A Critical Evaluation of the Pons-Fleischmann Effect (Part 1), E. K. Storms, Infinite Energy **6**, #31 (2000) 10.
A Critical Evaluation of the Pons-Fleischmann Effect (Part 2), E. K. Storms, Infinite Energy, **6**, #32 (2000) 52.

A Critical Evaluation of the Pons-Fleischmann Effect (Parts 1 and 2)

Edmund Storms
2140 Paseo Ponderosa
Santa Fe, NM 87501
e-mail: storms2@ix.netcom.com

ABSTRACT

Many new studies are available to make an objective evaluation of the Pons-Fleischmann effect possible. The phenomenon is conventionally known as “cold fusion,”or “chemically assisted nuclear reactions (CANR)” when the environment is emphasized, or “low-energy nuclear-reactions (LENR)” if emphasis is placed on the process. A wide range of observations involving anomalous production of energy as well as nuclear products have been published. While many of the claims are still open to interpretation, the general conclusion is that an important, novel phenomenon has been discovered which deserves renewed interest.

1. INTRODUCTION

Since the claims by Profs. Pons and Fleischmann [1](P-F) were announced ten years ago, studies have been undertaken by hundreds of scientists in laboratories in at least nine countries[2; [3; 4] in an attempt to verify what they then called called “cold fusion.” Some of the results support the idea that anomalous nuclear reactions can be made to occur in special solid materials. Many more investigations failed to show the claimed effects. Although this body of work is largely unknown to the general scientific community, it nevertheless is believed by many to show the claims to be false.

Ten years of work worldwide have produced over 2500 published papers[5], many peer-reviewed, which have answered most of the objections leveled by critics. It is now possible to make a more objective evaluation of the phenomenon than was previously possible. Unfortunately, during this time the claims have been the subject of considerable distortion. The reader is asked to lay aside the emotional reaction “cold fusion” can generate and read the following arguments with an open mind.

Some readers will be put off by the clear conflict between claimed behavior and well-accepted theory of nuclear interaction presently in vogue. The author is well aware of this problem. Nevertheless, a large collection of anomalous behavior must be explained. The fact that this behavior cannot be explained by conventional theory should only serve to challenge theoreticians rather than be used as justification for rejection. In fact, many approaches to this problem are being pursued and a few will be discussed later in the paper.

The field which is conventionally called “Cold Fusion” has grown and now should be called “Chemically-Assisted Nuclear Reactions” or “Low-Energy Nuclear Reactions,” depending on the emphasis one wishes to apply. The claims are supported by a wide range of anomalous behaviors involving nuclear reactions and energy production. Many methods and chemical

environments have been found to produce consistent patterns of behavior. This paper will only address the claims for heat production using the electrolytic technique with palladium as the cathode and heavy-water as the electrolyte, as was originally used by Pons and Fleischmann.[6] Also evaluated will be the nuclear reaction which is proposed to be the source of this claimed anomalous energy. A broader understanding can be obtained by reading several reviews which are available.[2; 3; 4]

Only a small number of selected studies are examined here to which criticisms raised by numerous skeptics are applied. An attempt is made to discover whether these objections are justified and to show why reproducibility has been so difficult. Of course, many studies have been poorly done and cannot be used to evaluate the claims either way. Such deficiencies are common in all aspects of science and, hence, can be reasonably ignored. The essential question requiring an answer is whether the most complete studies are sufficiently free of counter explanations to allow a belief in the claims to prosper. In addition, an attempt will be made to determine how well the claims have been replicated and whether consistent patterns of behavior have been revealed. For good reason, these are the techniques science demands be followed when any new idea is evaluated.

In contrast to these conventional criteria, numerous critics have observed that "extraordinary claims require extraordinary proof." This is a very high standard which has prematurely doomed many new ideas to the trash bin, some deserving and some not. We need to realize that potential errors can be found by clever critics in any study, no matter how well done. Hence, a perfect proof is almost impossible to obtain until considerable information has accumulated. Such an accumulation is very slow and difficult if an idea is completely rejected, as has been done in this case. Consequently, at the very least, I would hope that the skeptical reader would entertain the possibility that some part of the claims deserve further study, even though all important questions have not, as yet, been answered.

This review is being published in two parts. The claims for anomalous energy are discussed in this, Part 1, and the second part will address production of helium as a nuclear product and the proposed explanations.

2. 0 ANOMALOUS ENERGY EVALUATION

2.1 Energy Measurement

For the moment we need to put aside the acknowledged mistakes made during the early work. Also we need to forget the many failed attempts at replication made by uninformed and rushed efforts early in the field's history. Although these studies had an inordinate negative effect, they were flawed by any reasonable standard as has been argued in various papers.[7; 8; [9; 10]

Some scientists require neutron emission be observed before they will accept the claim for a fusion reaction.[11] Significant neutron emission is not observed during anomalous energy production. The question then becomes, if the process does not involve conventional fusion, what is producing the anomalous energy? Critics attribute the extra energy to error in measurement or normal, overlooked chemical processes. This assertion will be addressed in the following section.

Four questions must be answered when evaluating this experimental work.

1. Was the calorimetric technique used by Pons and Fleischmann sufficiently stable and accurate to see the claimed extra energy?

2. Can prosaic sources of chemical energy be ruled out?

3. Have other people replicated the claims using sufficiently stable and accurate calorimeters?

4. Have reasons for success or failure been discovered?

Before answering the first question, a general comment about the calorimetric method is necessary. Critics have misunderstood the difference between relative and absolute calorimetry in their search for errors.[12] Although the absolute approach was used during early measurements in order to detect an immediate production of energy, this method was later found to be unnecessary, because production of energy was found to require a long wait. This delay allows a null condition to be defined, independent of absolute knowledge of power production. Any random variation in the signal is also revealed during this interval. In addition, repeated calibration during this delay can be used to demonstrate that the calorimeter is stable. Consequently, referencing the data to an initial zero value, as is done in most publications, is convenient but not necessary. Instead, power production is claimed when the signal rises above a previously steady but arbitrary background value. Seeing a signal rise out of the noise is easy and does not depend in any way on knowing the actual amount of heat being produced in the cell. The magnitude of the resulting energy is then calculated using the *change* in cell conditions and the calibration constant. All absolute values of error in temperature, voltage, current, and other conditions cancel, provided the values for these quantities have remained constant. As a result, the observed presence of excess energy is more certain than is its absolute value. If an error is to be found, it must explain how a sudden change can occur in previously stable conditions and how this change can be missed by repeated calibrations and studies of inert materials, so-called control experiments. Nevertheless, some overlooked errors are important and will be discussed.

2.1.1 QUESTION 1: Was the calorimetric technique used by Pons and Fleischmann sufficiently stable and accurate to see the claimed extra energy?

P-F used an open cell which was not mechanically stirred. As a result, objections were raised as to the uncertain amount of unrecombined oxygen and deuterium gases leaving the cell and the uncertain temperature within the cell. In addition, their mathematical analysis of the method was complex and open to misinterpretation. Each of these complaints will be examined.

2.1.1.1 Discussion of Recombination

Electrolytic action decomposes heavy water to give D_2 and O_2, which carry away chemical energy upon leaving the cell. Should some fraction of these gases unexpectedly react to reform water within the cell, the actual amount of energy being generated in the calorimeter would be uncertain. Kreysa *et al*.[13] immediately raised this issue because P-F did not address the problem in their original paper. Later P-F [14] stated that the amount of recombination was determined by measuring the amount of water which disappeared from the cell as a function of time and applied current, and that the amount was insignificant. In spite of this statement, Jones *et al*.[15], using applied currents between 0.96 mA and 8.08 mA, suggested much later that all such anomalous heat production can be explained by uncertain recombination. Will [16] did an analytical analysis of this effect and concluded that the conclusion reached by Jones *et al*. was wrong. Unfortunately, this false explanation has been widely advertised by Morrison, a vocal critic of the claims. [17] These claims and counter claims are resolved in the following description of the

recombination process.

At low current, the following is true and not in dispute:

1. Bubbles are small and convection currents are weak. Hence, some bubbles can diffuse through the solution and reach the opposite electrode surface where they are available to react.

2. Electrolytic gas production is inadequate to saturate all active sites on the electrode surface. Consequently, some active sites remain and these can absorb the opposite gas, thereby allowing recombination. The presence of deposited platinum on the cathode surface increases the population of active sites[18] and can enhance the process.

3. A small but fixed amount of the gases can dissolve in the solution and bathe the opposite electrode. In this case, recombination occurs after an atom has diffused through the layer of opposite gas created by electrolytic action and encountered an active site.

Therefore, a significant fraction of generated gas can recombine when the current is small. On the other hand, at larger currents, additional factors operate.

4. Ions formed during electrolysis recombine to form bubbles of gas at the same active sites needed as a precursor to recombination. Consequently, a blanket of evolving gas protects the very sites needed for recombination. The amount of this gas blanket increases as current is increased.

5. Increasingly larger and more numerous bubbles create a convection current which rapidly carries many bubbles to the surface where they lose their contents to the ambient gas. The amount of this convection increases with applied current. Indeed, Jones *et al.*[15] showed that simply increasing convection by bubbling nitrogen through the electrolyte had a linear effect, while reducing recombination to trivial levels.

Consequently, recombination at high current will be limited by the availability of active sites as well as by the availability of gas. As a result, the fraction of gas which can recombine on electrode surfaces will decrease as applied current is increased, regardless of how potentially active the surface may become. Indeed, Jones *et al.*[15] noted that application of currents higher than those used during their published study reduced the amount of recombination. Nevertheless, they insisted on applying their experience to cold fusion studies which used higher currents.

The effect of a gas blanket was measured directly by Divisek *et al.*[18] In this case, the amount of recombination was high early in the loading process, when all generated hydrogen was being absorbed by the cathode, hence not available to protect active sites or to generate convection. On the other hand, no recombination was detected after the cathode became fully loaded, when hydrogen gas was being evolved from the surface. However, this is not the interpretation given by the authors.

A study done for this paper is shown in Figure 1 where the fraction of recombination is plotted as a function of the log of applied current. Stirring the cell and use of palladium or platinum as the cathode made no difference. Also shown are the results of Jones *et al.*[15], who used a nickel cathode, and the calculations obtained by Will[16] based on a model. Jones *et al.*[15] found that increasing the area decreased the amount of recombination for the same applied current. This and other studies show that recombination is trivial above about 100 mA applied cur-

rent. Therefore, the conclusion reached by Jones *et al.* applies only to cells studied at very low currents. As can be seen in Table 1, most of the studies claimed by P-F to make anomalous energy employed currents well in excess of 100 mA. In addition, excess energy has been claimed using closed cells containing a recombiner, to which this error does not apply.

