODS?

Eight other techniques have also produce AE besides electrolysis, two of which are described below. Of course, some attempts to replicate these methods have failed. Even successful studies have many failures before success is achieved. As argued below with respect to the P-F method, failure only gives an insight when the reasons are known, not when the reasons are based on speculation. Many of the reasons for failure using the P-F method are now known and will be discussed in Question #5.

D_2 gas applied to finely divided palladium:

Prof. Arata {Note: Prof. Arata is the only physicist to be awarded the Emperor's Prize in Japan for his contribution to the Japanese hot fusion program.} and Dr. Zhang (Japan) [52-55] developed a way to load finely divided palladium powder (palladium-black) with very pure deuterium and measured the resulting AE and NP. The apparatus consists of a sealed palladium tube containing powdered palladium. This is used as the cathode in an electrolytic cell containing D_2O. Deuterium is generated at the cathode surface, diffuses through the palladium wall, and accumulated inside where it reacts with the palladium-black. Consequently, electrolytic action is only used to generate very pure D_2 gas, in contrast to the P-F method. These scientists find that after the D_2 pressure had increased to several atmospheres, AP is generated. Anomalous energy production can be maintained for months and it is accompanied by helium and tritium generation. This work has been replicated at SRI [56] using a flow-type calorimeter different from the one used by Arata and Zhang. The relationship between the AP and applied power is shown in Fig. 3, where the AE produced using H_2O and D_2O is compared. Clarke et al. [57]

failed to find He-4 in a sample of the Pd-black used in the SRI study, but did detect He-3 that resulted from the decay of tritium [58]. Based on the decay rate, this tritium apparently was produced during the SRI study.

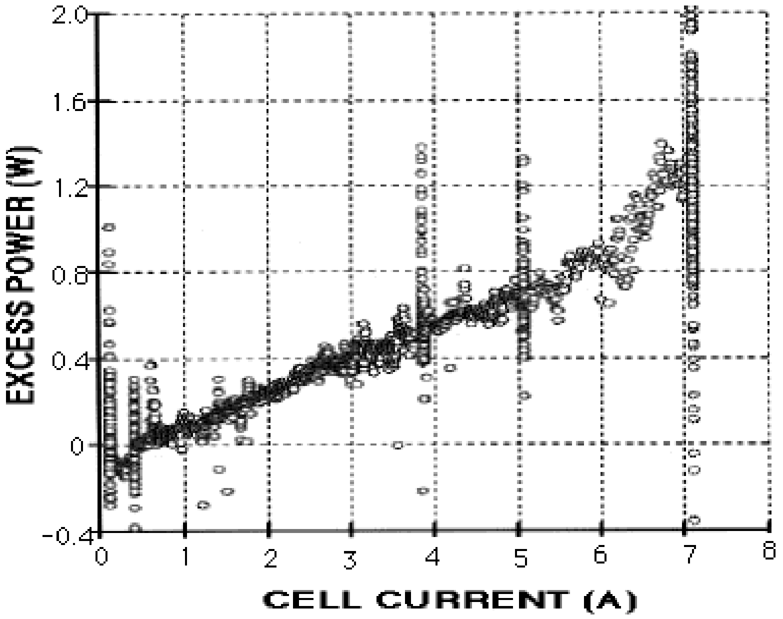

FIGURE 2. Relationship between anomalous (excess) power and current applied to a Pons-Fleischmann cell containing a Pd cathode and a D_2O+LiOD electrolyte. The study was done at SRI.

Dr. Case[59, 60] explored a variation of this method by using a commercial catalyst consisting of finely divided palladium deposited on charcoal. This material has the advantage that the isolated Pd particles will not lose their small size by sintering together when the material is heated, unlike particles in palladium-black which are in contact. When this material is heated to about 250° C with a temperature gradient and about 3 atm of D_2 is applied, AP is produced along with helium. This work has been replicated at least 5 times at SRI.[56] The relationship between AP, based on two independent methods, and helium measured in the gas is shown in Fig. 4. Helium concentration in the gas eventually exceeds 5.2 ppm, the measured concentration in the laboratory air. Consequently, this helium can not result from leaks in the system. Also, the initial catalyst was tested for absorbed helium and found to be essentially free of this element. The implied energy for the helium producing reaction shown in the figure is an upper limit because some helium is retained by the catalyst. When this helium is measured and taken into account, the value is consistent with the expected value of 24 MeV/helium.

These two methods show the same patterns of behavior, i.e. finely divided Pd produces AE and NP when exposed to D_2, but not when exposed to H_2. As noted below, finely divided Pd also is found to make AE when it is applied to an inert cathode surface in a P-F cell. [61]

It is important to realize that success using these two gas-loading methods depends critically on being able to remove impurities from the surface of the small palladium particles, not an easy task. Also, the presence of light hydrogen is expected to be a poison for the nuclear reaction, similar to the behavior of the P-F method.

Proton conductor: A number of semiconductors can dissolve a little hydrogen (deuterium) and become conducting by electromigration of hydrogen ions when the material is heated and a voltage is applied. Because current is very small, the amount of applied power is much less than used for a P-F cell. Use of deuterium is reported to result in AE and occasional transmutation. Ordinary hydrogen shows no effect.

Mizuno et al.[62, 63] made discs using a mixture of strontium, cerium, yttrium and niobium oxides, with platinum applied to opposite sides as electrical contacts. Upon heating to 400-700°C and introducing D_2 at 0.1-50 Torr, five out of fifty discs were found to make AE. Gamma emission was observed and attributed to ^{197}Pt formed from ^{196}Pt by neutron absorption.[64] Direct detection of neutron emission has not been very successful.[65] Production of neutrons and subsequent activation of Pt might be caused by occasional cracking with the resulting fractofusion, consequently may have nothing to do with an anomalous nuclear reaction. With Mizuno's help, Oriani[66] was able to duplicate production of AE. A similar complex oxide was studied by Samgin et al.[67] and it also was found to produce AE.

Biberian et al.[68] applied the same method to $LaAlO_3$ and reported detecting AE. Single crystals were not active.

QUESTION #5. WHY IS THE EFFECT SO DIFFICULT TO REPRODUCE?

Failure to replicate these claims is frequently attributed to errors in the successful work that are not present during the unsuccessful studies. Thus, the failed studies are considered to be well done and correct, while successful studies are thought to be deficient in some way. Ironically, while some famous failed studies were considered well done at the time, later analysis revealed actual production of anomalous energy.[69-73]

A better explanation attributes failure to various properties of the materials being used, which have nothing to do with error although some error is certainly present. This explanation shifts attention away from possible sources of error and instead emphasizes how the cathode material was treated. As will be shown below, this approach has considerable experimental support, especially for the P-F method.

