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Research Article

Random Thermal Spikes Observed in 99% Palladium – 1% Uranium Alloy Foil Electrolytically Charged with Deuterium: Confirmation of Solid-State Fusion

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Abstract

Random thermal spikes have been experimentally observed at ambient temperature in small palladium metal foils electrolytically loaded with deuterium. We believe these spikes can be identified with deuterium fusion events triggered by alpha-particle emission from a small amount of depleted uranium melted into the foils.
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1. Introduction

The objective of this research was to investigate the viability of a patent application of one of the authors, Douglas Pinnow, namely Patent Application Publication No. U.S. 2016/0314856 A1, dated 2016 October 27 and titled *SPONTANEOUS ALPHA PARTICLE EMITTING METAL ALLOYS AND METHOD FOR REACTION OF DEUTERIDES*. Our hypothesis is that a radioactive triggering event, either incidental or deliberate, is required to initiate a deuterium-fusion reaction in the palladium electrode of a Fleischmann and Pons–type electrolytic cell. The results of our experiments show that the spontaneous decay of an alpha particle–emitting isotope (such as uranium-238) in palladium metal loaded with deuterium will cause very brief and localized heating, which we calculate can raise the temperature at a microscopic scale in the immediate vicinity of the alpha-emitter to a value comparable to that found inside of the sun, enough to induce fusion of nearby deuterium ions. Such localized heating has long been known [23] but is not widely recognized. Since it is essential to the work covered in this paper, it is quantitatively explored in Appendix A. The heat generated by a deuterium-deuterium fusion reaction along one pathway, D + D → tritium + proton, produces 4.03 MeV of thermal energy, which may cause additional fusion events and potentially lead to a chain reaction. The patent application publication cited above proposes that this process may be a viable alternative energy source to fossil fuels.

*For a virtual tour of the laboratory, click here.

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In our experiments we have consistently observed temperature spikes on a macroscopic scale in an alloy of 99% palladium and 1% depleted uranium (principally uranium-238). The temperature spikes occur only after the foils have been loaded with deuterium ions by a rather conventional electrochemical process. This result is consistent with the results announced by Martin Fleischmann and Stanley Pons in a press conference held at the University of Utah on March 23, 1989. That conference was broadly covered on national TV and in the press [2]. Their work, dubbed 'cold fusion' by the press, became a cover story of *Time* Magazine in 1989 [3].

In short order, the story was heavily criticized and ultimately dismissed by most of the scientific community because it had not been reproduced by others with the consistency necessary to support such a world-changing claim [4]. (See Appendix F for our evaluation of two failed attempts to replicate their findings.) The major difference between the present work and that of Fleischmann and Pons is that they never contemplated the addition of alpha-particle emitters into their palladium cathode to help trigger (initiate) the fusion.

In stark contrast to many protracted attempts to reproduce Fleischmann and Pons' work, which mostly ended in failure, we found that after approximately two hours of electrolytic loading with deuterium, our palladium electrode consistently produced temperature spikes that were detected by attached thermocouples. We attribute the promptness and consistency of our results to the addition of a small amount of depleted uranium to the foil (1% by mass), the spontaneous decay of which we believe provides sufficient energy to trigger deuterium fusion in the foil. Both deuterium and a spontaneous radiation source were required to achieve positive results. Temperature spikes were not observed in test runs where we used a palladium-uranium foil in an electrolyte made from normal water (H_2O), nor in runs with an electrolyte made from heavy water (D_2O) but using a palladium foil without uranium – which rules out the possibility that the observed temperature spikes were merely caused by alpha decay. We found the pattern of temperature spikes when both heavy water and a triggering source were used to be random over the surface of the foil as well as random in time. We calculated that the substantial magnitude of the spikes could not possibly be due to a single alpha-particle emission or a single deuterium-deuterium fusion reaction. Rather, billions of such reactions must have been involved, closely clustered in time as a chain-reaction (see Appendix C). Others have also suggested the possibility of chain reactions related to the Fleischmann-Pons effect, including the report of explosive equipment damage in one case [5] and enhanced neutron emissions in another [6].

Based on these results, we believe that we turned our palladium foils into miniature nuclear fusion reactors that reached criticality. We have found that their power output can be controlled by adjusting the electrolytic loading current much like the output of a conventional fission reactor is controlled by moving its control rods.

We identify our results with the broad topic of SOLID-STATE FUSION (SSF), in contrast to the PLASMA FUSION that presently dominates the field of fusion research. SSF is being broadly investigated around the world in government institutions, universities, and industrial companies [22], [8]–[10]. Yet heretofore SSF has not been broadly accepted as a legitimate science, and the basic physical principles behind it remain elusive. The present work represents a strong confirmation of SSF.

2. Description of the Experiment

Our experiment was designed around three basic approaches: (1) to take full advantage of the electrochemical methods reported by Fleischmann and Pons, and those who followed them, for loading palladium with deuterium; (2) to substitute a thin palladium foil, that could be loaded with deuterium relatively quickly, for the more massive cylindrical rod employed by Fleischmann and Pons; and (3) to calculate the degree of deuterium loading by precisely measuring the change in mass of the palladium foil.