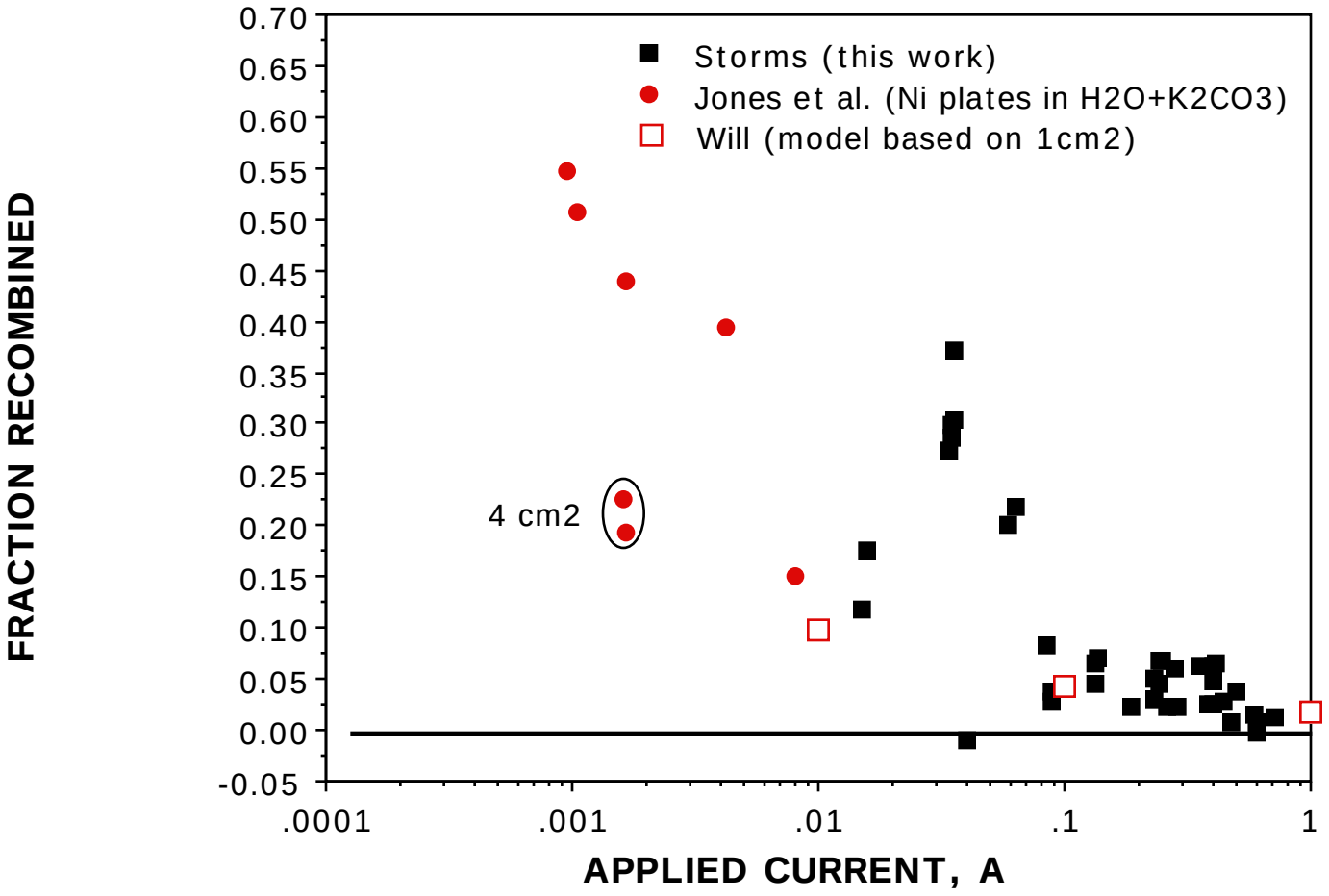

Figure 1. Effect of applied current on the fraction of evolving gas being recombined. The present work uses LiOD+D_2O with a 4 cm^2 cathode and Pt mesh anode. The data given by Jones *et al.* [15] is converted to fraction of recombination by dividing the measured apparent excess power by the applied power, assuming no anomalous energy is being produced. These values are based on 1 cm^2 and 4 cm^2 nickel cathodes. The calculations of Will[16] are based on a cathode area of 1 cm^2.

2.1.1.2 Discussion of Temperature Errors

An isoperibolic, or ΔT, calorimeter, as used by P-F, requires the average interior fluid temperature be well-known and stable. Electrolytic action creates local heat production, which can produce temperature gradients. Consequently, the location where temperature is measured is important. Miskelly *et al.*[19] proposed that insufficient mixing occurred within the P-F calorimeter and N. Lewis [20] made this a major point in his early criticism of the P-F work.

To answer this criticism, a number of people studied this effect [21; 22; 23] and found it to

be trivial. P-F answered the criticism by using five thermistors to show that the gradient was less than 0.01°[24] in their typical cell. Results from a study by the author[25] using a similar configuration are plotted in Figure. 2. Shown is the temperature gradient between the top and bottom of the fluid as a function of applied electrolytic current. An internal heater supplies constant power to the electrolyte. In the absence of bubbles, a large gradient is detected. When electrolytic power is applied, thereby creating bubbles, the gradient rapidly disappears.

The unanimous conclusion from this collection of experience is that bubble mixing is able to produce a sufficiently uniform temperature within the electrolyte. Therefore, the effect proposed by Lewis has not been supported by subsequent work. Unfortunately, this criticism provided a major reason for early rejection of the P-F work, a situation which continues.

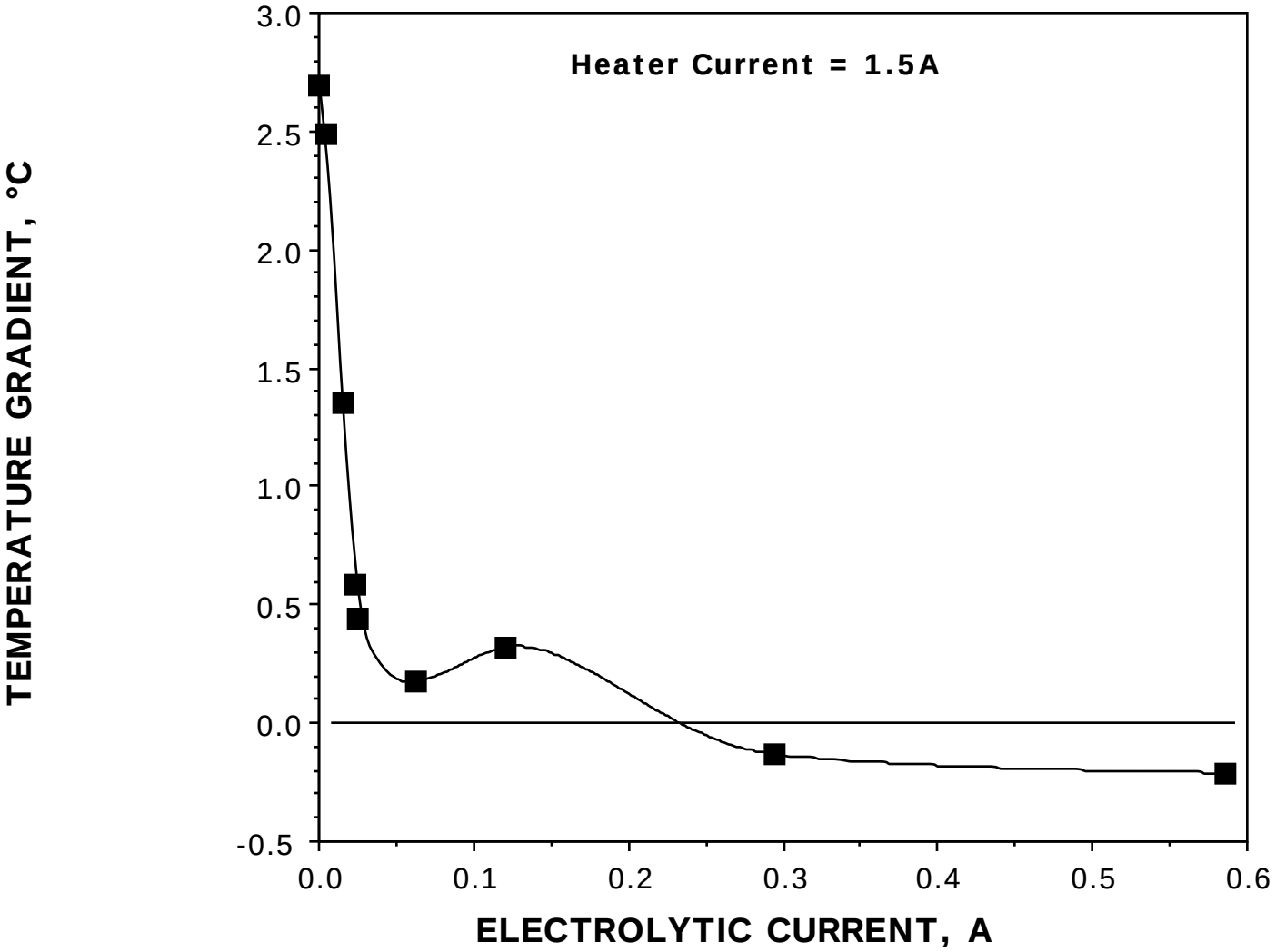

Figure 2. Reduction in gradient as electrolysis current is increased at fixed heater current.

Overlooked by these studies is another possible source of error. Knowledge of the amount of energy being produced in such a calorimeter requires the thermal conductivity of the wall be known and stable. Stirring changes the effective thermal conductivity of the wall because the

amount of stagnate fluid next to the wall is changed. This factor is very sensitive to the amount of fluid convection next to the wall and shows no saturation as convection is increased.[25] This effect can be seen in Figure 3 which shows the relationship between effective thermal conductivity of the cell wall as a function of stirring rate. Even mechanically stirred devices will suffer an error if the stirring rate should change. Whether this effect is important depends on the frequency of calibration, the type of calibration used, and the constancy of bubble action. Therefore, the effect of this error on the various studies using the isoperibolic method is hard to judge. To the extent that it operates, one should see an apparent positive as well as negative anomalous energy. All reported data show only positive excursions. While it is possible that an experimentalist could eliminate all negative excursions as being nonreal, this nonscientific approach does not appear to be common. This error would not apply to flow-type, double-layer isoperibolic-type or Seebeck-type calorimeters, each of which has been used to demonstrate anomalous energy, as will be described in a later section. In addition, several cell designs used by P-F would be immune to the effect because the thermal barrier, *i.e.* the barrier across which heat flow is measured, was located in the gas space, above the fluid.

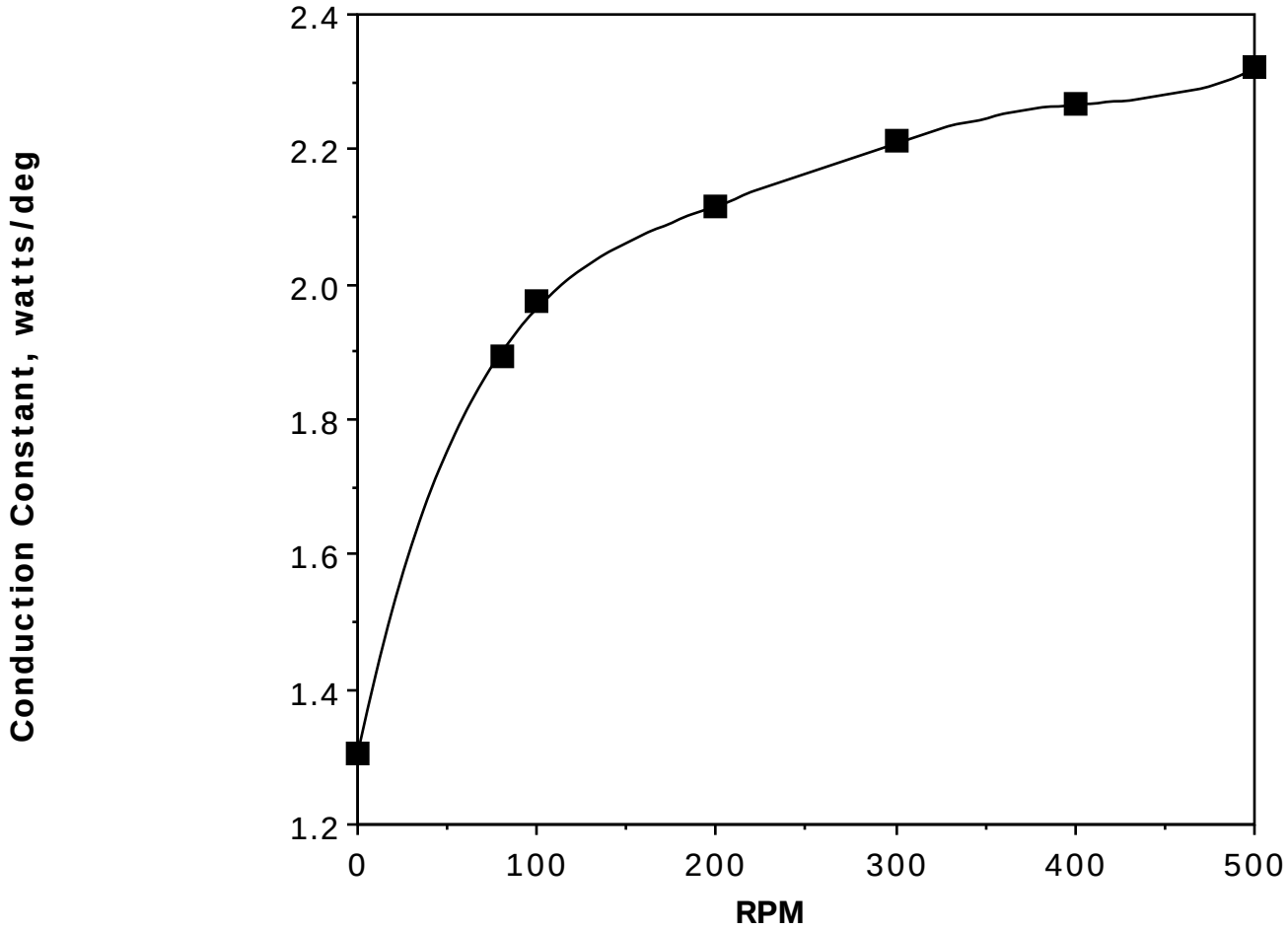

Figure 3. Effect of stirring rate on the effective thermal conductivity of a cell wall. Power is applied electrolytically to a typical cell design. Stirring is done using a Teflon covered magnetic bar located at the bottom of the cell.