Some of the methods listed in Table 1 are easily to reproduce and some are not. In most cases, the reasons are not yet known. Unfortunately, the method chosen by P-F has been especially difficult to reproduce because certain properties of palladium can not be duplicated from sample to sample. For example, most of the time, this metal forms cracks when it reacts with hydrogen or deuterium[44, 74, 75], a process that opens paths through which dissolved deuterium can escape as D_2 gas. As a result, the cathode can not achieve the required high deuterium content. Everyone who has studied the effect using bulk palladium has discovered certain batches to be more likely to work. Successful material has been shown not to form such cracks. One example of this experience is shown in Table 3.[76] Another example is provided by the experience of Storms[44], Kobayashi et al.[77], and Miyamaru and Takahashi [78]. Each of these workers used palladium from the same batch prepared by Tanaka metals (Japan) and each found AE. This palladium was especially free of cracks. A subsequent batch containing many cracks was found to be dead by the same people. Thus, when the same batches were studied using different equipment by three independent laboratories, the same behavior was observed.

Minor impurities such as light water [79, 80], as shown in Fig. 5, kill the effect. This observation is important for three reasons. First, it is hard to imagine how so little H_2O in the D_2O can remove those errors thought by critics to have produced an apparent excess energy before H_2O was added. Second, this effect means that p-d fusion does not contribute to energy production. Third, this is one more reason why the effect has not been easy to duplicate. Heavy water quickly absorbs light water from the atmosphere unless the cell is sealed, a rare precaution during early studies. Dissolved impurity metals in the electrolyte can also quickly kill the effect. In fact, commercial D_2O has been found to contain up to 9 ppm of impurity, material that must be removed by distillation or by pre-electrolyzing with a dummy cathode [44].

These observations suggest that the factors preventing duplication of the P-F effect are associated with the properties of bulk palladium and impurities within the electrolyte. On the other hand, once a piece of palladium has made AE, most people find this particular piece of metal to be active every time it is studied, unless the surface layer is altered [81] or unless cracks begin to form, something repeated reloading will encourage[82]. For example, Miles [83] took a piece of palladium found to be active in his laboratory at China Lake in the US to the NHE laboratory in Japan, where it again was found to be active. Other people frequently find this kind of reproducibility within their own laboratories.

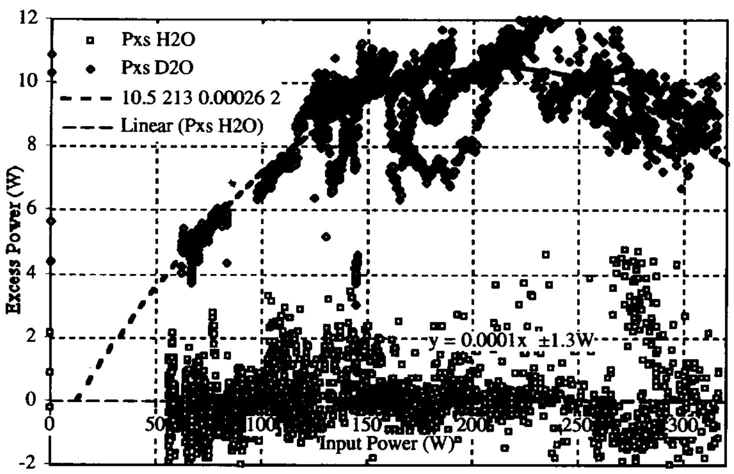

FIGURE 3. Relationship between applied power and anomalous power produced by an Arata-type cell containing palladium-black using an electrolyte containing D_2O or H_2O. This study was done at SRI with the help of Prof. Arata.

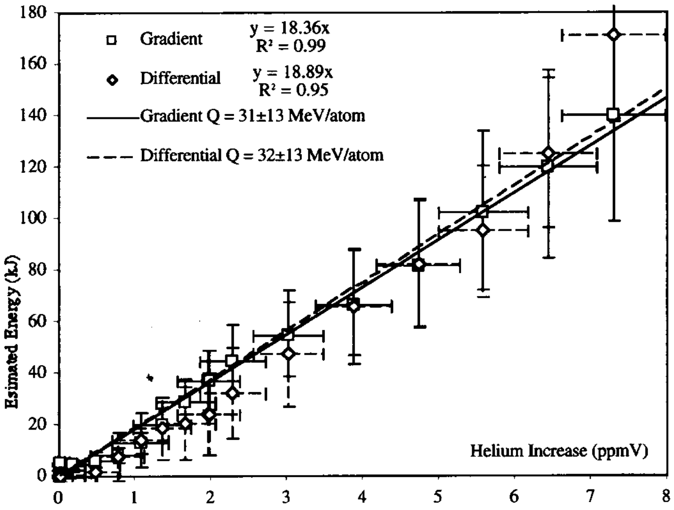

FIGURE 4. Relationship between the amount of anomalous energy and the amount of helium produced in a cell containing Pd on charcoal surrounded by D_2 gas. This study was done at SRI with the help of Drs. Case and George.

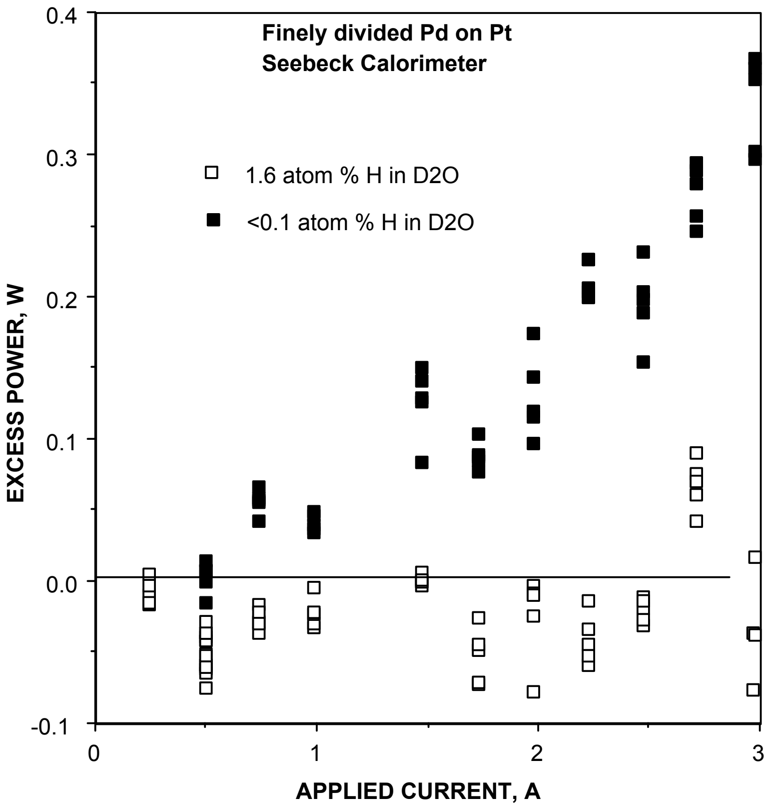

FIGURE 5. Effect of placing an active cathode in an electrolyte containing H_2O. The same calorimeter was used for both measurements. This work was done at the author's laboratory in Santa Fe, NM.