Further discussion on these three approaches follows to help those who may wish to confirm our results or go beyond them:

(1) Fleischmann and Pons did not report their work in sufficient detail to easily evaluate it and their claims. A photograph of Fleischmann and Pons holding their electrochemical cell was shown on the cover of Time Magazine in 1989 [3]. Their cell consisted of a quart-sized glass dewar with a rod-shaped palladium cathode surrounded by

a concentric helical coil of platinum-wire anode. The palladium cathode was approximately 6 mm in diameter, and both the cathode and anode, as well as a thermometer, passed through a rubber stopper at the top of the dewar. The dewar was filled with an electrolytic solution of lithium ions in heavy water (D_2O). A battery connecting the palladium cathode and the platinum anode drove the electrolytic charging of the palladium with deuterium to some unreported level. While such a description served as a useful starting point, there were many parameters that needed to be filled in by later researchers who attempted to verify Fleischmann and Pons' work.

One significant unknown is the concentration of their electrolytic solution. Following previous researchers, we decided on a 10-weight-percent solution of lithium deuteroxide (LiOD) in heavy water (D_2O). Due to the high price and extremely long delivery time (over one year) required to acquire LiOD, we decided to make it ourselves by chemically reacting lithium metal with heavy water. (To see how we made this solution, click here.)

Another decision we made was to gradually increase the loading current, starting with a low 30 milliamperes for the first 20 minutes, increasing to 60 milliamperes for the next 20 minutes, followed by a further increase to 120 milliamperes. This schedule was chosen to mitigate the possibility of stress-related cracking of the palladium foil [11]. In some cases, further increases to 240 and 300 milliamperes were explored with the objective of loading the foil with a higher concentration of deuterium. We found that these higher currents tended to increase the magnitude and frequency of the temperature spikes we observed in the foils.

Importantly, we calculated (see Appendix B) and subsequently observed that the time required to load our 1.2-gram palladium foils with an electrical current of 120 milliamperes was approximately 2½ hours. This was short enough to complete a deuterium-loading run and produce temperature spikes on the same day.

(2) As a practical matter, the price of palladium has substantially increased since Fleischmann and Pons conducted their research in 1989. It is now comparable to that of gold. We therefore chose to use modest-sized palladium cathodes to keep costs down for us and for others who might continue our research. Our choice for the shape of the palladium cathode was also an important decision. We decided on thin flat foils of palladium metal with the objective to reduce the time required to load the palladium with deuterium, as that time depends on the distance of diffusion into the metal. We selected palladium foil 125 μm (nominal 0.005 inches) thick. We found that postage stamp–sized cathodes, cut to 2-cm $\times$ 2-cm square, were convenient to handle, and we are confident that our results using them reflect the behavior of bulk palladium (see Appendix D) rather than the behavior of the thin films that have been used in other related research [12], [13].

Over the years, many attempts have been made to duplicate the positive results of heat production reported by Fleischmann and Pons in 1989. The main guiding principle for these efforts has been to set up electrochemical cells like that of Fleischmann and Pons and to wait with great patience for heat production to begin while loading the palladium electrode with deuterium. Some researchers charged their cells for days, weeks, and even months in hopes of success – all the while bubbling off expensive heavy water from their electrolyte. Many gave up in frustration. But Fleischmann and Pons encouraged patience, advising that cell-charging should continue for at least three months before abandoning a nonperforming cell. Subsequently, McKubre and Tanzella [14] drew the *empirical conjecture* that high Pd/D ratios and high current fluxes "must be maintained for hundreds of hours sufficient to produce a new state or phase which gives rise to an anomalous excess heat…"

Over the past four decades, a limited number of partial successes have been reported, but reproducibility has remained elusive and the results continue to be clouded in uncertainty and doubt, tainted by the fact that even Fleischmann and Pons were unable to consistently repeat the world-shaking results that they had reported in 1989.

Our work has been guided by a much different strategy than having patience. Quite the opposite. We discovered that if we could load a palladium foil that contained a small amount of well-dispersed uranium-238 with a sufficient concentration of deuterium, heat production on a macroscopic scale would quickly follow. We interpret this as localized fusion triggered by the high temperatures produced at a microscopic scale by the spontaneous alpha decay of the uranium. There is no need to stress patience or to speculate on the production of a new state or phase of matter.

(3) One of our objectives to facilitate this research was to precisely monitor the deuterium loading in the palladium foil so that we could determine when we had reached the critical deuterium concentration that would support a deuterium-deuterium fusion chain reaction [24]. It was our premise that a sufficiently high concentration of deuterium would be required to sustain such a reaction, just as a high concentration of uranium-235 is required to reach criticality in a conventional fission reactor. Pinnow, who worked at the U.S. Atomic Energy Commission in the 1960's, knew that an external triggering event, initiated by a source that produces neutrons, is helpful to begin a chain-reaction when a fission reactor first starts up operation. By analogy, his 2016 patent application publication, mentioned above, claimed that alpha-particle decay would be helpful to initiate a chain-reaction in a fusion reactor charged with deuterium. This research effort was initiated in part to support that patent application.

The technique we settled on to monitor the deuterium-loading level in the palladium was to employ a very sensitive scale to measure the change in weight of the foil. The scale, a Mettler Model XSR64, has a precision of one ten-thousandth of a gram. To the best of our knowledge, this is the first time such a sensitive instrument has been used in conjunction with fusion research.

