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Research Article

High Energy Density and Power Density Events in Lattice-enabled Nuclear Reaction Experiments and Generators

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Abstract

The rapid release of energy from Lattice Enabled (or Low Energy) Nuclear Reactions is of interest for three reasons. First, it constrains and challenges theories about the mechanism(s) active in producing LENR. Next, it might heavily influence the design of heat and electrical generators based on LENR, since they have to be safe for use by a wide variety of people. Finally, there has long been interest in whether or not LENR could be used to augment existing weapons or produce to entirely new weapons. This paper first reviews reports in the literature of meltdowns or explosions that might have been caused by LENR. Then, each of the three areas cited above is examined. It is clear that reported high energy or high power events will heavily impact theories about LENR and the development of safe products. It is unclear now if LENR will be weaponized in any form. Control of the initiation of explosive LENR events is obviously necessary for that possibility.

Keywords: Craters, Explosions, High-power, LENR, Meltdowns

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1. Introduction

Meltdowns and explosions have already been observed in LENR experiments and tests of prototypes of products. Analyzing and understanding those events are relevant to scientific understanding of LENR, the operational safety of generators based on LENR and, possibly, the weaponization of LENR. The major scientific question is whether or not chain reactions can occur in LENR systems. The development of safe products based on LENR is mandatory, if they are going to be used widely. Using LENR in or for weapons has already been studied and, undoubtedly, will continue to get attention.

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Sections 2–5 review instances of the fast release of energy in LENR experiments. Then three sections deal with the influence of such events on the science, commercialization and weaponization of LENR. A few comments on research needed to address the fast release of energy by LENR are in Section 9.

2. Fleischmann–Pons Meltdown

Fleischmann and Pons started their experiments on loading deuterons into palladium long before the controversial press conference in March of 1989. They were already performing such experiments more than four years earlier. In or about February of 1985 they were running an electrochemical experiment in which the cathode was a cube of Pd 1 cm on a side. One morning, they came to laboratory to find that the experiment was destroyed. They described the situation in a journal article [1]. "We have to report here that under the conditions of the last experiment, even using D_2O alone, a substantial portion of the cathode fused (melting point 1554°C), part of it vaporized, and the cell and contents and a part of the fume cupboard housing the experiment were destroyed." Kevin Ashely was a graduate student with a laboratory nearby that of Fleischmann and Pons. He is quoted in the book by Charles Beaudette [2]. "The bench was one of those black top benches that was made of a very, very hard material. I was astonished that there was a hole through the thing. The hole was about a foot in diameter." Chase Petersen was President of the University of Utah at that time. He wrote in his autobiography [3]. "There was a hole in the lab counter top it had occupied but no evidence of an explosion. Beneath the countertop was a hole in the cement floor some eight inches wide and three or four inches deep." Many of us found that report to be incredible. Could one cubic centimeter of even superheated Pd liquid cause such damage to concrete after burning through the experimental cell and the benchtop? Later, Larry Forsely wrote [4]. "I last discussed this with Martin Fleischmann at his home in 2007. He stated that the damage to the concrete floor in the bottom of the cabinet was the size of the tip of his thumb and about 1/2 inch deep. He acknowledged that the structure was destroyed, with a fist size hole in the benchtop... Both he and Stan Pons were scared that they would be shut down and worse." This level of damage seemed more reasonable. However, it was still remarkable.

Jed Rothwell offered his view of the event in his book "Cold Fusion and the Future" [5]. "Unfortunately we know nothing about the nature of the February 1985 explosion, because Fleischmann and Pons did not keep any physical evidence from this event, such as a piece of the burned table or scraps of the exploded cathode. In my opinion, this was irresponsible and unprofessional. Fleischmann ruefully agrees." Despite variations in reports of the effects of the meltdown, and the lack of either physical evidence or photographs, it happened and is significant.

As can be seen from these reports, there was confusion concerning the nature of the event in the Fleischmann–Pons laboratory. Both melting (fusing) and exploding were mentioned. However, it is clear now that the event was a meltdown. An explosion would not have produced damage to the bench and floor only directly under the experiment. It is understandable why Fleischmann and Pons did not want photographs of the damage to their laboratory circulated. However, it is very regrettable that such photographs are not available for scientific analysis. Further, it is odd that no one seems to have tried to replicate the experiments using cubic cathodes of Pd. Doing experiments with cube-shaped cathodes of varied size, say 2, 4, 8 and 16 mm, could be very instructive. Of course, they would have to be done in a safe place, probably on the floor of a bare concrete room. Full-time video monitoring would be easy, with a high speed camera available to be triggered by any sudden temperature rise.