TABLE 3

Source and Number of Samples Found to Produce Anomalous Energy

	EXCESS ENERGY	
SOURCE	Success	Total
Boron Containing		
Samples made at NRL	7	8
J-M Pd	15	26
NRL Pd	1	6
WESGO Pd	0	6
NRL Pd-Ag	0	3
IMRA Pd-Ag	0	2
Pd-Cu	0	2
Pd-Ce	2	2
Co-deposition	2	34

J-M: Johnson and Matthey Company
NRL: Naval Research Laboratory
IMRA: IMRA Japan
Co-deposition: Pd plated from solution during heat measurement
WESCO: A secondary supplier used early in the work

Thin layers of palladium deposited on an inert substrate make AE more easily than does bulk palladium.[61, 84, 85]. Therefore, a person wishing to replicate the claims of P-F should use this approach. Other electrode materials are less susceptible to their bulk properties, although surface conditions are still important.[51, 61, 86-90].

If anomalous energy is accepted as being real, the next question is:

QUESTION #6: DOES AE HAVE A NUCLEAR SOURCE?

Three types of answers are offered. First, the amount of energy is too great to be explained by any other process. This argument is weak because the amount of energy depends on how long the sample appears to make AP. If an offset error is present, a large amount of apparent AE can be created simply by being patient. Second, no chemical products have been found to accumulate in cells making AE. This argument is stronger than the first one, but still relies on not finding something that available techniques might miss. Third, nuclear products are seen to accumulate within the cell in amounts consistent with the amount of AE being measured. This is the strongest argument, but the most difficult to demonstrate because very small quantities of material are involved, some of which might well come from conventional sources.

Possible products of a fusion reaction are neutrons, tritium, charged particles, gamma emission and ^{4}He. All of these nuclear products have been looked for and found. Because the first two products result from “normal” fusion, they were frequently sought in early studies. Recent studies have looked for elements resulting from transmutation reactions, which have the potential to produce a wide spectrum of nuclei.

Neutrons: Because neutron emission is easy to detect, at least 500 attempts were made to find this product. All of this effort has revealed that neutrons are not emitted from CANR cells in amounts consistent with the AE. When neutrons are found, they are emitted when AE is produced and when it is not. In either case, the measured energy is 2.54 MeV and up. The behavior would suggest that fractofusion [91-94] is occurring within the deuterium containing metal. This process occurs when a crack forms and generates a large voltage gradient. This voltage can accelerate D+ ions and produce normal, high-energy fusion. Because cracks form easily in palladium [75, 95], it is impossible to know whether the few detected neutrons are emitted only from the anomalous cold fusion reaction or result from localized “normal” fusion. In addition, other reactions having nothing to do with fusion might also be the source under special conditions. In any case, neutron emission, when it occurs at all, is from a minor reaction path.

Mizuno et al. [96] have proposed that a mixture of light and heavy hydrogen enhances neutron emission during the electrolytic process. They observe most neutron bursts to occur after considerable electrolysis has taken place, when H_2O has had a chance to enter the D_2O electrolyte. To test this idea, they loaded a Pd electrode in D_2O and then transferred the cathode to a cell containing H_2O. Neutron bursts frequently occurred shortly after electrolysis was started and when the cell voltage was increased, thereby providing more H_2 to the cathode. The improved reproducibility and magnitude of neutron emission might explain why neutron emission is seen so infrequently when efforts are made to keep the electrolyte free of H_2O. However, this behavior is not inconsistent with fractofusion because loading with hydrogen, especially at high-applied voltage, will stress the material more than when deuterium was used, hence will produce more cracking. However, if neutrons at 2.54 MeV were found to be absent, another process would be indicated.

Tritium: Over 200 attempts have been made to detect tritium with about 24 reporting this product, sometimes at significant levels, but not enough to account for the AE. Apparently, the tritium-producing reaction is rare and difficult to initiate. Three particularly compelling results have been published using the P-F method, a low-energy gas discharge, and gas loading of palladium-black.

Dr. Chien et al. (Texas A & M) [97] measured the tritium content of an open electrolytic cell containing a Pd cathode and LiOD in heavy water. They found the tritium content of the electrolyte was influenced by changes in the cell current (overvoltage) and was a linear function of time when conditions were constant, as shown in Fig. 6. However, shaking the cell caused tritium production to stop. It is hard to imagine how this simple act could influence tritium pickup from a prosaic source. On the other had, it suggests that tritium production is associated with surface features that are easy to shake off. Taubes [98] claimed that tritium was being added by a student. This accusation was not supported by an investigation at the university. In addition, thirty-five tritium additions would be needed, each at precisely the correct time and in precisely the correct amount, a feat very hard to keep undetected at a university where people come and go at will. Other people have suggested tritium was present in the palladium cathode and was slowly released by electrolytic action. To counter this argument, Storms[82] used the same technique to study a sample of Pd known to contain tritium. He found that tritium, which was dissolved in the metal, appeared in the evolving gas rather than in the electrolyte where it was detected by Chien et al. This work demonstrated that the tritium claimed by Chien et al. could not result from tritium contamination. The study by Storms also demonstrates that anomalous tritium originates at the surface where it can exchange with the surrounding electrolyte rather than being lost as DT gas, as would be the case if it formed within the bulk material. In addition, a very complete analysis for tritium in palladium obtained from many suppliers shows that palladium from commercial sources simply does not contain tritium.[99, 100] Tritium enrichment is also a possible source of increased tritium concentration because deuterium is lost faster from such cells than is tritium. The enrichment factor is known [101-103] and can not account for all of the tritium found in this study.