While all metals are known to absorb a limited amount of hydrogen or deuterium, palladium is unrivaled in its capacity to absorb large amounts of deuterium in an electrolytic cell. We watched this process taking place in a transparent borosilicate glass cell 80 mm in diameter, with a capacity of 100 ml. This cylindrical shaped cell offered a 360-degree view of the electrolysis. It is worth mentioning here that we left the top of our cell open during the deuterium-loading runs. This provided extra visibility of the palladium foil and facilitated its quick removal for weighing. (In most cases, it is prudent during electrolysis to use a closed cell that is well ventilated to avoid possible explosions when the effluent oxygen and hydrogen gases are released. However, due to the small size of our test samples, the total amount of hydrogen (deuterium) gas generated during a charging run was very low, in the range of 0.01 grams. Adequate ventilation was accomplished simply by opening a nearby window.)

3. Sample Preparation

Our preparation procedure started with a one-gram sample of highly purified depleted uranium. We used a file with a fine pitch to file off approximately 5% of the uranium metal. This was done inside of a sealed glove box and we carefully monitored the radiation level with a hand-held Geiger counter. The filings were guided to fall onto the surface of a 2-cm $\times$ 4-cm foil of 99.9%-pure palladium [15]. This foil was then folded in half to make a 2-cm $\times$ 2-cm foil with the uranium sandwiched between two layers of palladium. The sandwich was then run through a small rolling mill to secure the filings in place.

Next, the sandwich was placed onto a refractory block of ceramic alumina and heated above the melting point of palladium (1,552 °C) and well above the melting point of uranium (1,132 °C) using a small oxy-hydrogen torch. Uranium is miscible in palladium.

During heating, the palladium melted and surface tension caused it to form into a smooth button shape that was smaller and thicker than the original foil. We turned this button over and continued heating for several additional minutes with the objective of providing time for the uranium to disperse into the melted palladium matrix. After cooling, the palladium/uranium bead was rolled back into a foil in the rolling mill, using many small thickness-reduction steps to reduce the possibility of fracture. This rolling process took approximately one hour. (Sample preparation can be viewed by clicking here).

4. Setup

The center of the experiment was a simple electrolytic cell. This consisted of an open borosilicate dish filled with a concentrated electrolyte, a 10 weight-percent solution of LiOD in D_2O. For the cathode, we submerged the palladium-uranium alloy foil fully into the electrolyte and attached it to an insulated platinum wire that connected it to the power

Figure 1. Compressed view of the entire deuterium-loading run. Note the changing lab temperature (red trace) and electrolyte temperature (blue trace). The green, violet, ocher and pink traces are the four thermocouples. The main events in this figure are indicated by Roman numerals: (I) Start of run. (II) Region of sub-critical electrical charging of the palladium foil. (III) First temperature spikes (shown in expanded detail in Figs. 2) as regions of the palladium cathode go critical and heat production starts at three of the thermocouples; the temperature of the electrolyte drops gradually toward ambient air temperature in (II), but after (III) starts rising again. (IV) Moment when the fourth channel goes critical, as signaled by the large temperature spike and subsequent drop in temperature in all channels, as shown in detail in Fig. 3. (V) Region of critical operation of the palladium foil fusion reactor. (VI) End of the run. The loading current was increased at (III), again between (III) and (IV) just after 4 pm, and again at (IV). Between (IV) and (VI) there was a temporary reduction in charging current and a corresponding reduction in power output due to a problem with a wiring connection. The problem was corrected before the end of the run.

source. For the anode we used a plain platinum wire. K-type (nickel-alumel) thermocouples were clamped to the palladium foil; the more thermocouples were used, the more temperature spikes were detected. For the run illustrated in the figures, four thermocouples were used, attached with a pair of spring-loaded clips spaced approximately 1 cm apart. One thermocouple under each clip was in contact with the front surface of the foil, the other directly behind it on the back surface. Leads from the thermocouples were run through a multi-channel data logger (Pico Technology USB TC-08). The locations of these thermocouples on the foil, and the corresponding numbers of the data-logger channels and colors of the traces of each channel in the figures are as follows:

Left front: Channel 3 (Green),
Left back: Channel 4 (Ocher),
Right front: Channel 5 (Pink),
Right back: Channel 6 (Violet).

We used two additional thermocouples to measure the ambient temperature of the cell and of the palladium foil:

Channel 1 (Red) Air temperature in the lab
Channel 2 (Blue) Electrolyte temperature in the cell

The list of channels is displayed in Fig. 2B.