It seems surprising that there are no published analyses of the Fleischmann–Pons meltdown, given its importance. It is not difficult to make some simple estimates. The cathode in the experiment was a cube of Pd 1 cm on a side (11.9 g). It contained 6.7×10^{22} Pd atoms, so if it was fully loaded with deuterons, there would be that number of deuterons in the cube. Assume that deloading the deuterium atoms from the Pd cube takes no energy. The oxidation of that number of deuterons would produce 12.8 kJ. It takes 0.53 kJ/g to melt Pd, taking into account the specific heat and heat of fusion. Hence, 12.8 kJ would melt 24.2 g of Pd. However, the dynamics of the situation would prevent that from happening. That is, the release of the deuterium might have been too slow, at least initially, to get the Pd to its melting point. And, if the deuterium were burned on the surface of the cube, only a fraction of the heat of combustion would have been transferred into the Pd cube.

The 1985 meltdown should be simulated using the temperature dependent properties of palladium, with various assumptions about the location, duration and magnitude of the LENR energy release. An estimate of the total amount of energy required to produce the observed effects, and possibly an upper limit on the duration of the release, might result.

3. Explosions Attributed to LENR

LENR experiments often involve high pressures. This is true of both electrochemical experiments and gas loading approaches to LENR. Hence, it is possible for explosions to occur because of the sudden release of pressure, an entirely mechanical event. In electrochemical experiments accumulation of gaseous hydrogen and oxygen above an operating cell can produce a dangerous mixture. Ignition leads to a rapid, explosive chemical reaction. Neither of these types of events is due to rapid release of energy by LENR. Two such events have been reported, one at SRI International [6] and the other at the University of Hokkaido [7].

There are three published reports of explosions during experiments that were attributed to LENR. The earliest was published in 1992 by Xinwei Zhang and six Collaborators [8]. Their setup is shown in Fig. 1. They were using a hollow Pd cathode 8 cm long with a 1.67 mm OD and 500 μm wall thickness. Three explosions in April of 1991 occurred with no one present. In two cases, the rubber stopper and electrodes were blown 1.5–2 m away, and the bottom of the cell was blown out. The water bath temperature increased 5°C. The authors wrote "…the real explosion cannot be caused by chemical reaction" and "The heat burst in the explosion reached MW per cm^3 Pd." That is, their estimate of the power density from the explosions was very high. In the abstract of a recent paper on thermal analyses of these explosions, five of the scientists state "The average power was greater than 6.7 W (65W cm^{-3} Pd or 430% of input power). Thermal analysis indicates that the power of the explosion was 5.1–5.5 kW (or 50–53 kW cm^{-3} Pd), and the event developed in 2–17 s" [9].

A second explosion that could only be attributed to LENR was reported by Mizuno and Toriyabe in 2006 [10]. They were using a tungsten cathode 1.5 mm in diameter and 29 cm long. A length of 3 cm was in 0.2 M K_2CO_3 H_2O electrolyte. The experiment is shown schematically in Fig. 2. The cell with 700 ml of electrolyte heated from 30°C to 80°C in 10 s, and then exploded. The authors took into account the heat capacity of the electrolyte and the measured hydrogen production. They stated that "The estimated heat output was 800 times higher than the input…" This is the highest reported energy gain in an LENR experiment. Gains in the range from 80 to 415 were reported by Focardi and Rossi [11]. Other, lesser reports of energy gains are available and were reviewed recently [12]. However, even the smaller reported energy gains are adequate for the commercial success of LENR heating units.

Another explosion attributed to LENR was reported by Biberian in 2009 [13]. He was using a hollow Pd cathode 10 cm long, 2 mm OD and 200 μm wall thickness. The experiment had been running for 30 days with 0.1 M LiOD in D_2O prior to explosion. The setup and the aftermath of the explosion are shown in Fig. 3. Biberian attempted twice to replicate the observed damage by inducing chemical explosions of hydrogen and oxygen in a similar Dewar, but did not shatter it. He concluded that "It is very likely that under some not yet understood conditions, chain reactions occur in highly loaded palladium samples giving rise to an explosion." Biberian's experience was consistent with, but not proof of chain reactions.