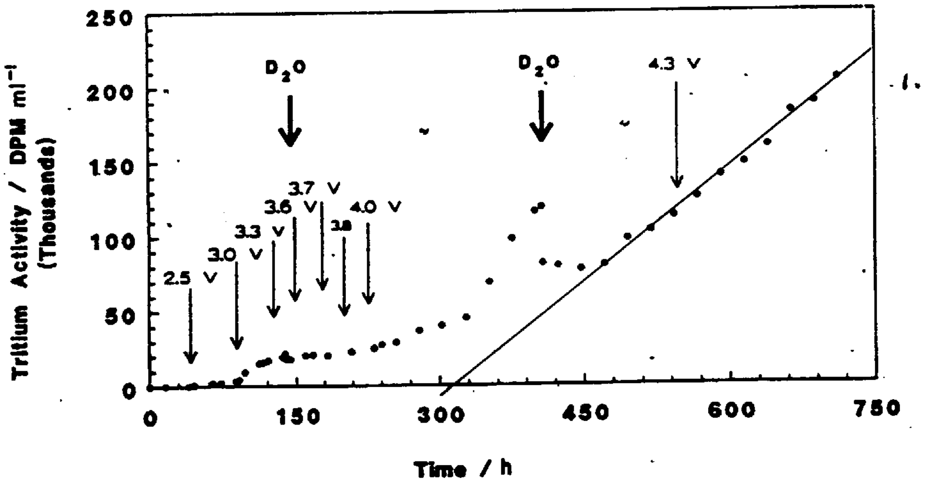

FIGURE 6. Tritium concentration as a function of time found in a Pons-Fleischmann-type cell being electrolyzed at the indicated voltage. Heavy-water was added to the electrolyte at the indicated times. This work was done at Texas A & M University.

Dr. Claytor [104, 105] and co-workers have studied tritium production at the Los Alamos National Laboratory for many years using a pulsed discharge method in low-pressure D_2 gas. The voltage is too low to produce tritium by conventional processes. Tritium is measured in real time using an ionization detector within the gas line and later as total tritium content by converting the gas to D_2O. Tritium contained in the resulting D_2O is measured using scintillation counting. Both techniques are very sensitive and show good agreement. A variety of alloys have been studied which slow that tritium production is very sensitive to the material used for the cathode. Although the amounts produced are small, no prosaic explanation has stood the test of detailed examination by many reviewers, both inside and outside the laboratory.

Arata and Zhang [106] as well as McKubre et al. detected He-3 in the D_2 gas after excess energy was made. This He-3 was found to result from decay of tritium. The amount of He-3 combined with the decay rate showed that the tritium was created at the same time EP was being produced. However, the amount of tritium was much too small to contribute significant energy to the process.

Each of these studies suggests tritium forms on nanosized particles. Such locations being rare and difficult to form, tritium production is seldom detected. Why an isotope like tritium, i.e. one containing excess energy should form in this environment instead of the ground-state (^{3}He), is a major challenge for any theory.

Helium: If these products are not the source of AE, what is? Helium-4 is claimed when AE is produced. However, formation of ^{4}He is expected to generate gamma emission. Gamma emission from a CANR cell, although detected sometimes at low levels, is not consistent with the amount of ^{4}He detected. For this inconsistency to be resolved, the presence of ^{4}He needs to be proven. Several problems make this difficult. Air contains about 6 ppm of helium, making an air leak a possible source of anomalous helium. Of course, a leak will not add this much helium to the contained gas unless all of the gas in the apparatus during helium analysis is air. Clearly all of the deuterium could not be replaced by air without this fact being recognized. Absence of argon in the gas eliminates an air leak as an explanation for detected helium. Most studies have failed to detect argon in the D_2 gas. Even preferential diffusion of He through the walls would not result in the air concentration being achieved within the apparatus in any reasonable time. Therefore, detecting He-4 even close to the air concentration would be proof that the He resulted from some process within the apparatus.

A possible source of helium within the apparatus is that which is dissolved in or absorbed on the cell components. Studies have shown that helium dissolved in palladium deeper than a few microns can not be removed unless the material is almost melted.[107] Therefore, this source is precluded when helium is found in a P-F cell. Charcoal, on the other hand, can absorb helium at room temperature and above, and this can be removed by flushing with hydrogen. Consequently, care must be used when examining a charcoal containing material for helium production.

Numerous samples of palladium have been examined for their helium content after having produced AE., with mixed success . On the other hand, four studies have shown a quantitative relationship between helium found in the surrounding gas and AE production.

Miles et al.[108-110], working at the Naval Air Warfare Center (China Lake), recovered gases being generated in a P-F type cell while making AE and measured the amount of contained ^{4}He. A double-wall isoperibolic calorimeter was used and gas was collected in metal flasks. An earlier study [111] using glass flasks is ignored here even though the result is consistent with their latter work. Six samples are reported to make AE along with helium at levels above background. Five samples showed no AE and the helium concentration was at background. Bush and Lagowski[112] repeated this study using a Seebeck calorimeter, a different stainless steel apparatus, and at a different laboratory (SRI). These results are compared in Fig. 7. Jones and Hansen [113] criticized the Miles work for confusion in reporting some values, for not running proper controls, for poor calorimetry, and for not measuring possible recombination properly. Their latter criticism is shown not to be valid in a previous section. Miles responded first in a question and answer secession [114] and then in a formal publication.[115] Jones et al. [116] had the last word after much of Miles' response was omitted by the journal. While the issues were not resolved and remain clouded in misunderstanding, a relationship between heat production and helium production has a high probability of being real. Gozzi et al. [117, 118] monitored the real-time production of ^{4}He from an active cell using an inline mass spectrometer. Although some problems with air leaks were acknowledged, they demonstrated a clear relationship between energy and helium production. When these three studies are added to the helium-energy values reported by McKubre et al., as shown in Fig. 4, the reality becomes even stronger. Apparently the nuclear reaction producing helium has an energy close to that expected from d-d fusion.

The insistence that gamma emission must accompany helium production is based on how this fusion branch behaves in a plasma. Because the reaction d + d = ^{4}He has two nuclei producing one nucleus, gamma radiation must occur to conserve momentum. On the other hand, suppose the following reaction occurs in a lattice where the d concentration is very high[119] [120]:

$$\mathrm{d+d+d+d} \rightarrow \{^{8}\mathrm{Be}\} \rightarrow 2\ ^{4}\mathrm{He}.$$

Such a reaction would not require gamma emission because ^{8}Be would promptly decompose into two particles, each having 23.8 MeV. Other, similar reactions can be proposed to avoid the need to emit gamma radiation. This suggestion shifts the problem from requiring gamma emission, to accepting that such reactions can actually occur. Evidence for such multibody interaction has been reported by Takahashi et al.[121] based on the energy of tritons emitted when titanium is bombarded by D+.