2.1.1.3 Discussion of Mathematical Approach

Three studies have evaluated the basic design of the P-F calorimeter. The first was commissioned by General Electric Co. and reported by Wilson *et al.* [26]. The two most serious problems they note are the change in calibration constant produced by liquid level change, and potential loss of heavy water with the evolving gases, thereby producing a loss of overlooked energy. The authors acknowledged that P-F avoided the effect of these errors, as well as several others, by frequent calibration. Thus, changes in cell conditions could be quickly eliminated as being the cause of anomalous energy. Although the authors claimed to find some minor mistakes, the final conclusion of this analysis is that only the magnitude of the anomalous energy can be questioned by their analysis, not its existence. Because their attempts to duplicate the claimed energy production using various types of palladium, cell designs, electrolytes, and anode metals were unsuccessful, they were not optimistic about the reality of the claims.

Next, the State of Utah requested another evaluation to be undertaken by W. N. Hansen [27], a professor in the Physics Department at Utah State University. Prof. Hansen had the advantage of access to the raw data of P-F. First of all, he was able to show, using experimental measurements, that the model used by P-F was accurate to within ±2% up to 90° C. Thus, the limitations proposed by Wilson *et al.*[26] are shown not to be important. Use of the heat-pulse calibration method is found to be completely valid. Hansen's analysis also shows that the data are consistent with excess energy being produced at normal temperatures, using the measured calibration constant, and at the boiling point, using the rate of boiloff. Examples of excess energy of 114 kJ or 470% of applied power at the boiling point and 1.5 watts for 2 days at normal temperatures in another case are noted. Several potential deficiencies are discussed. Cells showing the highest energy production had the largest calibration constant, and some cells were not regularly calibrated by heat-pulse. Nevertheless, Prof. Hansen concludes that sufficient evidence exists to warrant further studies.

Shortly after P-F were funded by Technova and a new laboratory was set up in France, the Japanese government created the New Hydrogen Laboratory (NHE) in Sapporo, Japan. Pons and Fleischmann worked with this laboratory in an effort to duplicate their claims. As a part of this collaboration, Saito *et al*.[28] evaluated the P-F calorimetric approach. They conclude, based on their study of a similar cell, that the minimum detectable power is ±0.3 W using the model proposed by P-F, compared to a claimed uncertainty of ±0.1% (±0.1 to ±0.0002 W). [29] Modifications to this model allows a new proposed limit of ±0.03 W. However, this improved approach failed to reveal anomalous energy during many attempts at the NHE laboratory. This problem will be discussed in a later section.

While room for debate still exists as to the accuracy of the P-F technique, three independent evaluations conclude that P-F could detect the amount of anomalous energy they claim. Whether they actually produced anomalous energy must depend, in part, on the ability of other workers to reproduce the claims.

Before going on to examine attempts at replication, it is worth first discussing the P-F measurements in detail because they were the focus of so much criticism. Figure 4 shows a drawing of the P-F cell. In this case, electrolytic action occurs in a cell which is surrounded by a vacuum jacket that is silvered except near the top. Thus, the thermal barrier is located at the top of the cell, including the lid. This assembly is placed in a constant-temperature water bath. Contained in the cell along with the anode (Pt) and cathode (Pd) are a glass-covered heater, a single glass-covered thermistor, and a reference electrode. P-F answered some of the criticisms in several papers[30; 31; 32] from which the following observations can be summarized:

Currents between 25 mA and 804 mA were used with most measurements taken above 100 mA. Thus, most measurements were outside of the critical current range for internal recombina-

tion. Furthermore, they state that the amount of recombination was measured by monitoring the amount of D_2O used. Recombination was found to be no greater than 1% of applied power. Mixing was found to be adequate to eliminate temperature gradients based on experimental observation as noted above. Calibration was based on a pulse of heat applied to the submerged resistor with the resulting temperature rise and decay noted. This type of calibration allowed pulsed as well as sustained heat production to be evaluated. Heat production which caused boiling was evaluated by noting the rate at which liquid was converted to vapor . In this case, energy evolution was determined using three independent methods. These are normal isoperibolic calorimetry (i.e. using a temperature difference), rate of temperature change using the measured heat capacity of the cell, and energy consumption obtained by measuring the amount of water vaporized. Each method showed anomalous energy production. Indeed, excess heat production at the boiling point has been duplicated by Mengoli *et al*..[33]

Table 1 lists excess power values published by P-F. A wide range of conditions were explored as well as a number of inert, control cells. Clearly, a level of excess power was claimed which far exceeds the error proposed by the most critical evaluations of their work. In addition, they found some cells to continue producing power even after electrolytic current was turned off, so called “heat-after-death”.[34] Recently, they have explored in more detail energy production at the boiling point. They noted an important pattern of behavior, which was that the amount of excess power increased as the amount of current was increased. The effect of increased applied current can also seen in a partial list of other studies[35], some of which used an internal recombiner catalyst, as shown in Figure 5. [36] The line defines the upper limit created by all reported studies as of 1991, some of which are not within the boundaries of the graph. A more extensive plot can be seen in Storms. [35] The scatter is now thought to be caused by variations in the properties of available palladium. More will be said about this problem later.

In contrast to the great care P-F used in describing and evaluating their calorimeter, they showed no interest in the properties of palladium. The source, treatment, and achieved D/Pd ratio are not noted. Indeed, it is impossible to know whether the listed measurements were made on a few or many samples of metal. This oversight is the main reason subsequent studies have had so much trouble duplicating the results and it represents a major flaw in their work.

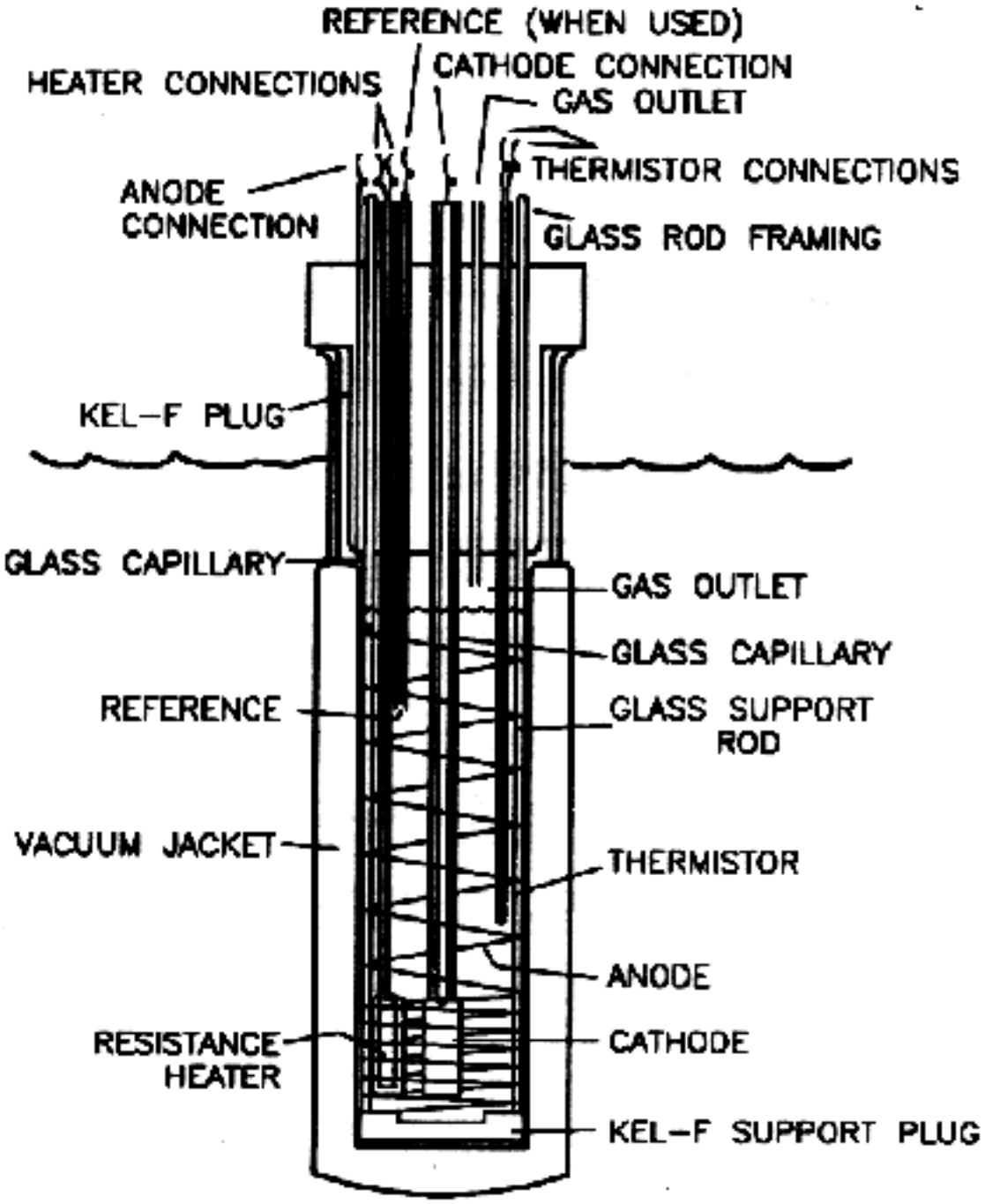

Figure 4. Drawing of P-F calorimeter. The upper section was silvered in later versions.