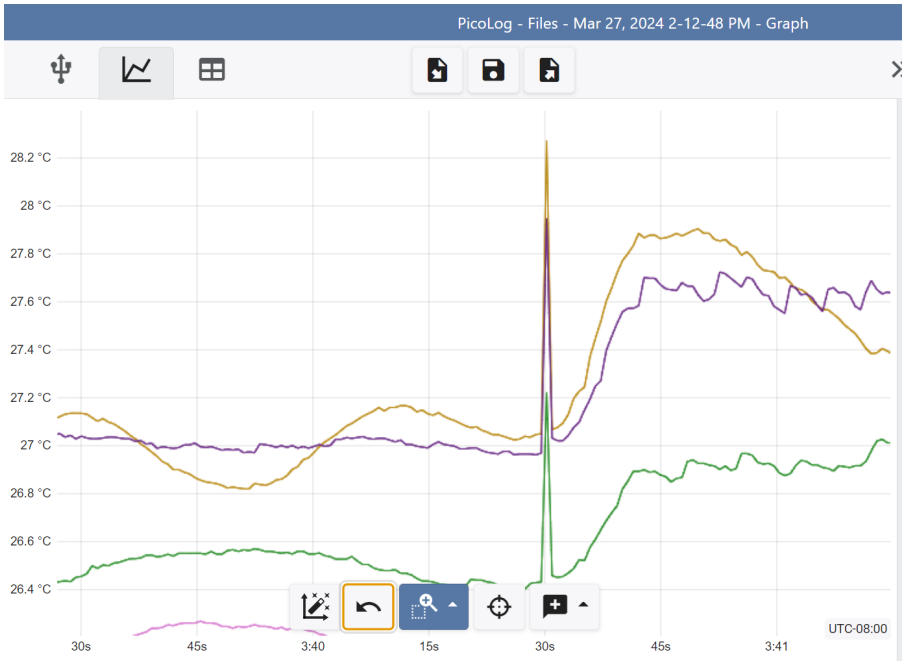

Figure 2A. Simultaneous temperature spikes on three thermocouples at 1 hour and 43 minutes after starting the deuterium-loading run. This event is marked (III) in Fig. 1.

5. Results

We started our first deuterium-loading run using a palladium-uranium foil with only a single thermocouple attached. We began with an electrolytic charging current of 30 mA. No gas bubbled off the palladium foil, indicating that the deuterium produced by the electrolysis was being fully absorbed. We increased the current to 60 mA half an hour in, and to 120 mA at 45 minutes. At 2 hours 14 minutes into the run – approaching the time we calculated it would take to fully load the palladium with deuterium (see Appendix B) we saw what appeared to be a temperature spike of 1.2 °C. By the end of the four-hour run we observed three more apparent temperature spikes.

The following table shows the times after the start of the run that the four apparent temperature spikes occurred, their peak changes in temperature and the loading current at the time of each spike:

Spike Number	Time after Start	Loading Current	Delta Temp.
1	2 hr, 15 min	180 mA	+1.1 °C
2	3 hr, 18 min	240 mA	+0.2 °C
3	3 hr, 23 min	240 mA	+0.2 °C
4	3 hr, 24 min	240 mA	+0.1 °C

All of the spikes returned to baseline temperature within 1 second.

After observing these apparent temperature spikes, we decided to halt the run to investigate their cause. Initially, we were unsure if they were due to fusion events or were simply glitches caused by some defect in our monitoring equipment. We eventually ruled out the latter by making several subsequent deuterium-loading runs that consistently

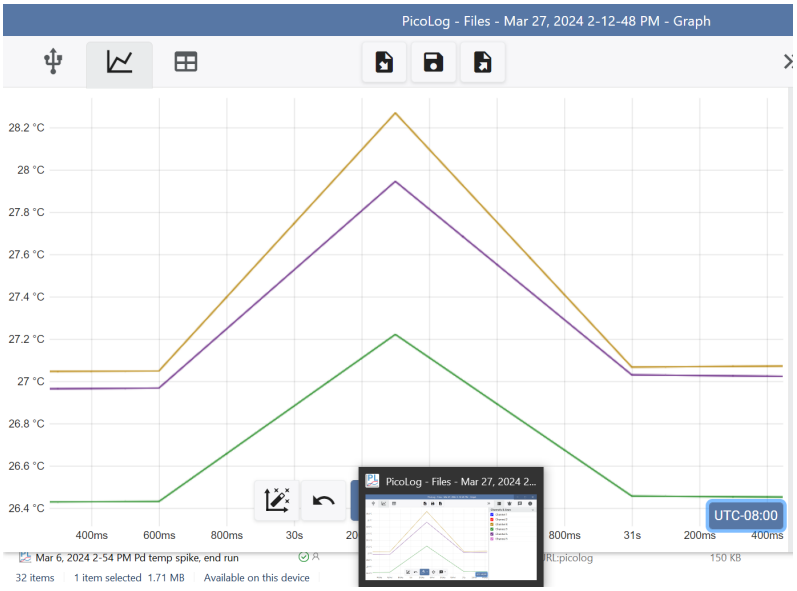

Figure 2B. Expanded scale of the event seen in Fig. 2A. The three spikes are simultaneous to within the measurement resolution of our equipment: Their widths are limited to 1/10 second by the response time of the low-mass thermocouples that were used.

produced multiple temperature spikes with similar time signatures. For these runs we decided to use a total of four fast-responding thermocouples (one tenth-second response time) so that we could better observe the temporal and spatial distribution of the temperature spikes over the surface of the foil. We also refreshed our electrolyte solution to eliminate the possibility of cross-contamination from earlier charging runs.

During our final run using a palladium-uranium foil with these equipment changes (Fig. 1), we observed multiple temperature spikes, shown in Fig. 2, 3, and 4. How exciting it was to see the multitude of random temperature spikes recorded in Fig. 4!