Transmutation: Transmutation describes a nuclear reaction involving nuclei heavier than hydrogen. Such reactions occur when hydrogen or a heavier nucleus enters another heavy nucleus causing it to transmute (change) to another element. Because the Coulomb barrier is very high for such reactions, significant energy is normally required. For this reason, claims for such reactions in the CANR environment are surprising and difficult to explain without invoking prosaic processes or error. If true, these observations imply that the Coulomb barrier, no matter how large, can be reduced to insignificant values by a process available within a solid.

Transmutation reactions have been reported to occur in all environments to which the CANR process has been applied. The easiest method involves creating a plasma under water. This can be done by applying sufficient voltage (up to 150 V) to form an arc between two carbon rods immersed in an electrolyte containing various salts dissolved in water [122-124]. The method is reported to generate a magnetic precipitate in addition to various elements and is easy to duplicate. A tungsten electrode can also be used[125-127] or the discharge can be made to occur in a cell made of zirconium[128, 129]. Each has been reported to generate elements not previously detected in the materials, sometimes with abnormal isotopic abundance. The most complete study was undertaken by Prof. Miley [130-132] using electrolytic current applied to a nickel cathode in H_2O-based electrolyte. Figure 8 shows the rate of element formation as a function of atomic number. Many of the observed elements also had an abnormal isotopic ratio. Of course, some of these elements might have resulted from contamination or from errors in chemical analysis. On the other hand, Ag and Cu exceed potential contamination by several orders of magnitude. The number of elements found and the pattern shown by the data are hard to explain based on prosaic sources.

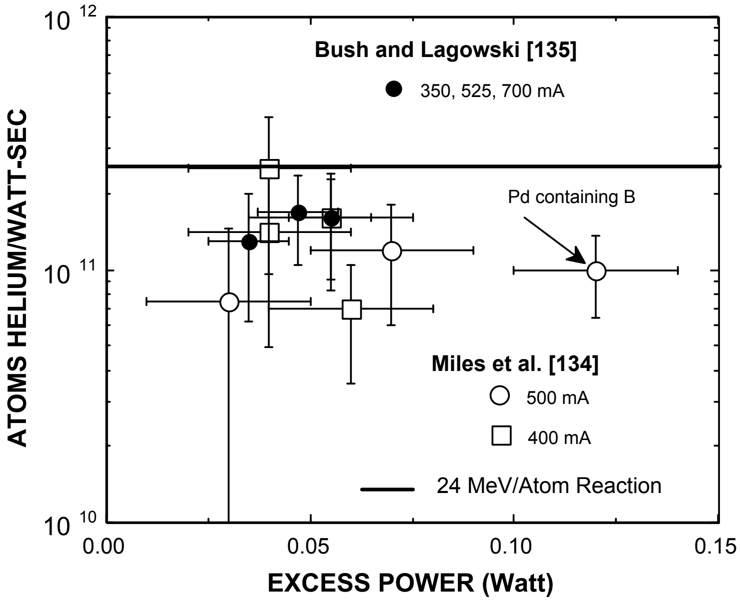

FIGURE 7. Relationship between atoms of helium per watt-sec of energy and anomalous power generated in a Pons-Fleischmann cell. Helium was measured in the generated gas and does not include helium retained by the palladium cathode. This work was done at the Naval Air Warfare Center at China Lake and at SRI.

Transmutation is claimed to occur in living systems where the process becomes especially difficult to believe or understand. Indeed, people have advised me not to discuss this subject, as if a potential reader would be too immature to handle the intellectual conflict this discussion might cause. Readers are warned to skip this section if such information would damage their open mind.

A scientist in Japan[133-137] started the process to duplicate claims made popular [138] by Kervran [139] and published the results first in France. He used modern analytical methods to study eight different biological cultures of bacteria and yeast, each made deficient in K, Mg, Ca, or Fe. The growing cells are found to make the deficient element from the other elements present. The following reactions are proposed:

$^{23}Na + ^{16}O = ^{39}K$
$^{23}Na + ^{1}H = ^{24}Mg$
$^{39}K + ^{1}H = ^{40}Ca$
$^{24}Mg + ^{16}O = ^{40}Ca$
$^{28}Si + ^{12}C = ^{40}Ca$

Later, Russian workers started a similar study[140, 141]. This team first made cultures of three different bacilli and one yeast, all of which could live in either D_2O or H_2O. The cultures were made iron-free, but contained a small amount of $MnSO_4$. After a suitable

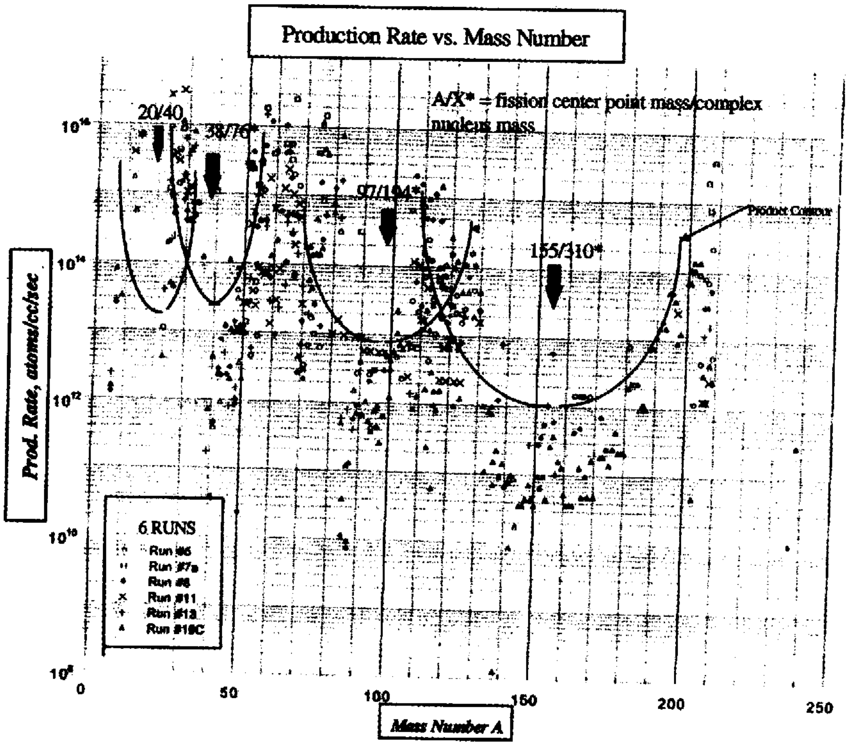

FIGURE 8. Rate of element production in an electrolytic cell using a Ni cathode and a H_2O-based electrolyte as a function of atomic number of the element produced. This study was done at the University of Illinois.