TABLE 1

Excess Power Reported by Pons and Fleischmann
using D_2O+LiOD and D_2O+Li_2SO_4 electrolyte

Sample Type	Area cm^2	Current mA/cm^2	Excess Power W	Reference
Rod	3.1	8	0.0075	[1]
	3.1	64	0.079	[1]
	3.1	64	0.042	[24]
	0.4	64	0.001	[24]
	3.1	128	0.160	[24]
	0.4	128	0.005	[24]
	3.1	256	0.313	[24]
	0.4	512	0.170	[24]
	3.1	512	1.05	[24]
	0.4	1024	1.03	[24]
	6.2	8	0.036	[1]
	6.2	64	0.123	[24]
	6.2	64	0.006	[24]
	6.2	64	0.024	[24]
	6.2	64	0.493	[1]
	6.2	128	1.65	[24]
	0.4	128	0.028	[24]
	6.2	256	0.056	[24]
	0.4	512	0.66	[24]
	0.4	512	0.603	[24]
	0.4	1024	2.80	[24]
	12.4	8	0.153	[1]
	12.4	64	0.502	[24]
	12.4	64	0.263	[24]
	11.0	64	0.117	[24]
	0.4	64	0.0005	[24]
	12.4	64	1.751	[1]
	12.4	128	1.05	[24]
	0.4	256	0.311	[24]
	0.4	512	2.18	[24]
	0.4	512	1.65	[24]
Plate	128.	0.8	0.0	[1]
	128.	1.8	0.027	[1]
	128.	1.6	0.079	[1]
Controls Using Light-Water or Platinum				
Rod	3.1	32	-0.001	[24] H_2O
	3.1	64	-0.001	[24] H_2O
	3.1	128	-0.001	[24] H_2O
	3.1	256	-0.001	[24] H_2O
	3.1	512	-0.001	[24] H_2O
	3.1	64	0.000	[24] Pt
	3.1	64	-0.001	[24] Pt
	3.1	256	-0.001	[24] Pt
	3.1	64	-0.002	[24] Pt
	3.1	64	-0.003	[24] Pt
	3.1	512	-0.001	[24] Pt

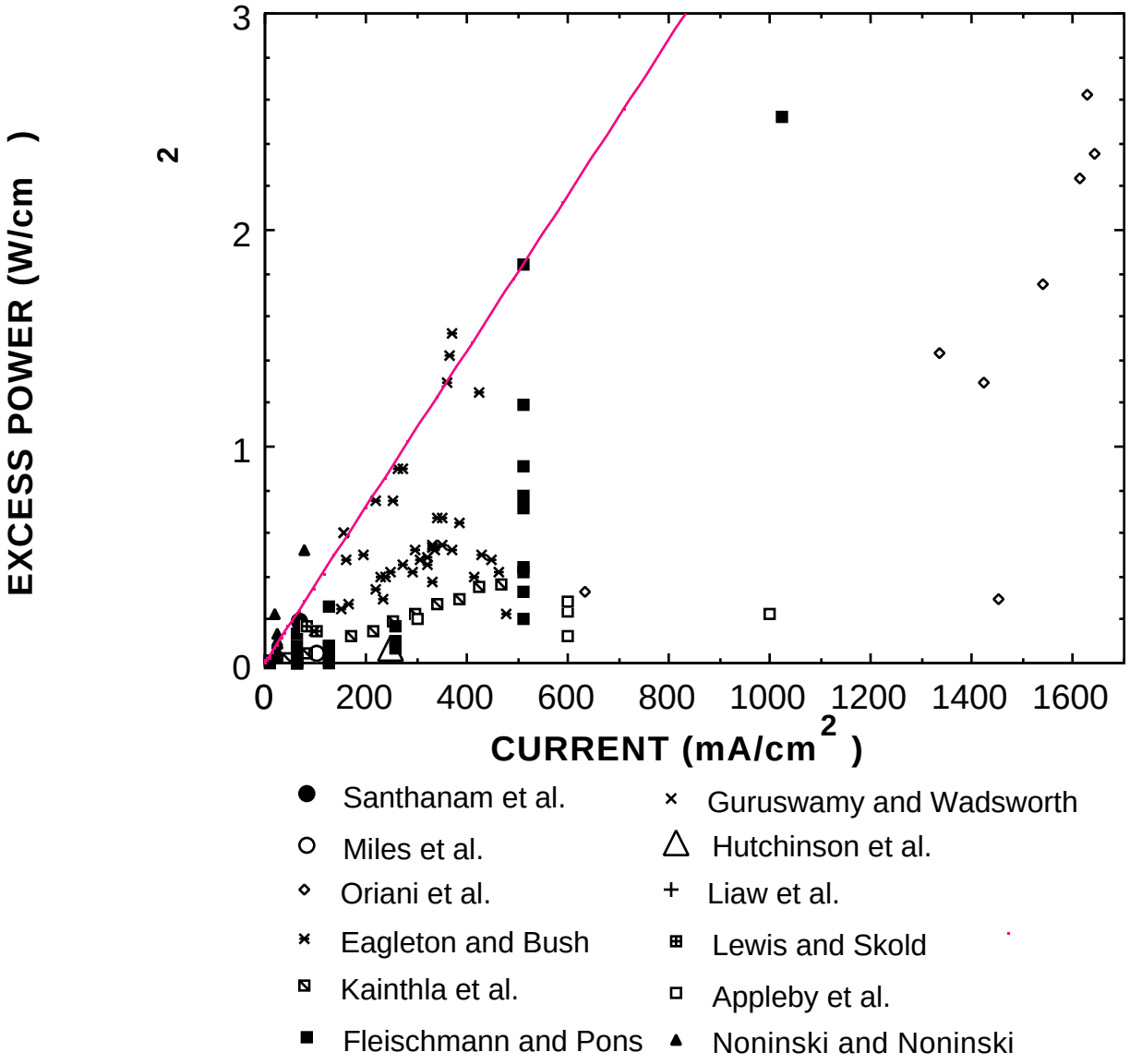

Figure 5. A comparison of power production as a function of applied current density. The line shows the upper limit of all reported values, some of which are off the graph.

2.2 QUESTION 2 : Can prosaic sources of chemical energy be ruled out?

The hard-to-accept claim for a nuclear source is based, in part, on the belief that observed energy production exceeds any known chemical source. Therefore, the potential chemical sources must be examined. Before discussing this subject in detail, the reader should realize that a typical cell contains very few chemical components, all of which are stable with respect to each other. A chemical reaction can only be initiated by applying an electric current, a process which uses energy. Only after the water has been split into deuterium and oxygen can chemical reactions occur. This process causes several chemical reactions, including an uptake of deuterium by the palladium and slow deposition of lithium and platinum on the cathode surface. Each

of these reactions involve very little energy. Strain energy accumulates in the palladium and small amounts of reaction products such as D_2O_2 can accumulate in the solution under proper conditions. These processes have the potential to store energy within the cell. Only release of stored energy can be used to explain the anomalous energy, which appears after many hours of electrolysis.

The magnitude of such processes was addressed in several papers. Kainthla *et al.*[37] discussed eight possible sources, including recombination, which has been already discussed above. The other sources are the energetics of PdD formation, the energetics of PdLi formation, and energy accumulation as stress. Each of these was found to be much too small to account for even the smallest reported excess energy. Handel[38] proposed that heat could be pumped into the cell by a temperature gradient operating between the anode and cathode lead wires, *i.e.* a Peltier Effect. Two problems exist with this explanation. A significant temperature difference seldom exists between the two lead wires and the necessary difference between the Peltier coefficients of the wires must be unreasonably large to produce an observable effect. Most people use platinum for both wires, which would have a zero difference in the Peltier coefficient.

Balej and Divisek[39] compiled all necessary thermochemical values and calculated the energy involved in electrolytic formation of β-PdD. Measured energy using inert palladium is consistent with these values,[18] as is true of all negative studies. Berlouis *et al.*[40] reported a direct measurement of the heat of dissociation of $PdH_{0.9}$, formed by electrolysis, using thermal analytical techniques. The result is consistent with values obtained by using other techniques. Consequently, no anomalies have been found in the energetics of β-PdD. However, it is possible for an unknown compound to form which, when decomposed, could give off the observed energy. While such a compound has been sought, it has not been detected. In addition, such a material would have to be able to store hundreds of megajoules of energy in the few grams of palladium normally used. If this were the energy source, the material would have an energy density greater than the most powerful chemical explosive. This conclusion, if true, would be as important as a nuclear source.

Mills and Kneizys[41] have proposed formation of the hydrino[42] atom as the source of energy. In this model, the electron of deuterium is caused a shift in to a lower level below the conventional ground-state with release of energy. The resulting shrunken atom is able to diffuse out of the cell without reacting with oxygen, hence does not accumulate. This explanation is not consistent with experience, because a closed, sealed cell containing a recombiner would then experience a steady accumulation of oxygen during excess energy production, a condition which is not observed.

2.3 QUESTION 3: Have other people replicated the claims using sufficiently stable and accurate calorimeters?

Of the more than fifty reports of excess energy, a few of which are shown in Figure 5, the work at Stanford Research International (SRI) [43] is the most complete and accurate. Initially, this work was funded by a $6 million grant from the Electric Power Research Institute (EPRI). After this program was terminated, work was continued by IMRA, Japan at nearly the same level. Now a very small effort is being funded by the U. S. government. Over the course of this study, several designs of flow-type calorimeters were used. These share the following features:[44]

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 the change

in gas pressure.

2. The cells contain a heater which maintains a constant inner temperature. Power to this heater is adjusted to compensate for any change in power production within the cell produced 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 the cooling fluid, is accurate. A sensitivity of 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 constant temperature of 30°C.
5. A constant flow pump is used to circulate cooling fluid. Flow rate is checked periodically by weighing the fluid. 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 RTDs are used for temperature measurement.
7. The deuterium content of the palladium cathode is determined by measuring its change in resistance.
8. Most studies involve a similar calorimeter containing an inert cathode as a reference. Both calorimeters are run electrically in series and measurements alternate between the two systems using the same voltage and current meters.

Flow calorimetry is relatively simple and suffers from fewer errors compared to the isoperibolic method used by other people, as well as by P-F. Only four physical measurements are required. The applied power is determined by measuring applied voltage and current at the isothermal boundary, and the released power is obtained by measuring the flow rate and the temperature change of the cooling fluid. Internal temperature gradients are not important, stirring is not an issue, and uncertain recombination is not a source of potential error. Only unexpected changes in the measuring systems can introduce error. McKubre *et al*. have demonstrated their instruments to be stable and accurate through years of use.

On the other hand, an evaluation of this study can assume prosaic errors which might have been overlooked in spite of this experience, as several skeptics have attempted to do. Two possibilities will be examined.

1. The location of heat production within the cell might change and this change might allow a different fraction of the produced energy to be captured by the cooling water.

This assertion can be answered in three ways. First, less than 2% of the heat is missed by the cooling water. Any change in internal conditions would only impact on this small residual. Even if the total amount of residual should change, insufficient error is created to account for the observed anomalous energy. Second, the proposed effect was studied by placing a heat source at different locations. No effect was observed.[45] Third, no mechanism exists in the cell to allow the source of energy to change location. The suggested shift in recombination from the recombiner to the electrode surface would not allow a significant change to take place as has been discussed above.

2. The voltage and current might be occasionally incorrectly determined because rapid fluctuations might be introduced by bubble action. These variations are proposed to be missed by the DC circuitry.

If some fraction of the AC component were to be ignored by the measuring circuit, the effect would be complex.[46] At constant current, a reduction in apparent current would cause the voltage to rise in an attempt by the power supply to restore the set current. This would cause power applied to the cell to increase and this increase would be seen as excess energy. If, in addition, the measured voltage were lower than the actual voltage of the AC plus DC voltage component, the result could be interpreted as additional excess power. Studies by the author found a typical cell to have a maximum AC component of about 50 mV. Assuming all of this is missed by the measuring circuit and the applied current is 3 A, the maximum apparent excess power would be 0.15 W. This value is small compared to power measured when 3 A was applied to the quoted studies. Many studies that use small samples do not even reach this level of current. However, it is impossible to know just how this one experience might apply to all studies, because all reported data are found to become more scattered as applied power is increased. This scatter is caused by variations in the measured voltage and in temperature within the electrolyte. While these variations appear to be random, they might cause a net shift in conditions so as to be misinterpreted as excess energy. If this were the explanation, it seems unlikely that apparent anomalous heat would be reported by so many investigators using different measuring circuits, applied current, and calorimeter designs. Furthermore, this effect would not be sensitive to the nature of the palladium cathode as anomalous energy is found to be. Such an effect in the SRI studies would be observed in the reference cell as well as in the active cell. No such error was detected in this study. While these considerations do not fully answer the question, they do reduce the likelihood of this being the total explanation.

Another way to judge whether this study is observing a real phenomenon is to determine whether patterns of behavior associated with anomalous energy production are also seen by other workers. Five significant patterns have been observed.

1. The D/Pd ratio must exceed a critical value.
2. The current must be maintained for a critical time.
3. The current density must be above a critical value.
4. Inert palladium can sometimes be activated by adding certain impurities to the electrolyte.
5. The effect occurs in only a small fraction of samples but more often in certain batches than in others.