The traces in Fig. 2A show that three of the four thermocouples (Channels 3, 4, and 6) recorded reaching criticality simultaneously, with temperature spikes of 0.8 °C, 1.0 °C and 1.2 °C, respectively. The fourth thermocouple (Channel 5) remained unaffected. Fig. 2B shows the same event with an expanded time scale. One can see that the temperature spikes occurred at the same time in all three active channels. This implies that wherever the fusion event was first triggered in the palladium foil, it propagated so fast that we could not resolve its advance. This indicates a propagation speed greater than 10 cm per second, as the thermocouples on Channels 3 and 6 were placed approximately 1 cm apart and our minimum sampling-time interval was 0.1 sec. One gets a picture of a macroscopic deuterium fusion event that quickly filled the space between thermocouples 3, 4, and 6 and then, almost as quickly, died out – likely due to depleting the deuterium that had been maintaining criticality in this region. During the following 10 seconds, the temperature built up at thermocouples 3, 4, and 6 and more temperature-spiking continued at a somewhat lower level and persisted long after.

As the electrolytic charging of the foil continued, it is reasonable to assume that the concentration of unreacted deuterium near the quiescent thermocouple 5 continued to increase until it also ‘fired off’ 38 minutes later with the largest temperature spike that we observed (5.7 °C). This extraordinary temperature spike is shown in Fig. 3. It should also be noted in this figure that there were simultaneous temperature reductions in thermocouple channels 3, 4, and

Figure 3. The largest temperature spike observed, at 5.7 °C (pink). This event is marked (IV) in Fig. 1. It was followed by immediate temperature drops on all channels. These drops were unexpected but are now believed to be understood, as discussed in the text.

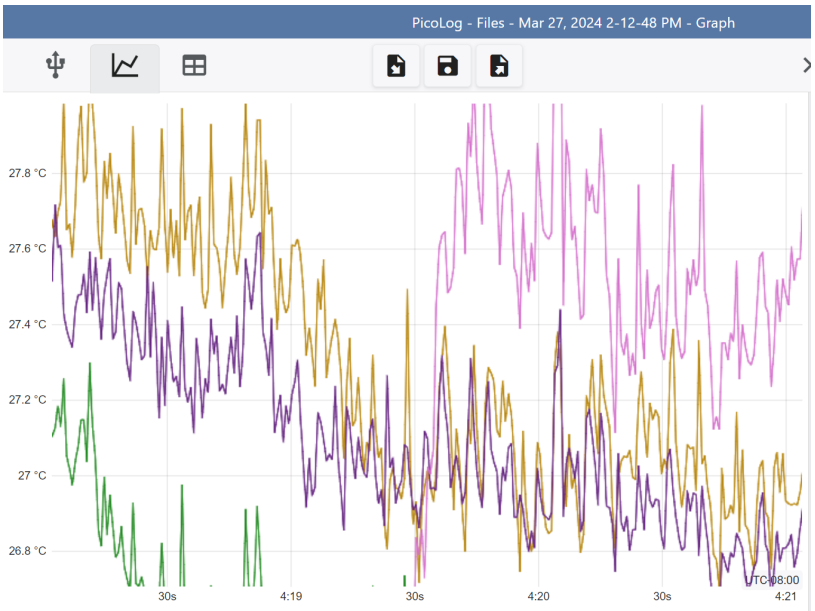

Figure 4. Numerous temperature spikes observed after reaching criticality. The time starts 30 seconds after the large spike seen in Fig. 3, with an expanded vertical scale.

6. At first, we were puzzled by these unexpected temperature reductions. Eventually we realized that the very large temperature spike in the region of thermocouple 5 may have reduced (burned out) quite a lot of deuterium in this location and this may, in turn, have caused deuterium ions in regions 3, 4, and 6 to quickly move to fill the void in region 5. On the short term, this would tend to reduce power production in regions 3, 4, and 6, as observed, followed by a return to temperature-spiking in these regions, but at a somewhat lower level than before the 5.7 °C temperature spike in region 5. Subsequent temperature-spiking at a reduced level continued in all four thermocouple channels until the end of the deuterium-loading run.

Fig. 1 provides a compressed overview of the data we collected during this electrolysis run. There one can see that the thermocouple monitoring the ambient air temperature in our laboratory (Red) showed a slow but monotonic decline as the afternoon sun was setting, and that the thermocouple monitoring the temperature of the electrolytic bath (Blue) began showing a slow increase after the temperature spikes began (region V on the plot). By the end of the run, the temperature of the electrolytic bath had increased by approximately 1.5 °C relative to the minimum value measured at the first temperature spike, while the ambient air temperature continued to decrease. While some of this increase relative to the electrolyte bath might be attributed to electrical heating associated with electrolysis, we saw no such effect in an immediately prior run using a palladium foil that did not contain any added uranium. We concluded that most of the temperature increase was caused by nuclear fusion.

6. Conclusion

After considering many improbable alternatives, we believe that the extensive thermal spiking we observed confirms Solid State Fusion. The substantial magnitude of the spikes seen in the figures could not be due to single alpha-particle emissions or to single deuterium-deuterium fusion events. Rather, many reactions must have been clustered closely together in time. Specifically, we calculate in Appendix C that 3×10^9 fusion events would be required to produce enough energy to raise the temperature of our thermocouple by 1 °C.