It is curious that two of the three explosions, which were attributed to LENR by the experimenters, occurred when hollow Pd cathodes were being used. This might be nothing more than an odd coincidence. However, it does suggest that more experiments be performed with tubular Pd cathodes. Such geometries have the added advantage of being able to insert sensors inside of an active cathode during electrolysis.

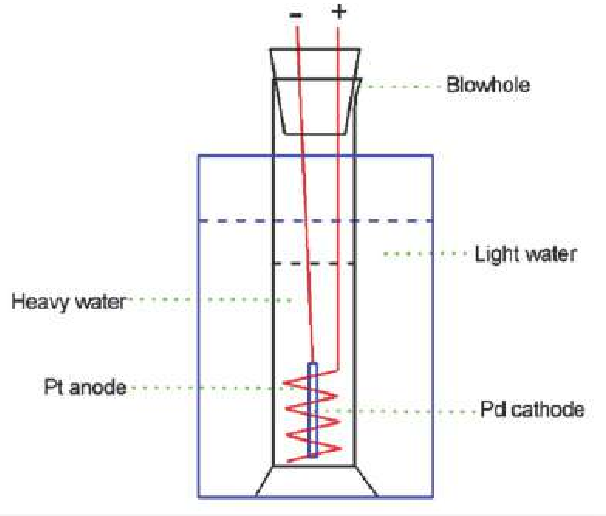

Figure 1. The experimental setup of Zhang and his colleagues .

The three explosions just discussed are not the only ones reported during LENR experiments. There have been other reported explosions, although not with detailed documentation. Hence, it is unclear whether the events were due to LENR or other causes. Krivit wrote [14] "…a source who wishes to remain anonymous states that the Lawrence Livermore National Laboratory had a Fleischman–Pons type explosion in 1989, as well." This leaves open the question of whether the event at that laboratory was a meltdown or, as reported, an actual explosion. Recently, there was an explosive event in the laboratory of the MFMP [15]. "An attempt by the Martin Fleischmann Memorial Project to

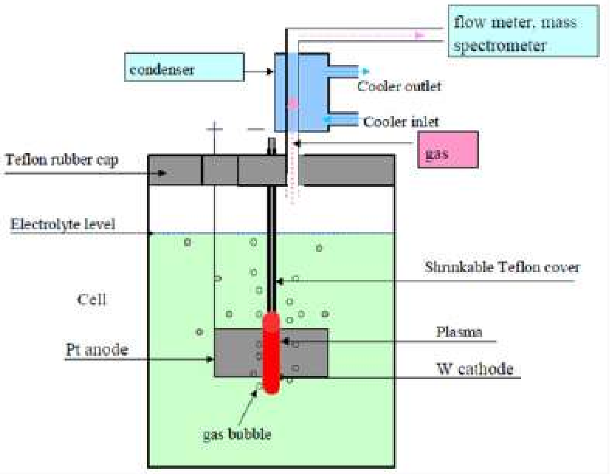

Figure 2. Drawing of the experiment of Mizuno and Toriyabe.