Each of these claims is consistent with other studies when the necessary measurements were made. Consequently, many studies not only support the claims of P-F but the same observed patterns of behavior also have been reproduced. Let's examine each of these patterns in more detail.

1. The D/Pd ratio must exceed a critical value.

Before examining the data, it important to realize that a reported D/Pd ratio is, in every case, an average value for the entire sample. This average is sensitive to the size and shape of the sample, because the deuterium content is not uniform within the material. Edges of plates and ends of rods will experience a lower deuterium content than regions remoted from these loss sites. All else being equal, wires will have a higher average composition than do plates. In addition, the method used to determine the average composition will influence the observed value. Therefore, comparison between absolute values is not possible, only trends in behavior can be compared.

Figure 6 shows the relationship between excess energy and composition for a wire sample studied at SRI. After examining 214 wire samples which gave 177,640 hours of data, McKubre *et al.*[47] report that when excess power was measured, it was detected every time when the cathode achieved a loading of D/Pd≥0.95. It was detected approximately half the time when D/Pd was between 0.90 and 0.95, and only one time when D/Pd was below 0.90.

The behavior of several plates studied by Hasegewa *et al.*[48] in Japan is shown in Figure 7. An earlier study by the same group[49] using wire can be seen in Figure 8. Other workers have shown the same effect but not in as much detail. For example, Storms[50] studied a collection of plates supplied by IMRA Japan and found excess energy production when the average composition exceeded a D/Pd of 0.82. However, some samples are occasionally found to achieve high compositions without producing excess energy. Further study[25] showed surface composition to be the important variable and this quantity was not always directly related to average bulk composition. In addition, deposition of certain impurities into the surface is also thought to be required before a sample can become active.

Because evidence for anomalous behavior is only seen at isolated and scattered spots on the surface, the highly variable nature of the relationship between average composition and heat production apparently is caused by the well known, highly variable nature of a palladium surface. Clearly some pieces of palladium contain more active regions than do others, thus the lack of consistency in the measurements.

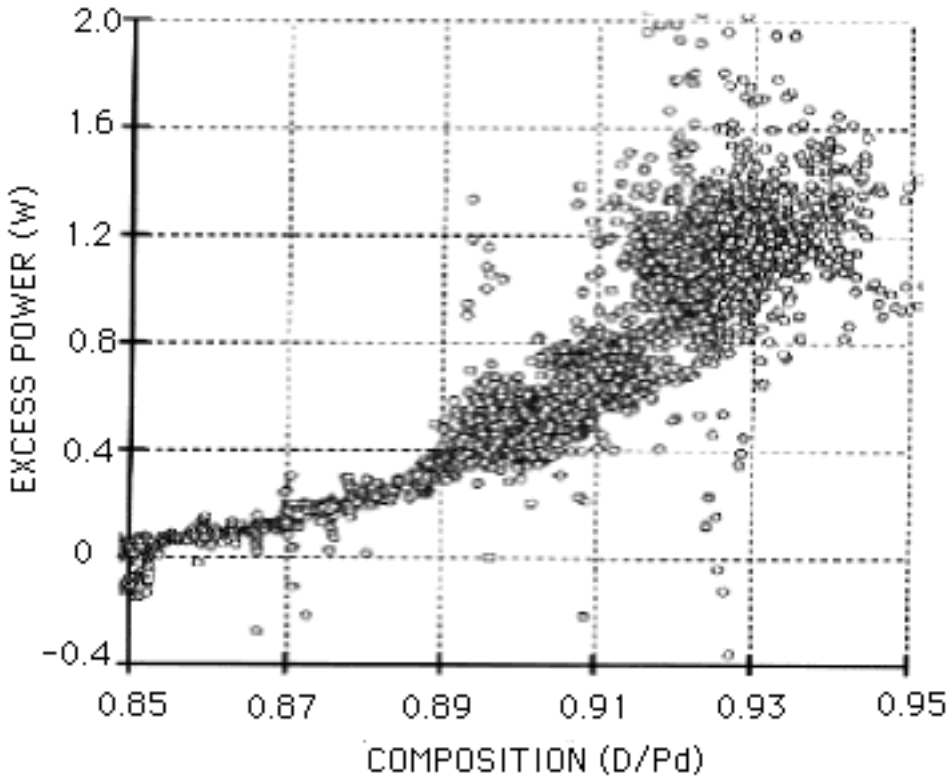

Figure 6. Typical effect of average bulk composition of a wire on the production of excess energy. Data was obtained at SRI using a flow calorimeter. Composition is based on changes in resistivity.

2. The current must be maintained for a critical time.

Every investigator reporting success using paladium has found a long delay between appli-

cation of current and onset of excess energy. This delay can range from a few hundred hours to months. The delay is much longer than the time needed to form the palladium-deuterium compound. During most of the time, the composition will slowly increase as various elements are slowly deposited on the surface. These elements, which include lithium and platinum, along with a steady flux of deuterium which diffuses through the surface, cause a slow change in surface properties. This change has been found necessary to produce conditions which proceed excess energy production. An example of a steady growth of excess heat production is shown in Fig. 9.

Skeptics have attributed this delay to the time required for the characteristics of the calorimeter to drift, thereby indicating an apparent excess when none actually exists. This criticism has been addressed by frequent calibration. While some drift is typically found, it is not sufficient to explain the reported excess energy.

3. The current density must be above a critical value.

Figure 5 compares many studies, some of which show a clear relationship between applied current density and heat production. In addition, an example obtained by McKubre *et al.* is shown in Figure 10. Similar studies by Storms [50] and by Hasegewa *et al.*[48] are shown in figures 9 and 11, respectively. Indeed, even P-F mentioned this behavior but their advice was largely ignored by those who suffered failure.

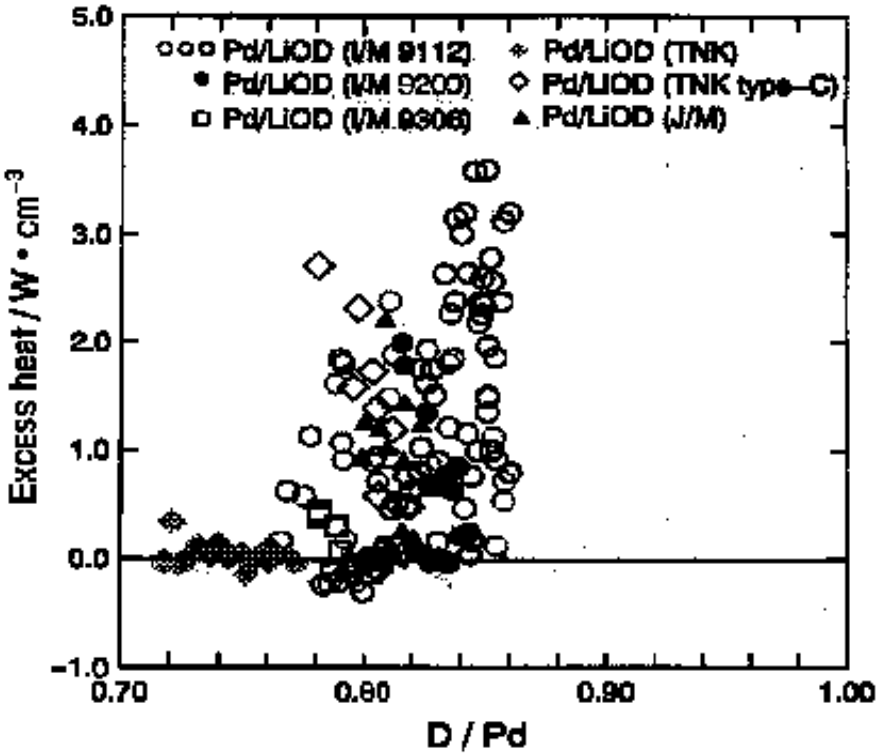

Figure 7. Effect of the average bulk composition of plates on excess power as reported by Hasegewa *et al.* (IMRA, JAPAN)

What prosaic process could cause the apparent excess energy to rise as applied current is increased?

Increased current has three major effects. It increases the AC component being measured in the DC current and voltage, increases the number of bubbles, increases the amount of energy

being dissipated by the cell, and increases the chemical activity of deuterium at the cathode surface. The effect of an error in the measured current and voltage has been discussed above.

Increased bubble production will cause increased mixing. For those studies using an isoperibolic calorimeter, this can only have a minor effect as explained above. Flow-type calorimeters would not be affected at all.

Increased production of heat could have an effect if the calibration constant were not constant, but changed as the electrolyte temperature changed. Failure to recognize this nonlinear behavior could produce an error at temperature or current extremes. The author has seen this behavior after the current was applied to an isoperibolic calorimeter for a long time. Apparently, the path for heat loss can change, thereby changing the behavior of the calibration constant.

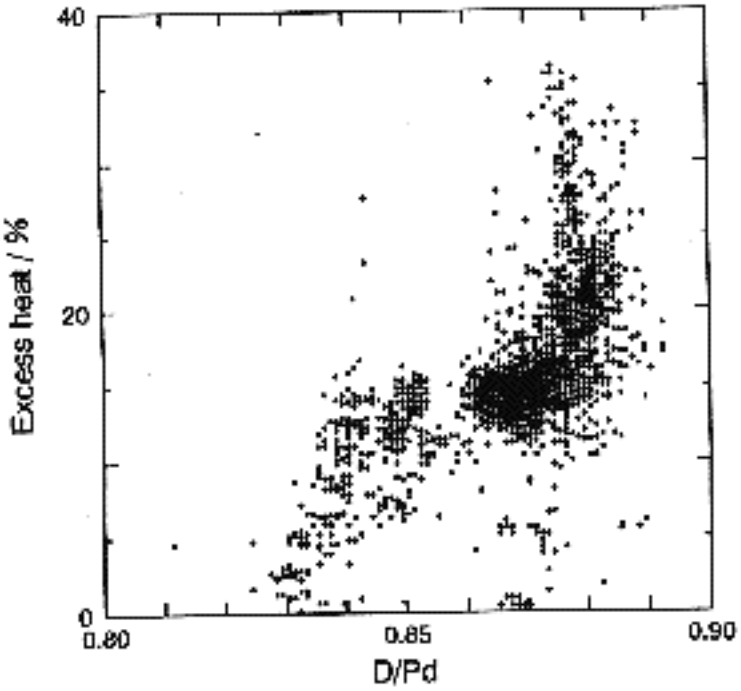

Figure 8. Effect of average bulk composition on production of excess power using palladium wire.

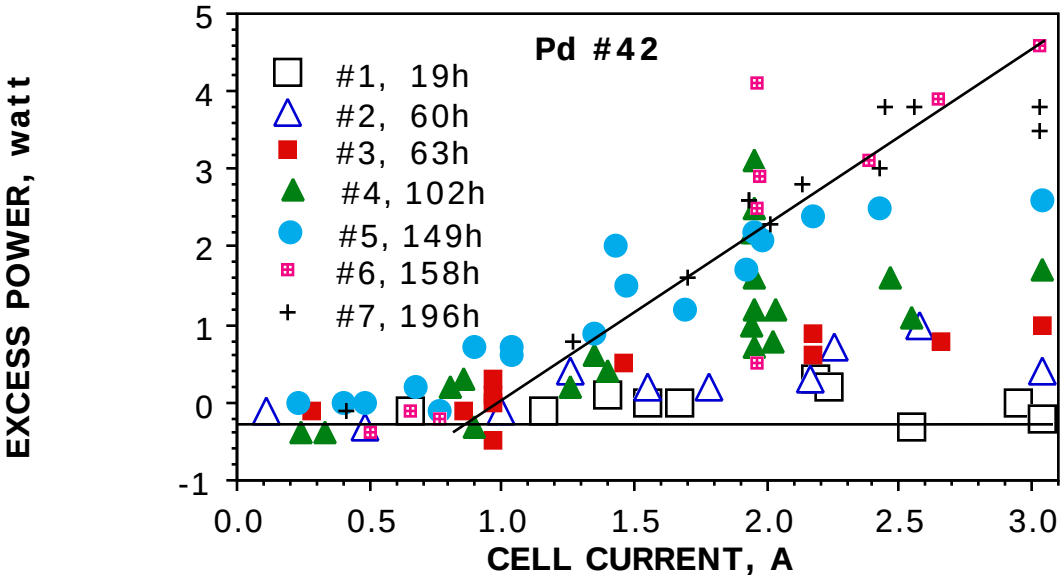

Figure 9. Excess power as a function of applied current shown after various times. The plate had an area of 4 cm^2.