We find it helpful to think of the palladium foil in its electrolytic cell as analogous to a conventional fission-reactor core inside its reactor vessel, and believe that the temperature spikes we observed were due to transient nuclear-fusion chain reactions triggered by alpha decay of the uranium mixed into the foil, similar to what happens during the cold startup of a fission reactor when control rods are pulled and a chain reaction begins. If this is the case, the fact that the power output is in the form of spikes, rather than sustained at a continuous level, suggests that the palladium foil must have been operating just above the critical level. As calculated in Appendix C, each alpha-decay triggering event would have to be multiplied by a factor of at least 3×10^9.

We calculate that an alpha decay produces extraordinarily high, albeit extremely localized, temperatures within the palladium crystal lattice (see Appendix A), temperatures sufficient to initiate a fusion chain reaction among the deuterium ions dispersed in the lattice. This means that ‘cold fusion’ is not actually a cold process. Rather, ‘cold fusion’ is a misnomer for a process better defined as ‘solid-state fusion,’ which occurs at temperatures comparable to those inside the sun.

This explanation goes a long way to account for the mysteries surrounding Fleischmann and Pon’s inconsistent results, as well as the many frustrating attempts to replicate them. The likely explanation for some previously claimed successes in achieving ‘cold fusion’ by very patient researchers who waited weeks and months for heat production to begin, is that these results were likely due to fortuitous fusion reactions triggered either by a random cosmic ray or by the spontaneous decay of a trace radioactive contaminant in their palladium. Other researchers were not so lucky. Appendix F describes two major projects that were started in 1990s to replicate the work of Fleischmann and Pons, and why they may have failed.

Try to think of the possibilities for a solid-state fusion reactor the size of a postage-stamp!

7. Acknowledgements

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APPENDIX A: Temperature of an Alpha-Particle Decay

When any atom undergoes a nuclear reaction, fission or fusion, in a solid material, nuclear energy is released in the form of rapidly moving subatomic byproducts that can impact neighboring atoms so vigorously that localized melting, quickly followed by refreezing, occurs on a microscopic scale. This effect is known to cause a substantial increase in the total number of atomic voids in metals [23]. This discovery was made by researchers who were recruited in the 1940s to 1960s to direct programs that would investigate the cumulative effects of radiation on the materials used to build nuclear fission reactors. One of their most significant findings is that metals tend to swell (typically by 2% to 5%) and distort under continual neutron bombardment, due to the accumulation, over the lifetime of a typical nuclear reactor, of these atomic voids.

The focus of these researchers was on the mechanical strength and durability of materials under irradiation, not on the local temperatures that occurred during these events. If one asked a mainstream physicist how high the temperature goes within such a submicroscopic burst of heat produced by a fission or fusion event, they would likely be reluctant to give a definitive answer because temperature is defined by the average kinetic energy of a group of particles in thermodynamic equilibrium. The physicist would tell you that the atoms involved in such submicroscopic bursts heat up and cool down so quickly that there is not sufficient time to establish thermodynamic equilibrium. But if pressed, the physicist would likely agree with Wigner and Seitz that shortly after the peak of the burst the total released nuclear energy would be shared by, say, ten thousand or so neighboring atoms [23]. Since the fusion of two deuterium atoms releases 4.03 million electron volts (MeV) of energy, each atom within such a burst region would on average acquire roughly 403 electron volts of thermal energy. As the kinetic energy is proportional to temperature, and the average thermal kinetic energy of an atom at room temperature (20 °C = 293 K) is 1/40 eV, one can very approximately estimate the temperature in the neighborhood of a nuclear event to be T = (403 eV)(293 K)/(1/40 eV) = 4.7 million kelvin. Such a high temperature is typical of most spontaneous nuclear reactions, both fission and fusion. The kinetic energy would be much higher for atoms that are closer to the fission or fusion event, likely approaching or exceeding the energies associated with the 15 million-K temperature in the fusing core of the sun.

APPENDIX B: Foil-Charging Time

Many researchers who have attempted to reproduce Fleischmann and Pons' 1989 results believe it is essential to load the palladium with an extremely high concentration of deuterium for heat to be produced. Michael McKubre, a former student of Fleischmann's and subsequently Director of the Energy Research Center at the Stanford Research Institute (SRI International) in Palo Alto, California (now retired), reported that the ratio of deuterium ions to palladium atoms should be 0.875 or greater – that is, a ratio of $PdD_{0.875}$ or greater [24]. To reach this level requires high-quality palladium and considerable care in loading.

Although some researchers observed excess heat-generation only after days or weeks of electrolysis, the deuterium-loading time should not be nearly that long. Faraday's Law of Electrolysis can be used for a rough estimate. The following calculation finds the minimum time to achieve a deuterium/palladium ratio of 1.0, in the ideal case that all deuterium dissociated at the palladium cathode is absorbed by it.

One can estimate the time, t, to load a palladium cathode with deuterium by equating the electrical charge, Q, delivered by a current, I, to produce a number of deuterium ions equal to the number of palladium atoms in the cathode, in a 1:1 ratio. Specifically:

$Q = I \times t$ = number of palladium atoms in the cathode × charge per deuteron
= (moles of palladium, n)(Avogadro's number, N_A)(electron charge, e)

Solving for t results in:

$t = nN_Ae/I = nF/I$ (1)

where $F = N_A$ e is the Faraday constant and t = nF/I is Faraday's second law [17].