time, the presence of ^{57}Fe was measured using the Mössbauer effect. Iron 57 was only detected when both $MnSO_4$ and D_2O were present in the cultures. The proposed reaction is $^{55}Mn + ^{2}D = ^{57}Fe$. The rate of growth was measured and was calculated to give no more than 50 mW to the growing media. Of course, the culture containing H_2O would be expected to make ^{56}Fe, which would be invisible to the Mössbauer method. It is interesting that Kervran [139] published a study over forty years ago in which $MnSO_4$ placed in a culture growing in H_2O made iron that was easily observed. Naturally, this work was ignored. The Russian team has filed a patent for the process. The team has now explored the reaction $^{23}Na + ^{31}P = ^{54}Fe$. A time of flight mass spectrometer was used to determine the concentrations of reactants and product. They report that a culture made deficient in iron would generate iron only when both Na and P were present.

QUESTION #7: HOW CAN THE CLAIMS BE EXPLAINED?

Objections to cold fusion being real rely on the following arguments. First, a large application of energy is required to overcome the Coulomb barrier. If a nuclear reaction should occur, the immediate release of energy can not be communicated to the lattice in the time available. When such energy is released under "normal" conditions, energetic particles are emitted along with various kinds of radiation, only a few of which are seen by CANR studies. In addition, gamma emission must accompany helium, and production of neutrons and tritium, in equal amounts, must accompany any fusion reaction. None of these conditions is observed during the claimed CANR effect, no matter how carefully or how often they have been sought. Furthermore, many attempts to calculate fusion rates based on conventional models fail to support the claimed rates within PdD. The atoms are simply too far apart.

Failure to discover just what the nuclear-active-environment really looks like is a major problem in answering some of these challenges. A few observations suggest where to look. When the electrolytic method is used, AE is produced on the surface within small, isolated regions.[84, 142] These regions heat up in a random fashion, thereby losing the required deuterium content, which stops further reaction. Thousands of such local regions flash on and off, adding their resulting energy to the total. This process is self-regulating and usually produces a smooth generation of heat energy. Occasionally, a region will generate enough energy to cause local melting[143, 144]. Once in awhile, large bursts of total energy are observed. The number of such regions on the surface determines just how much total power will be produced. This description implies that power density in the active regions is extremely high and has no relationship at all to the often quoted power density based on the physical volume of the sample.

While the nature of these regions is still unknown, they are clearly not β-PdD [145], as most people have assumed when the P-F method is used. Not only is the active composition in excess of $PdD_{1.0}$ [146-148], the upper composition limit for this phase, but deposition of various impurities makes the surface a complex alloy [149-155]. Neither the structure nor the composition of this alloy is known. In fact, the nuclear-active material may not contain palladium at all.

A growing number of materials, besides palladium, are found to be useful for the P-F method, with bulk palladium being the most difficult to make active. Two conditions appear to be required: the ability of the material to acquire a high deuterium content and the size of the active regions. The required size appears to be less than 1 μm. A high flux of deuterium through the material also seems to be beneficial [156-158], although not necessary. The active material will be equally difficult to locate and identify when other methods, besides electrolysis, are examined.

In summary, the active material within a P-F cell is on the surface and located in very small, isolated regions. Bulk properties have little relationship to the properties of these regions, which consist of a complex alloy having very little in common with β-PdD. Very little progress will be made until the proposed models are applied to the real world rather than using the ideal environment within β-PdD. In addition, bulk behavior can not be used to support a model or to reject the claims.

Ordinary hydrogen produces both AE and NP using the same methods applied to deuterium. Obviously, fusion can not be a source of either product. In addition, the materials required to initiate anomalous effects are different between the two isotopes. For example, palladium is found to be nuclear-active with deuterium while only nickel is found to be active with hydrogen. As expected, the types of nuclear reactions are different, as well as the environments in which they occur. This difference suggests several different mechanisms may be operating. Such a possibility needs to be considered when evaluating the proposed models.

Once the environment has been created, what process might allow a nuclear reaction to take place? Only a few proposed mechanisms have been developed in sufficient detail to be useful or to allow an evaluation. A useful model must address more than just the conditions thought to exist when the P-F method is used and must consider the following:

#1. describe how the Coulomb barrier is overcome,
#2. show how the released nuclear energy is distributed throughout the atomic lattice,
#3. show why and how different environments produce different nuclear reactions, and
#4. recognize the unique characteristics required of a nuclear-active environment.

Proposed theories can be evaluated with respect to the initial assumptions, to the accuracy of the applied mathematics, and to how well the theory treats the above conditions. Only the latter evaluation will be applied here. Of course, many assumptions used to meet these conditions may not be considered reasonable. This part of the evaluation is left for the reader, although a few evaluations at this level have been published.[159-161]. The following discussion must, for space considerations, be very simple and omit many efforts to explain the effect. The author apologizes in advance for giving so much hard work so little attention.

Enhanced Cross Section: The observations imply a higher than expected cross-section for fusion at very low energy. To explore this possibility, Kasagi et al.[162] bombarded various metals and compounds with deuterons of various energies down to 2.5 keV and measured how much enhancement was produced in the reaction D(d,p)T, as shown in Figure 9. Apparently, an increase in cross-section does occur at low energy when the reaction occurs in a solid, in contrast to when the reaction is initiated in a plasma. In addition, enhancement is greater in PdO than in a number of pure elements[163], thereby showing that the nature of the chemical environment is important. Because the solids were not expected to be nuclear-active under the conditions of the study, the measured cross-sections represent only a lower limit for what might be possible when the "correct" solid is used. Other studies indicate that the branching ratio between tritium and neutron production might also change at low energy.[164-166] Once these possibilities are acknowledged, the next problem is to propose how the cross-sections might be increased at low energy by the surrounding atoms.