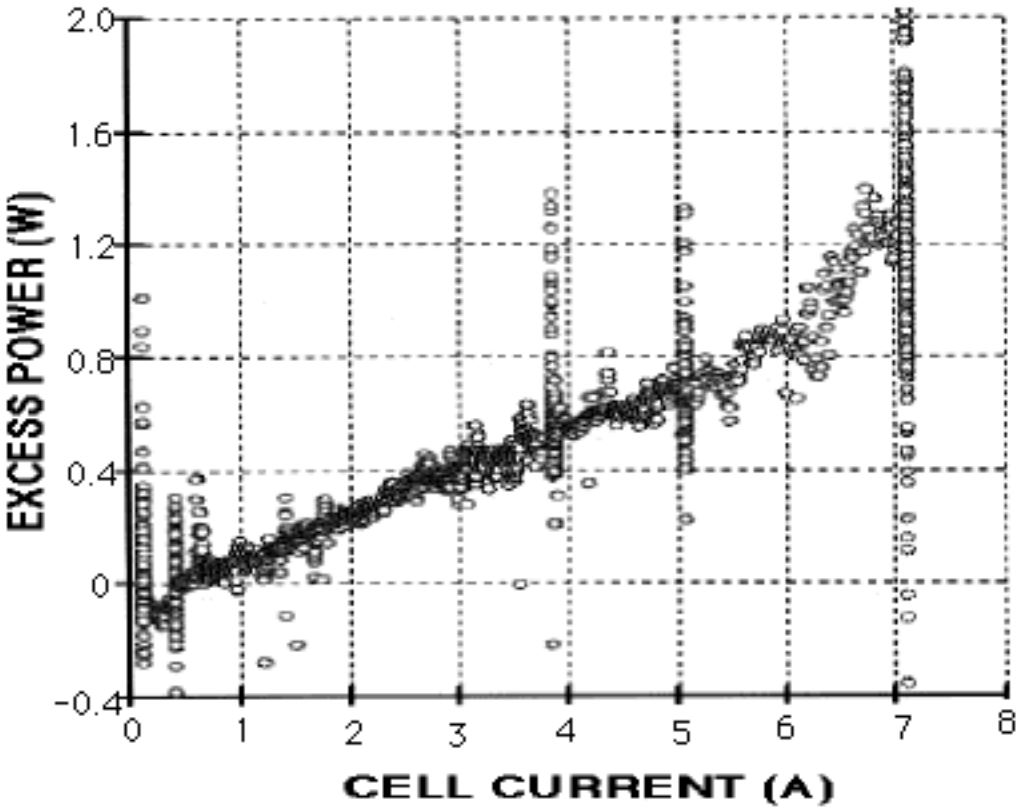

Figure 10 Typical effect of applied current on the production of excess power based on work done at SRI. The critical current varies between samples with a typical value being near 250 mA/cm^2.

However, the effect is small, causing less than a 0.5 W error. Repeated calibrations, as is done in many studies, would reveal the problem. This effect would not apply to a flow-type calorimeter such as used by McKubre *et al*. because such calorimeters are largely immune to where heat is being produced within the cell.

4. Inert palladium can sometimes be activated by adding certain impurities to the electrolyte.

McKubre *et al*.. and others have found that excess energy cannot be produced using a Teflon cell unless impurities are added. Powdered glass and aluminum metal have been found to work. These materials provide elements which electroplate on the surface, thereby allowing a higher surface composition to be achieved. The exact mechanism is still unknown although deactivation of those active sites which permit deuterium loss by D_2 gas formation is proposed as the mechanism. Most people use a Pyrex container which offers the needed impurities because of chemical attack by the alkaline electrolyte.

5. The effect occurs in only a small fraction of samples but more often in certain batches than in others.

Only a few organizations have the funding to allow many samples to be investigated for heat production. SRI [51] studied 176 samples with 19 giving excess energy. However, many of these studies were for the purpose of learning how high loading could be obtained rather than

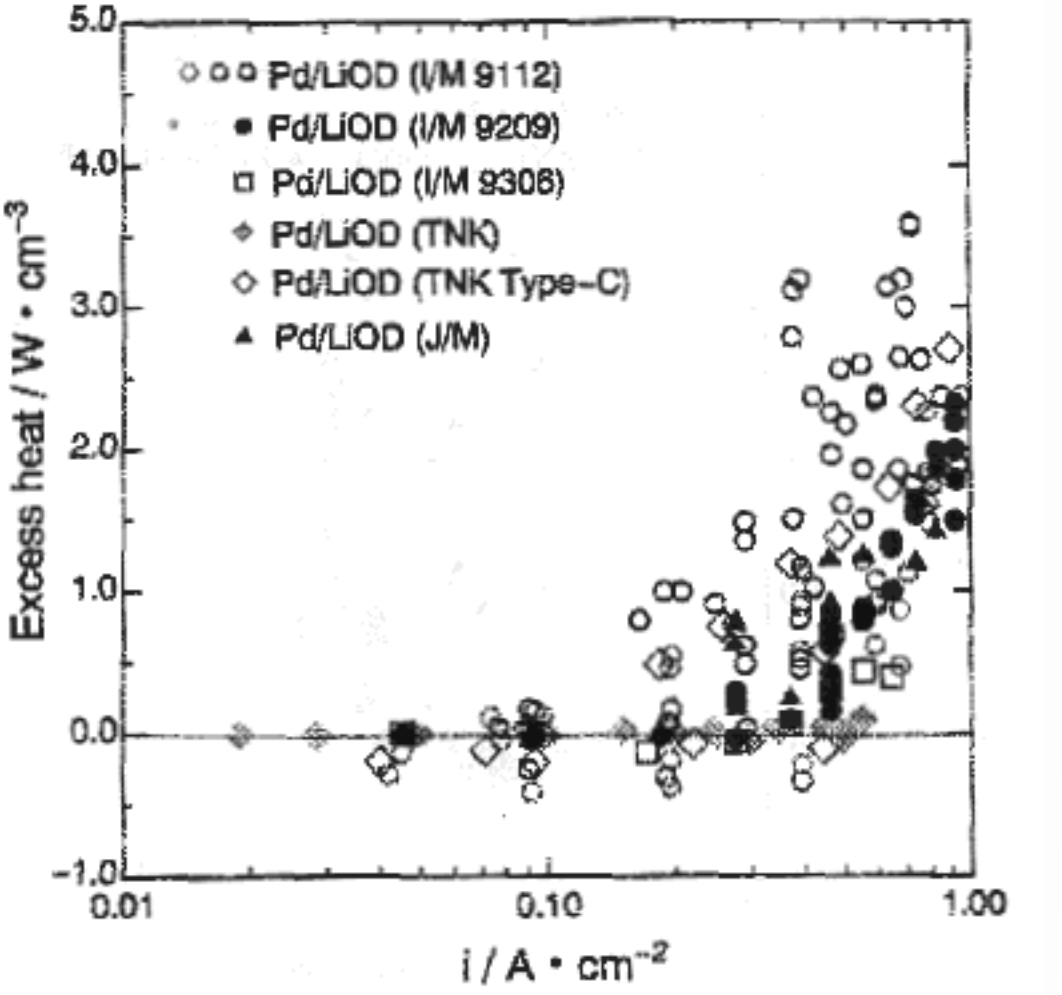

Figure 11. Effect of applied current on excess power shown by Hasegewa *et al.*[48]

seeking excess energy. The successful samples correlated to a high degree with the average composition and many came from the same batch.

Takahashi [52] reports studying twenty plates, only three of which gave excess energy in the 3-5 watt level. Both Storms[53] and Kobayashi *et al.*[54] were able to replicate excess energy production using material from the same batch of palladium which produced excess power for Takahashi. Ota *et al.* [55] studied 79 samples over a nine year period and found fourteen to give less than 0.25 W, 5 to give power between 0.25 W and 0.50 W and only three to produce greater than 0.50 W. The rest showed no sign of excess energy. Storms studied fourteen plates and found only six that produced excess power in the 1.1-4.5 watt range. The effect correlated with the amount of cracking experienced by the samples and the average composition. Miles *et al.*[56] found that 20% of their samples gave excess energy with a high fraction coming from a few batches.[57] The results are listed in Table 2. Those samples containing boron or cesium produced a high success

TABLE 2

SOURCE	EXCESS ENERGY	
	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

rate, while other samples and alloys were frequently dead. It is important to note that all samples supplied to Miles by P-F produced excess energy. In addition, a sample which was found to produce excess energy at China Lake (U.S.) also produced excess when it was studied at the NHE Laboratory in Japan.[58] Thus, once again, the effect could be duplicated when the same material was used.

This effect is attributed to the variable nature of palladium metal, especially because certain batches give a very high success rate. However, the behavior can also be explained by assuming poor stability in the calorimeters used, thus the insistence by critics that blank, control cells be studied. Unfortunately, no one working in this field has had funds to support an extensive study of blank cells, although most workers have studied a few such samples. Such blanks normally use platinum in place of palladium and H_2O in place of D_2O. When blank cells were studied, no excess energy is reported.[59] Many skeptics discount this claim by not trusting the experimenters to objectively evaluate the results or they attribute the claimed excess power to chance variations in the measuring system.

2.4 QUESTION 4: Have the reasons for success or failure been discovered?

The above requirements provide many avenues for failure. Success, first of all, requires palladium which is able to achieve a critical composition at the surface.[60] The average bulk composition is only important because it is required to support this high surface composition. Unfortunately, most palladium forms cracks when it loads with deuterium so that the deuterium escapes faster than it can be delivered.[50] Only a small fraction of available palladium does not show this behavior. Second, the heavywater must be free of normal water to prevent deuterium in palladium from being diluted by normal hydrogen.[61; 62] Because heavy water quickly picks up normal water from the air, it can easily become diluted and made inactive.

Once potentially active palladium has been acquired[63], it must be handled correctly. This includes making sure the surface is free of finger prints and other contaminants as well as scratches. Annealing must be done in a very good vacuum to prevent formation of even a

monolayer of surface impurity. The ease with which palladium can suffer surface contamination is one of the important problems which is frequently overlooked. Crystal size is also thought to be important, a property which is strongly influenced by annealing. Treatment with Aqua Regia is sometimes needed to remove unavoidable surface films. After these pretreatments, the material must be subjected to proper loading conditions. Applying only a small current for the first several days improves the chance of reaching a high composition. Only after the composition has been achieved at stable value should the current be increased into the critical range. Too fast loading or premature application of high current can produce cracking, followed by immediate loss of deuterium.[51; 64] Palladium is much more sensitive to how it is treated than most people realize.

These requirements were not known by most early workers in the field, hence success was more a matter of luck than skill. Even now, many attempts to duplicate the claims do not apply these lessons. Unless this experience is applied, a failed effort cannot be claimed as a true duplication.

3.0 NUCLEAR PRODUCT PRODUCTION

Profs. Pons and Fleischmann proposed that the source of energy was nuclear fusion. This explanation was quickly rejected when the expected high neutron emission was found to be absent. Tritium production would also be expected. This product has been detected occasionally at significant levels, but the amount does not account for the observed energy. Clearly, anomalous energy is not a product of a conventional fusion reaction, nor does it show the behavior found during "hot fusion."