Setting these to the mass of our cathode and a moderate current,

n = (1.2 g of Pd)/(106.4 g/mole) = 1.13×10^{-2} moles
F = 9.05×10^4 Amp-sec/mole
I = 0.120 Amp,

results in a time of 2.5 hours (2 hours per gram of palladium) for full deuterium-loading of our cathode using our default loading current of 120 mA under ideal conditions. This result is in the range of the time we needed to run the electrolytic cell before observing temperature spikes in the palladium-uranium foil.

APPENDIX C: Number of Fusion Events Required for a Moderate Temperature Spike

The number of fusion events required to produce a temperature spike of 1 °C can be approximated by equating the thermal energy necessary to heat the mass of the thermocouple tip by 1 °C to the number of 4.03-MeV fusion events required to produce the same amount of energy. This assumes that the region of heating is in direct contact with the thermocouple and that all heat produced is transferred to the thermocouple, and as such is a lower bound.

The fast-responding nickel-alumel thermocouples that we used had a spherical tip of diameter D = 0.9 mm, for a volume of $V = \pi D^3/6 = 3.8 \times 10^{-5}$ cm^3. The heat capacity, HC, for this bead can be calculated from the density, ρ (8.60 g/cm^3), and specific heat, SH (0.125 cal/g·°C), of nickel-alumel [18].

HC = V × ρ × SH
HC (in MeV)
= (3.8×10^{-5} cm^3)(8.60 g/cm^3)(0.125 cal/g·°C)(4.184 J/cal)(6.2×10^{12} MeV/J)
= 1.06×10^{10} MeV/°C.

Since each deuterium-deuterium fusion event produces 4.03 MeV of energy, a total of (1.06×10^{10} MeV/°C)/(4.03 MeV/event) = 2.6×10^9 deuterium-fusing events are required to heat the thermocouple tip by 1 °C. Based on the half life of uranium-238 relative to alpha particle decay of 4.468×10^9 years, we expect 200 alpha decays per second from the 18 mg of uranium in the foil.

APPENDIX D: Palladium Foil Behaves as Bulk Material

Palladium foil 125 μm thick behaves as bulk metal rather than as a thin film (such as those employed by Gordon *et al.* [12], [13]) because it requires approximately 32,000 palladium atoms to span the 125 μm thickness of the foil (125 μm / 3.89 angstroms between palladium atoms in their close-packed cubic lattice [22] = 32,000 atoms).

APPENDIX E: Pre-Polarized Oppenheimer-Phillips Effect

Early critics of Fleischmann and Pons' 1989 work on 'cold fusion' were quick to point out that the fusion reaction D + D $\rightarrow$ ^{4}He produces the helium in an excited state that quickly decays with equal probabilities along two pathways (branches):

(1) tritium + proton (^{3}H + p), and
(2) helium-3 + neutron (^{3}He + n).

These critics predicted that the neutrons produced by the second branch would have been lethal to Fleischmann and Pons if they had actually observed fusion. However, there may be situations in which the second branch is not comparable in strength to the first. One possibility is related to the Oppenheimer-Phillips effect, which was first investigated by Robert Oppenheimer and Melba Phillips in 1935 [19], though critics have claimed that this effect is too small to explain the lack of irradiation [20]. Based on the considerable amount of experimental evidence accumulated since 1989, it would seem that the deadly neutron-producing branch is not significant inside of metals such as palladium. But why? One possibility that may be viable is a low-temperature variant of the Oppenheimer-Phillips effect. Since this possibility is preliminary yet potentially significant, it is introduced here in an appendix rather than in the text. (Several other fusion alternatives have been explored; one that was proposed by Edmund Storms, a reaction of D + e + D $\rightarrow$ ^{4}H $\rightarrow$ ^{4}He + e + neutrino, is also consistent with the survival of Fleischmann and Pons [21].)

We believe that a modification of the Oppenheimer-Phillips Effect can explain the lack of lethal neutron radiation generated by Solid-State Fusion.

By way of background, here is a description of the Oppenheimer-Phillips effect given by Robert B. Leighton [19]:

> There are a few special situations which deserve special attention. One of these is that (deuteron, proton) reactions are much more commonly observed than would be expected ... The reason for this was deduced by Oppenheimer and Phillips (1935). When a deuteron approaches a nucleus, the repulsion between the nucleus and the proton causes the deuteron to become polarized with its proton end farther from the nucleus. The proton-neutron bond distance for the neutron is of such a size (approximately 5×10^{-15} m) that the neutron can be inside the nucleus before the proton has surmounted the Coulomb barrier. The weak bond (2 MeV) of the deuteron is easily broken, so that the proton can be ejected and the neutron retained.

Applying this effect to two deuterons on a collision course that might lead to a fusion event, one would expect that the more likely outcome would be the formation of tritium + proton rather than ^{3}helium + neutron. However, Koonin and Mukerjee argue that there is insufficient time in a hot-fusion reactor for the incident deuterons to rotate into a polarized orientation before they collide [20]. This would mean that the Oppenheimer-Phillips effect should be small to negligible.