Neutron Formation: Neutrons are assumed either to be present in the lattice within a stabilizing structure [167] or are created by collapse of an electron [168-177] into the nucleus of a hydrogen or deuterium. The latter collapse makes a dineutron.[178, 179] The importance of a neutron presence is suggested by the unusual effects observed when an external neutron flux is applied to a CANR cell. [180-184] Apparently, the environment acts like a neutron amplifier. This model answers only Requirement #1. In addition, one might ask why more neutrons are not detected as they are being released or created within the cell, especially when thin cathodes are used?

Fisher [185] [186] has proposed that large, stable neutron clusters can form and that these can attach themselves to normal nuclei to produce super-heavy atoms. A small concentration of such atoms is proposed to be present in all matter. Under the right conditions, these neutron clusters are released, thereby causing novel nuclear reactions. The work of Oriani [187] supports the existence of super-heavy carbon in electrodes subjected to CANR processes.

Particle-wave Transformation: Talbot and Scott Chubb (uncle and nephew) [188-190] have explored the possibility of particle-wave conversion, a process known to occur at very low temperatures. In this model, deuterons convert to waves in the correct environment and these waves interact to form a helium wave within the surrounding atomic lattice.

Once sufficient energy has been lost by the d-d-He wave packet, it becomes a ^{4}He particle. In their model, a periodic lattice of suitable size containing a very high concentration of deuterium nuclei is required. Helium already present within the structure and a deuteron flux are proposed to be beneficial. Liboff [191, 192] has also explored this theme in a different way.

This model answers Requirements #1, #2 and #4 very well, but answering #3 requires some less attractive assumptions. Also, one might wonder why the proton is not also converted to a wave and, as such, combine with a deuteron wave to make ^{3}He, an isotope not detected except as the decay product of tritium.

While not using the vocabulary of particle-wave conversion, Hagelstein[193] has arrived, after several detours, at a model he proposes answers all of the required conditions. He assumes phonons can interact with the nucleus and these interactions can be at different sites in a lattice, yet coupled together to produce the observed result. In this model, phonons provide the mechanism for coupling rather than wave formation of atoms. Of course, a phonon, which is a mathematical construct used to describe thermal vibrations, must accumulate energy either before reacting or within the nucleus[194] after reacting, two assumptions that are hard to justify.

Resonance, Tunneling and Screening: Deuterons in a lattice experience thermal vibration and, by this process, might get close enough to interact with each other or with the palladium nuclei. However, many calculations show that the atoms are too far apart in β-PdD to interact. If this type of interaction is to occur, neutralization of the Coulomb barrier by surrounding electrons (screening) and/or enhanced barrier penetration using a process called resonance tunneling, as first suggested by Turner[195], must be applied to the process. Each aspect of this process has been addressed in different ways. Agreement is far from universal that any variation on this theme, of which there are many, can explain the amount of AE observed. Only a few will be described here to give a general understanding of the methods being applied.

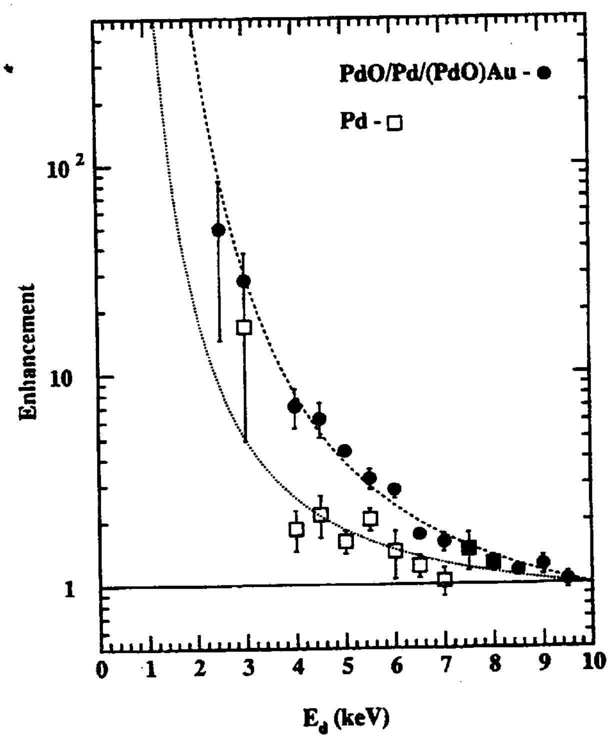

FIGURE 9. Enhancement over the effect found at high energy for the reaction D(d,p)T as a function of energy applied to D+ used to bombard the indicated targets. This work was done at Tohoku University, Japan.

Several people [196, 197] [198] have reformulated a calculation of the Gamow factor which defines how repulsive forces change with distance between nuclei and determines how much "normal" tunneling might take place. By applying a resonance process, a higher than expected fusion rate was calculated, consistent with the Jones [199] level of neutron emission, but not high enough to explain the P-F heat. As noted above, the neutron flux measured by Jones may not have originated from a CANR process at all, but be caused by fractofusion. Clearly, for such a theory to be useful, additional processes must operate. Parmenter[200] comes to the conclusion that "tunneling is most likely when the energy of the deuteron pair most closely matches that of the ^{4}He isomer. Pulsed loading is suggested as a way to achieve this end. This process may operate unintentionally as the active regions experience changes in loading produced by bubble action. However, this mechanism would not apply to the other methods.

Preparata[201] imagines a coherent plasma of electrons within the PdD structure that are able to off-set the charge at the nucleus. He assumes β-PdD exists only in the range $PdD_{0.6-0.7}$ while another phase (gamma), based on tetrahedral occupancy, forms at higher compositions. Unfortunately, the model involves a faulty understanding of the Pd-D system [202] because tetrahedral occupancy has never been observed in this system [203-205] even when its presence was sought. To add to the confusion, a previously designated gamma phase is seen only below 50 K at $PdH_{0.67}$ as an ordering of deuterium vacancies

[206]. The very large compositions reported for the surface of PdD, as noted above, suggests a new phase (PdD_2)[145] to which the model might be applied. Lo [207] has also explored this theme.

Exotic Particles: Several unusual particles are proposed to catalyze nuclear reactions. Such an explanation may answer Requirement #1 in an incomplete way but, in most cases, fails to address the other requirements. However, the implications go well beyond the CANR effect if the claims are true.

Bazhutov et al. [208-210] have proposed the existence of a heavy hadron (175 GeV/c^2) called Erzion, which they have identified in cosmic rays. In a similar manner, but independently, Rafelski et al.[211] visualize a stable, ultra heavy, negatively charged particle called X- to rain down from outer space. These models do not address Requirements #2, #3 or #4.