Nevertheless, anomalous emissions have been detected on numerous occasions, including neutrons, X-rays, γ-rays, charged particles, as well as radiation from radioactive products. While such radiation along with production of radioactive and nonradioactive products suggest anomalous nuclear activity, this paper will not attempt to assess these claims.

Helium is another possible nuclear product which can be produced by several nuclear reactions besides fusion. This element was looked for and found by numerous investigators in several different environments including in the gas[56; 65; 66; 67; 68; 69; 70], dissolved in the materials[71; 72; 73; 74; 75; 76; 77], and emitted as charged particles[78; 79; 80]. Naturally, not all studies are definitive and some failed to find helium when it was sought.

While these observations are suggestive, only two independent measurements have provided a quantitative relationship between anomalous power production and helium production rate. Both studies used all-metal systems and measured helium in the flowing gas generated during continuous electrolysis. Two different calorimeter types were used and the helium was measured at two different laboratories. These two studies are compared in Figure 12. Three conclusions can be drawn from the figure. First, the two studies agree very well, given the difficulty of the measurement. Second, the He/sec-watt values are largely independent of observed anomalous power, as would be expected if the two quantities are functionally related. Third, the average values are within a factor of 2 of being consistent with an energy of 24 MeV/helium atom, the value expected when ^{4}He is occasionally produced by conventional fusion. In addition, Bush *et al.*[66] as well as Gozzi *et al.*[68] found helium to be released slowly and only after a delay. Consequently, some of the helium might still remain within the solid palladium deuteride, which was not analyzed, thereby making the data even more consistent with a conventional fusion reaction. During the study by Miles *et al.*[56], seven cells using pure palladium produced no detectable excess energy in addition to the six successful experiments. In each case, no helium over the background value was found in these cells. Thus, anomalous helium was found only when anomalous heat was detected. Only one cell, which used a Pd-Ce alloy, showed heat but no

helium. This result is strongly against chance alone.

When the helium producing branch of the fusion reaction has been previously observed using conventional fusion, a 23 MeV gamma emission has been detected. This radiation results because fusion of two deuterons produces only one product nucleus. Gamma emission is required to conserve momentum. Because this gamma energy is not detected during claimed anomalous energy production, most critics dismiss the claimed helium as being an artifact. The other two branches more frequently observed during conventional fusion are apparently not the source of significant energy in this environment. This distortion of expectations also adds to the skepticism.

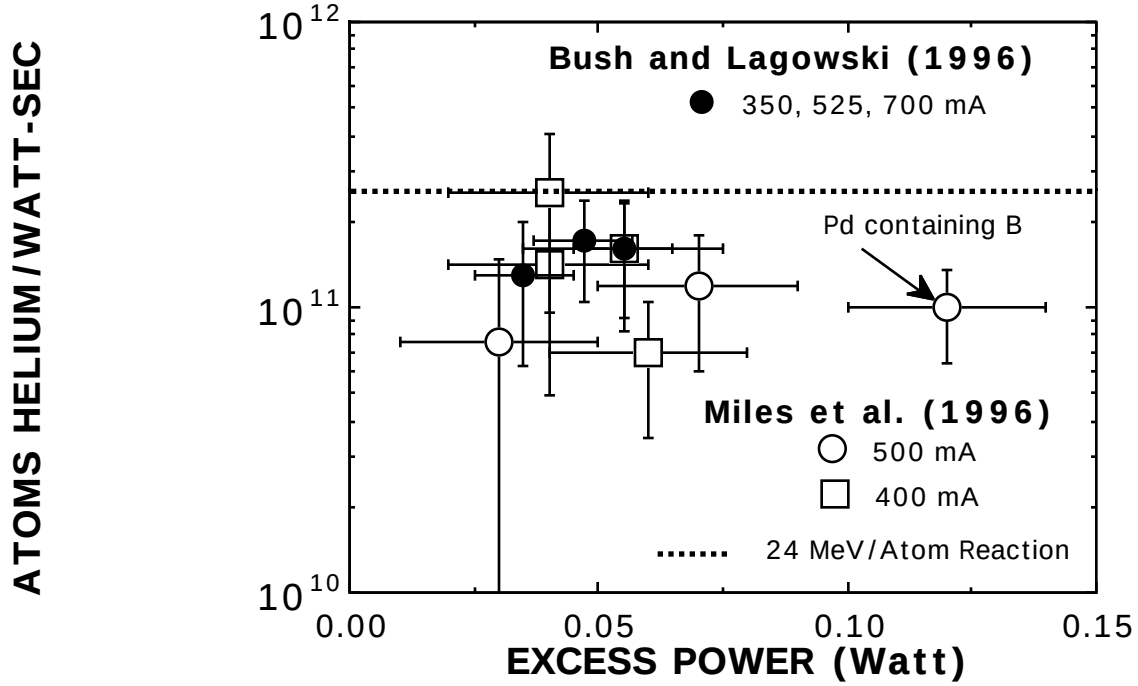

Figure 12. The number of atoms of ^{4}He collected in a flask while the cell was being electrolyzed using the indicated currents. One sample contained 500 ppm boron and gave the same result as the other samples containing less than 10 ppm boron.

What could be wrong with the helium measurement which would justify this view?

1. The results are very scattered and represent a narrow range of excess energy and helium. An off-set error in both measurements could generate the proposed relationship.

Answer: Error bars are shown which reflect the expected chance variation including any bias. All of the points agree within their expected error. While excess energy has a narrow range of plausible bias, the helium values can, in principle, range over several orders of magnitude, depending on the care used. Yet, the helium values are well clustered.

2. The helium concentrations are very small and well below ambient helium concentrations in surrounding air. A small leak or direct helium diffusion might allow sufficient helium to enter the gas stream.

Answer: Metal systems were used which allow insignificant helium diffusion. However, certain gasket materials, including certain metals, allow diffusion of significant helium. This prob-

lem was recognized and eliminated. Leaks would admit other elements such as Ar along with helium. When these gases were looked for in the mass spectrum, they were not found. In addition, leaks would be expected to be very erratic thereby leading to a very wide scatter in helium values. This kind of scatter is not seen.

3. The masses of D_2 and He are so close that the variable presence of D_2 could introduce an error in the He peak.

Answer: In each case, D_2 was removed by an absorption trap and, in addition, the mass spectrometers were able to completely resolve the two mass peaks.

4. The excess energy measurements were done using inaccurate calorimeters. While anomalous energy might be real, its measurement during the helium studies might be faulty. Therefore, the claimed correlation may not be real.

Answer: The studies by Miles *et al.* were based on using a double-walled isoperibolic calorimeter that did not contain a recombiner. Although the amount of excess power is small, it is well within the claimed accuracy and stability of the device. In addition, failure to detect excess energy correlated with a failure to detect helium in six cells. In other words, when heat was present, helium was present, and when heat was absent, helium was absent. A very stable Seebeck-type[81] calorimeter was used during the work by Bush. Again, the claimed excess power was well within the sensitivity of the device.

4.0 ATTEMPTS TO FIND AN EXPLANATION

4.1 Basic Properties

Before an explanation is attempted, several basic properties of β-PdD must be taken into account. The β-PdD phase has a face-centered cubic structure (fcc) with deuterium atoms occupying random positions within the deuterium sublattice under ideal conditions. However, composition gradients, impurities, and dislocations make actual occupancy very nonrandom. These atoms are sometimes described as occupying octahedral positions. The lattice parameter vs composition extrapolates to 0.4084 nm with smaller values at lower compositions. [82] The lower limit of the β phase is near $PdD_{0.70}$, depending on the temperature and applied D_2 pressure, while the upper limit is near $PdD_{1.0}$ as all vacant positions become occupied. In addition to this nonuniformity in composition, palladium can also acquire many dislocations in the palladium sublattice, which can easily degrade to microcracks. These factors combine to make the material very nonuniform in all its properties.

As deuterium content is increased, equilibrium pressure of deuterium increase, as shown in Figure 13.[83] The enormous pressure required to form the required large deuterium concentrations is the main reason these compositions are so difficult to achieve by electrolysis. Deuterium can readily leak out of the sample through the many cracks known to inhabit such material. Notice that pressure increases as temperature is increased, with no indication of a reverse temperature effect near $PdD_{0.85}$ as proposed by Fleischmann, [84] to explain energy production at higher temperatures. Indeed, all available data as well as the theory of such compounds predicts that all compositions of β-PdD will have a higher over pressure of D_2, hence lose deuterium, as temperature is increased. Consequently, either the improved excess energy production at higher temperatures does not take place in the β-phase or the effect does not require a high composition at higher temperatures.

Occasional reports are published claiming average compositions in excess of $PdD_{1.0}$.[25; 85; [86] These high compositions are proposed to be caused by deuterium ions occupying tetrahe-

dral sites[87] or by the formation of a new phase based on D_2 ions occupying octahedral sites. [88] The latter explanation would imply a two-phase region between PdD_{1-x} and PdD_{2-y} where x and y are small unknown numbers. Recent measurements indicate that this high composition forms in the near surface region and is required before anomalous energy is detected. In brief, the nuclear reactions do not occur in β-PdD, but in an unknown phase of higher deuterium content containing various impurities. Therefore all models which depend on the properties of pure β-PdD must be viewed with skepticism. This trans-beta phase, once formed, can be proposed to become more stable as temperature is increased, thereby explaining the claimed excess energy obtained at higher temperatures.

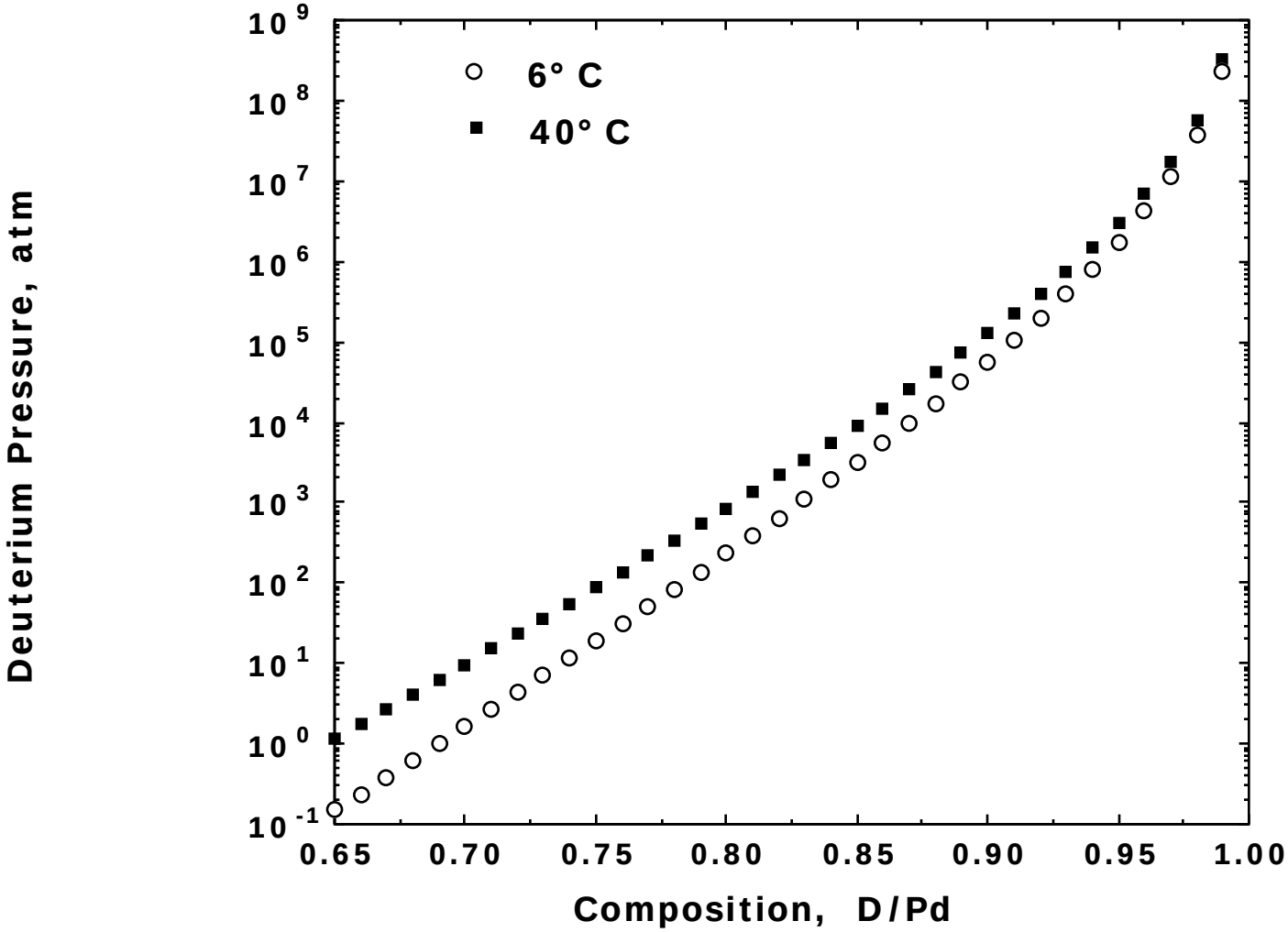

Figure 13. Equilibrium pressure of D_2 as a function of composition at two different temperatures.