While this does appear to be the case in a hot fusion plasma, the situation may be entirely different under the conditions inside the solid-state palladium lattice. It is possible that under normal room-temperature conditions, the deuterium ions dispersed in palladium may rotate to a polarized orientation, and thus no additional time would be required for polarization when an alpha-particle emission or other triggering event occurs, even with the high transient temperatures estimated in Appendix A for such an event. In effect, the deuterium ions may exist as pre-polarized pairs in the PdD lattice – much as they do in molecular deuterium gas (D_2) – so that the reaction branch D + D $\rightarrow$ tritium + proton is favored over the production of neutrons. Under such conditions, the Oppenheimer-Phillips effect would dominate.

We realized that this pre-polarization in palladium metal may be a possibility after recognizing the high mobility of deuterium across the foil. The deuterium ions appear to move through the palladium lattice almost like a gas, as demonstrated by Fig. 3. Analogy to polarized di-atomic gas gave rise to the idea of pre-polarized deuterium ions in the

palladium host. X-ray and neutron-diffraction studies show that the hydrogen ions in palladium hydride occupy the center of the metal's face-centered cubic lattice structure [22]; palladium deuteride should be similar. Measurements of the magnetic properties of palladium hydride indicate that when the hydrogen concentration passes 62% of the palladium atom concentration, $PdH_{0.62}$, the material becomes diamagnetic [25]. This suggests anti-parallel spin alignment of nearest neighboring palladium ions at the higher concentrations required for fusion. If the magnetic moments of adjacent deuterium ions tend to align by spin-spin coupling, one would expect a substantially enhanced Oppenheimer-Phillips effect: When a localized compression wave from an alpha decay or other energetic event propagates through the lattice, the half of adjacent deuterium ions that are oriented so that the neutrons are closest will selectively react, favoring the D + D $\rightarrow$ tritium + proton pathway, while the half oriented so that the protons are closest will resist approaching one another, damping the helium-3 + neutron pathway. The net result is strongly biased towards the first pathway. We have chosen to name this behavior in palladium hydride the *Pre-polarized Oppenheimer-Phillips effect*.

APPENDIX F: Case Histories of Cold Fusion Failures

Two case studies are particularly worth mentioning because they highlight the need for a triggering source.

When Fleischmann and Pons had difficulty reproducing their cold fusion experiments in 1990, their institution, the University of Utah, decided to establish a substantial new facility, named the National Cold Fusion Institute (NCFI), to carry out cold fusion research on a scale beyond what had been possible in their chemistry lab. Initial funding for the institute was five million dollars. A seasoned scientific manager with considerable industrial experience was hired to direct the Institute's efforts. Early on in this assignment, he decided to eliminate as many experimental variables as practical. Critically, he decided to use very high-purity palladium to eliminate the possibility that some unknown contaminant might influence the results. Eventually more than one hundred experiments were conducted, and all failed to produce any substantial excess heat – the work of the Institute was a total failure. When funding ran out in 1991, the institute was shut down, the director lost his job, and the careers of Fleischmann and Pons were destroyed. No one at the time had any idea of what had gone wrong. (Note: While the NCFI did not report any positive replication of Fleischmann and Pons' results, they *did* report positive results for tritium production [27] and observation of minor bursts of excess heat bursts [28].)

Considerably later, Pinnow had an opportunity to review many of the results at the Institute and elsewhere. He realized that the decision to use high-purity palladium was likely a fatal mistake. That decision eliminated the use of radio-frequency induction furnaces for the purification of the palladium that they used. It turns out that thorium (an alpha-particle emitter) is a typical trace contaminant in materials processed in these furnaces, which are used in many laboratories [26]. A low-density thorium oxide material, called *thorium frit*, is often used for support structures inside these furnaces. Some spalling of this frit occurs when the furnace temperature reaches high temperatures such as the melting point of palladium (1552 °C) [26]. It is necessary to exceed this temperature so that heavy impurities in the palladium will sink to the bottom of the melt and lighter impurities will float to the top, where they can be removed. The spalling at such temperatures can cause minor thorium-oxide contamination of the material being processed. Without some radioactive contamination of this nature in the palladium electrode to serve as a trigger for deuterium fusion, the experiments at the Institute were likely doomed.

There is another instance where the use of very high purity palladium did not produce hoped-for results: A program sponsored by the Japanese Ministry of International Trade and Industry (MITI) in the 1990s supported attempts to replicate the Stanford Research Institute's (SRI) version of the Fleischmann-Pons experiment, but with 0.99999-pure palladium in an effort to eliminate sources of inconsistency, including background contamination, between experiments conducted at different laboratories. Several hundred experiments were done around the world under this initiative. At the end, no one had positive results to show for years' worth of effort. This further supports our position that very high

purity palladium may not contain a sufficient content of nuclides capable of spontaneous alpha-particle decay and thus serving as fusion-triggering sources.

APPENDIX G: Hazard Analysis

Anyone undertaking experimental work in solid-state fusion is encouraged to conduct a diligent hazard analysis before proceeding. The consequences are potentially serious [5]. Our analysis revealed that if even a one-gram, postage-stamp-sized palladium foil were fully loaded with deuterium, and a single fusion chain-reaction were to somehow consume all of that deuterium, the resulting explosive release of energy would be in excess of 100 sticks of dynamite!

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