McKibben [212, 213] proposes the existence of three sets of fractionally charged particles called subquarks (1.15 amu, charge = +e/6), hemitrons (0.13 amu, charge =+e/2, and negative hemitrons (>0.13 amu, charge = -e/2). These are proposed to form into nuclei and mimic the properties of normal isotopes. However, because these pseudo-nuclei are more unstable than their normal counterpart, they can enter into and catalyze nuclear reactions more easily. This model concludes that nuclear-active material contains more of these pseudo-elements than does inactive material. Why the pseudo-elements should be so highly localized and why such a long delay exists for the production of AE are not addressed.

Formation of proton or deuteron clusters: Dufour et al.[214, 215] have observed unusual behavior when a low current-high voltage discharge occurs in H_2 or D_2. These authors have now developed a model based on clusters involving a large number of protons or deuterons combined with the required number of electrons. These clusters, called hydrex or deutex, can bind to a nucleus, thereby lowering the Coulomb barrier for various nuclear reactions.[216, 217] A variety of nuclear products have been found that depend on the materials placed in the discharge, as well as production of anomalous energy. Matsumoto[218] also proposes a deuteron cluster (Nattoh model) in which the fusion reaction is thought to occur. A new particle called Iton is proposed to be emitted from this reaction. Very strange tracks are found in photographic film placed near an active cell, which support this and other interpretations. [219, 220] These models answer only Requirement #1

Formation of electron clusters: Millions of electrons are proposed by Shoulders [221] to form into clusters during any spark discharge. These clusters interact with solids to produce local regions having very unusual properties. This proposal is based on years of study, the details of which have yet to be published, although patents have been issued. [222] When these electron clusters encounter a dielectric, they strongly interact to produce many effects including nuclear reactions. This concept has been applied by Fox et al.[223-225] to a number of conditions used to initiate the CANR effect. Lewis [226] has also proposed similar ideas. Some of the strange tracks found in film placed near a CANR cell [220] may be produced by such charge clusters. [224]

3. CONCLUSION

A growing number of successful replications of anomalous energy using different methods are being reported. This energy is clearly related to the nature of the environment and appears to be generated by various nuclear reactions. Two questions need answers. Do these observations show a real and novel feature of nature? If the observations are truly novel, then how does the nuclear active environment differ from ordinary matter, which is clearly inert? Which of the various observed nuclear reactions is favored also depends on the environment. This being the case, materials science plays a role as important as does nuclear physics.

Evidence for the reality of the claims comes from three sources. First, most of the methods that claim to produce anomalous effects have been duplicated, as noted in Table 1 and some have been replicated many times, especially the PF effect as listed in Table 2. As the reader can plainly see, this fact is in sharp contrast to public perception [227]. Nevertheless, replication is not always successful, requiring knowledge of the important variables and some luck in acquiring special materials. Thanks to the persistence of a few workers, replication is now much easier than was initially the case. Second, similar patterns of behavior have been observed by every investigator who bothered to make the necessary measurement. As an example, a universal relationship exists between the average deuterium content of the cathode and the amount of AP observed using the P-F effect. Third, a study of the D(d,p)T reaction using conventional ion implantation techniques shows that the cross-section for the reaction becomes greater the lower the bombarding energy below 2.5 keV and it is sensitive to the chemical environment. While the measured cross-section is too low to explain the observed EP, one might wonder what would be observed at energies near room temperature when a nuclear-active environment is used.

While many environments, including both metals and compounds, have been successful in hosting AP and NP production, the most successful common feature is the size of the active domain. Crystals having dimensions in the region between micro- and nanometers appear to be the most active. Unfortunately, these domains are frequently not part of the characterized bulk material, but are deposited by various processes on the surface. For example, they can be deposited by electrolysis when the P-F method is used or by ion bombardment during gas discharge. Once formed, these microregions need only to acquire deuterium or, in some cases, hydrogen to initiate a nuclear reaction. In addition to size, a flux of hydrogen or deuterium appears to be necessary. This flux can be generated using either a temperature or concentration gradient. The presence of other elements in the active environment add complexity to the resulting nuclear products.

Apparently, even large Coulomb barriers appear to be overcome by processes currently being explored. Although the mechanism is still not completely understood, no new physics appears to be necessary. Nevertheless, nuclear behavior is quite different from that experienced when high energy is used to initiate such reactions. Especially novel is the absence of radioactivity and energetic radiation, including neutron and gamma emissions. The challenge is to find a rational explanation. This explanation can not be found unless the observations are made known to the general scientific profession, thereby allowing a broad range of knowledge to be applied.

The large number of nuclear reactions being reported and the types of required environments give a particular challenge to theoreticians. In contrast to conventional experience based on using high energy to overcome the Coulomb barrier by brute force, the CANR environment apparently uses a mechanism that can neutralize the barrier. This more subtle method apparently is obscured when high energy is applied, this situation being like the difference between a rape and a seduction. The problem is to identify the nature of these environments. Up to now, almost all effort has been focused on explaining how the nuclear reactions can take place once the environment is created. While this insight is important, it has not been much help in finding the best environments. This approach needs to change if commercial applications are to be achieved and if the skeptical attitude is to change.

Everyone who has worked in this field has suffered an amount of professional rejection and personal attack well out of proportion to the scientific issues.[228-231] Professors Stanley Pons and Martin Fleischmann paid an especially high price at the hands of their fellow scientists. This attitude has even extended to the US Patent Office. With only a few exceptions, patents cannot be obtained in the US on this subject, although other countries issue patent protection on a routine basis. This rejecting attitude has also been adopted by industry and by most levels of government, especially the U.S. Department of Energy. In addition, a few individuals have repeatedly intervened to prevent an open and honest discussion of the subject, as described by Mallove and Rothwell [232]. In view of the expected energy shortage, the threat of global warming, and the growing accumulation of nuclear waste, the present attitude needs to change [233]. This phenomenon has the potential to solve several major problems if normal procedures for scientific discussion and study are allowed. In spite of this general rejection, the American Physical Society, the American Chemical Society and the American Nuclear Society are to be complimented for their willingness to permit discussion of this subject at their recent conferences. Fusion Technology, a publication of the American Nuclear Society, edited until recently by George Miley, and the Journal of Electroanalytical Chemistry have been especially helpful in the past. However, Physical Review B, Review of Modern Physics, Chemical Reviews, and J. Electroanalytical Chemistry turned down a request to publish this review. Fusion Science and Technology (formerly Fusion Technology), is also unwilling to publish papers on the subject.

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