4.2 Requirements of a Theory

Theoretical objections to the claims are based on the following arguments as summarized by Huizenga[11] and many other skeptics:

1. The deuterium nuclei in PdD are not close enough to allow nuclear interaction.
2. Energy required to overcome a Coulomb barrier is not available in a chemical compound.
3. If a fusion reaction should occur, the nuclear products would be the same as those observed when fusion is initiated using high energy methods. These products are not detected with the expected magnitude or in the expected ratio.
4. Any helium produced by a fusion reaction must be accompanied by gamma emission, which is not detected.
5. The resulting energetic nuclear products should produce intense X-ray emission, which is not detected.

The issue requiring resolution is whether unknown process exist which would allow a fusion reaction to occur in the unique environment of a chemical lattice. Adding to the challenge are the many other types of nuclear reactions now being claimed. A few attempts to discover this proposed process are discussed, but only to give the reader insight into the types of mechanisms being considered. A more detailed evaluation is not possible at the present time for various reasons. For example, the author finds that theoreticians seldom agree with each other, preferring instead to focus on their own favorite models. Consequently, agreement or at least objective discussion within the field is handicapped from the start. Partial evaluations have been undertaken by Preparata[89] and by Rabinowitz *et al.* [90], but with very little agreement. The author will only attempt to show the general approach and note whether the proposed models are consistent with experimental observation. Only models which have been developed to a high degree are cited. Many dozens of models, which involve only brief suggestions or address limited observations, are not included. For example, the fractofusion model, which has been given considerable attention, is not discussed because this process involves high energy processes and is expected to produce ”normal” nuclear products, hence is not consistent with the anomalous observations.

Models generally fall into two general overlapping categories. The first is a mechanism that explains how a nuclear reaction can occur once the necessary conditions are achieved, and the second is the nature of the necessary conditions. The first category involves nuclear physics and the second one involves chemistry. Both must be addressed by a successful theory.

To be successful, a theory must answer at least five basic questions to explain the P-F effect and several other questions if the entire range of published observation is to be explained.

1. What mechanism allows the Coulomb barrier to be overcome? This question is basic and will have to explain how nuclei as heavy as palladium can suffer a reaction with nuclei as heavy as oxygen, in addition to the proposed fusion between deuterium nuclei.

2. What mechanism distributes the released energy throughout the lattice rather than requiring it to be focused on a few individual particles? This mechanism must also explain why some nuclear energy is retained by the nuclear products when these products are produced very near a surface. Otherwise, charged particles having significant energy to leave the material would not be detected.

3. How is the proposed mechanism related to the physical environment? Most present theories assume the nuclear reactions occur in β-PdD having a composition near $PdD_{1.0}$. The model must explain why anomalous reactions occasionally involve other materials and why the required conditions are so difficult to achieve.

4. What nuclear reaction is the source of observed helium? Fusion is not the only conceivable source of helium as a nuclear product.

5. If helium results from a fusion reaction, what mechanism allows conservation of momentum and energy, and what mechanism distorts the reaction paths to produce helium rather than neutrons and tritium?

A single explanation seems impossible. The diverse nature of observed behavior and uncertain reality of the claims add to this problem. Therefore, this review will focus only on the environment claiming to produce energy when heavy-water and palladium are used. Any successful general theory will have to explain much more.

A quantitative test of any model is impossible using experimental data, because the palladium samples are very nonuniform, hence the fraction of active material is unknown. Indeed, a calculated power density based on the gross physical dimensions of the sample will greatly underestimate the actual local power density, hence the ultimate power density of which this phenomenon is capable. Therefore, comparing samples on the basis of watts/cm^2 or watts/cm^3, as is frequently done, is not appropriate. Indeed, evidence of local melting is frequently reported, suggesting very high local power density.

The models discussed below are placed in seven general categories, but with the understanding that to be successful, a model may have to invoke more than one category.

4.3 Proposed theories

4.3.1 Neutrons

The easiest way to solve the Coulomb barrier problem is to invoke the neutral neutron. However, free neutrons are unstable, hence are not present in sufficient numbers within a solid. Consequently, the various theories are forced to identify a steady source of virtual neutrons[91; 92; [93]. This search has taken several forms. Kozima[91] proposes trapped thermal neutrons to catalyze the cold fusion reaction (TNCF Model). While he has been very prolific in describing his theory, the model fails to answer several important questions such as: How are the trapped neutrons stabilized? Exactly what conditions cause their release? Why are they not emitted from the material and why do they not produce “normal” nuclear products? In addition, his efforts to compare the concentration of these neutrons to the observed effects is doomed to failure because the nuclear activity is highly localized and impossible to relate to the measured volume of the sample, a variable he uses in his model.

On the other hand, several workers have proposed direct formation through interaction between a proton or deuteron and an electron. However, complete formation of a neutron requires energy as well as a neutrino or antineutrino, both of which are not present in sufficient amounts. In addition, reaction with a neutron should produce “normal” nuclear products which are not observed. To eliminate these problems, the neutron is proposed to exist only as a partially collapsed structure. The manner of this partial collapse has been addressed by several workers[94] and the process is proposed to produce various structures called Hydrex[95], Itons[96], Hydron[97], and Hydrino.[98] This “virtual” neutron can, under special conditions, presumably be absorbed by a nucleus in the same manner as a real one, while producing anomalous nuclear products in the process . The source of the required neutrino has not been clearly identified. The process of partial electron collapse is also proposed to release energy without need for a nuclear reaction[98]. The region between partial collapse and complete reaction between an electron and a proton is a gray area in which many models can operate. As yet insufficient experimental information is available to decide which model or models are correct.

Another approach involves the existence of multineutron structures which are stable. The existence of dineutrons has been proposed before the CANR phenomenon needed such a model.

Fisher[99] has carried this idea one step further. He proposes 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. Within the confines of the assumptions, the model can explain many observations of CANR. In addition, the work of Oriani [100] suggests the existence of super-heavy carbon in electrodes subjected to CANR processes.

4.3.2 Novel particles

Various exotic particle, which have the ability to catalyze various nuclear reaction, are proposed to exist in nature. These are located within the structure as part of normal constituents or are provided by a steady flux from the outside. The models do not show why hard-to-create special chemical conditions are required for these particles to do their unique work. These particles are called Neutrium,[101] Quark,[102] Hemitrons,[103] Muon neutrinos,[104] or Erzion.[105]

4.3.3. Electron structure

Various modifications to the electron structure[106; 107; 108; 109], including impurities[110], stress[111], application of metal layers[112], diffusion[113], oscillation[114; 115] , applied current[116], or changes in the periodicity of the atomic structure[117; 118] are proposed to reduce the Coulomb barrier. The QED[87] theory addresses the latter process in some detail. While these processes are proposed to initiate nuclear reactions, they do not address which reactions might occur.

4.3.4 Phonons

Lattice vibrations are proposed to cause adjacent deuterons to get close enough to fuse.[119; [120], especially in the double layer at the electrolyzing surface.[121] The likelihood of this process is increased by the average atom position in the deuteride being closer than previously thought.[122; 123; 115]

3.3.5 Particle-wave transformation

Under special conditions, the deuterons dissolved in a periodic lattice are proposed to assume wave-like properties which permit fusion and deposition of the resulting energy throughout the lattice.[124; 125; 126; 127] This idea addresses problems associated with d-d fusion but it does not explain other claimed nuclear reactions.

4.3.6 Nuclear structure

The nucleus is proposed to have a structure which facilitates nuclear interaction, being composed of clusters of nucleons which can be easily lost or gained.[128; 129] These clusters are thought to felicitate various nuclear reactions once the barrier is overcome.

4.3.7 Reduced Barrier

The Gamow factor has been explored to see if unanticipated conditions can cause a reduction[130; 131], including a tunneling mechanism[132; 133; 134]. Apparently, the barrier is lower than previous calculations would predict but not as low as is required to explain the claimed observations.

5.0 DISCUSSION

Clever people can always find reasons to reject any idea or measurement. Numerous unjusti-

fied rejections of new ideas can be cited.[135; 136; 137; 138] The issue is not whether data suggesting a new idea are perfect and all criticisms can be answered. Such conditions are seldom achieved even after a new idea is eventually accepted. The issue is whether the supporting data would be considered good enough to support a typical accepted idea. Would a measurement or technique be given credibility when applied to normal phenomenon? For example, calorimetry is a well understood technique which has been applied in various forms for over a hundred years. A vast literature of chemistry and physics is based on such measurements. While measurement of power at the microwatt level is a challenge, measurement of watts, as is being done here, is not considered difficult. Prof. Hansen has suggested that a calorimeter cannot be trusted unless it has demonstrated accuracy in measuring the heat from a known reaction. This is a fair request provided absolute calorimetry is used. However, as noted at the beginning of this review, relative measurements are actually being made. Stability is the only requirement, a condition which is much easier to evaluate and much less prone to hidden error. This is not to say that all claims for anomalous energy are correct or accurate. The question which must be examined is whether some studies are sufficiently correct and accurate to demonstrate the claims to be highly probable, not necessarily absolutely certain.

When such evaluations are made, the critic needs to keep in mind the potential magnitude of suggested errors. Just because an error can be imagined and justified does not mean it can explain multiwatts of apparent power production. In general, the magnitude of the effect has frequently overwhelmed any plausible errors or prosaic explanations.

The statement that the claims are not convincing is often heard. While this euphemism is actually a gentle way of saying, ”I just don’t believe you,” one needs to ask just what is not believed and just what deserves additional study. Is it rational to reject everything just because some part does not make sense? Would it not be better to support some focused work on the subject to answer a few basic questions?

What are we to make of the consistent patterns of behavior as well as the influence of material properties and the presence of helium, a possible nuclear product? Is it reasonable to believe that numerous independent studies show the same patterns just because of chance? While such arguments are not a proof, they are commonly used by prudent people to evaluate all aspects of life. Indeed, this is the rationale behind requiring many duplications of a claim, a condition which has been met in this case.

When a new phenomena is evaluated, a belief system based on probabilities needs to be adopted. An absolute rejection or acceptance is not useful. The issue is whether the likelihood of the phenomena being real is sufficiently large so as to justify further work. In the case of the CANR claims, I suggest further study is justified.

6.0 CONCLUSION

The claims for anomalous energy production using electrolysis of heavy water have been evaluated and found to have a high probability of being caused by a novel phenomenon. In addition, the most likely source of the heat is a nuclear reaction which produces helium. This nuclear reaction is not normal fusion and it does not follow the rules required by conventional theory. Numerous models have been proposed to explain the observations, but none at the present time can account for all of the reported behaviors. More work is required to determine which of the behaviors are part of this novel phenomenon and which can be explained by ordinary processes. However, the claims have now reached a level of understanding which justifies a reexamination of the published work and attention by the scientific community.

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