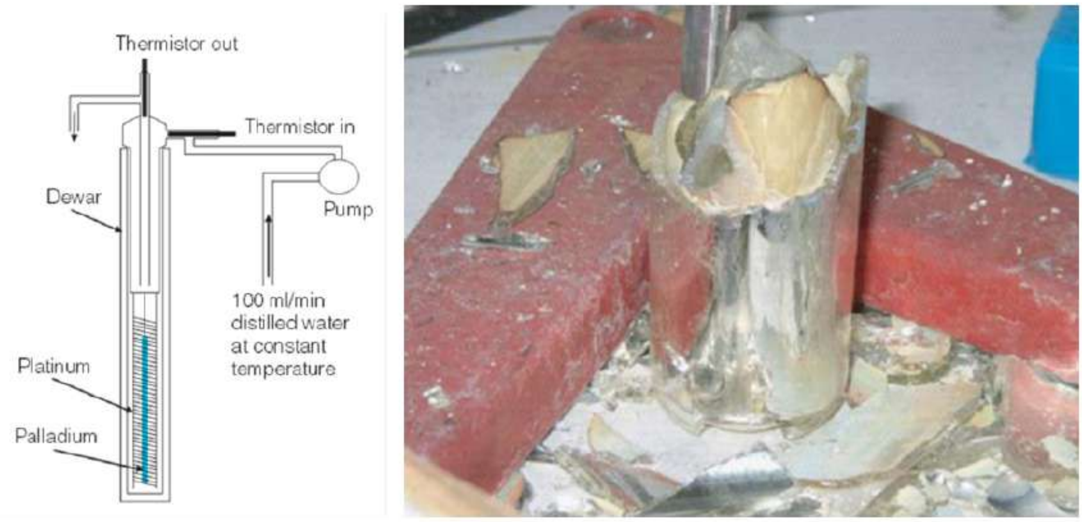

Figure 3. Schematic of Biberian's experiment and a photograph after it exploded.

replicate E-Cat, Andrea Rossi's alleged cold fusion reactor ended explosively yesterday after the reactor heated to over 1000°C." It is unclear whether this was due to LENR or high pressure or simply thermal stresses in the material. There have been unpublished reports of runaway events in LENR and related experiments by Francesco Piantelli, Stanislaw Szpak, Mark Snoswell, Vince Cockeram and Brian Ahern. It is very possible that other unreported meltdowns and explosions have occurred in LENR experiments. However, the fact that competent scientists have had explosive events occur during LENR experiments, and that they attributed them to LENR, is significant for scientific, commercial and, possibly, military reasons.

4. Explosions During Tests by Rossi

It appears that Rossi ran numerous tests of his E-Cat devices roughly during the time period from 2007 to 2009. There have been reports of explosions during such tests. In an interview [16], Christos Stremmenos stated that there were explosions during E-CAT tests in Bologna, fortunately all at night. Hank Mills wrote [17] "Andrea Rossi has stated many times in the past a self-sustaining system is dangerous, and there is a chance of explosions. He actually indicated that during stress testing of systems he has witnessed dozens of explosions". In response to a question by Hank Mills, Rossi wrote in his blog "We have seen explode hundreds of reactors…" [18]. It is clear that Rossi has paid a great deal of attention of control of his various E-Cat systems. In the first Levi report [19], control was achieved by the use of a square electrical waveform. When power was applied, the LENR reaction rate took off. Then, when the power was turned off, the reaction rate and heat production diminished. Chapter 12 of the book by Ventola and Nikolova is entitled "Control of Hot-Cat Reactions". It is the best available discussion of approaches to the willful variation of the output of Rossi's systems [20]. The absence of recent reports on E-Cat explosions indicates either they have been kept secret or have not occurred. The latter possibility seems the more likely.

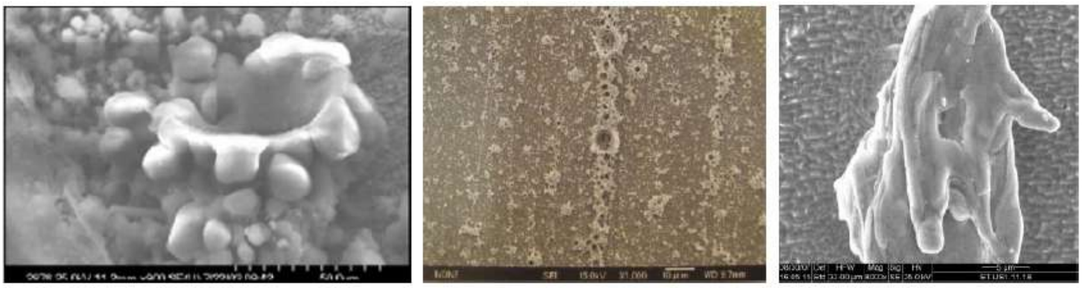

Figure 4. Examples of craters in the cathodes after electrochemical LENR experiments, which show evidence of melting. Sources of these images are cited in the text.

5. Crater Observations, Analyses and Simulations

Small craters in the surfaces of cathodes from LENR electrochemical experiments have been observed by several investigators. They generally range from about 1 to 100 μm in diameter. Many craters show evidence of melting and, hence, high temperatures. Three examples are exhibited in Fig. 4. They are, left to right, co-deposition of Pd with D [21], a gold surface with craters aligned along scratches [22], and Pd subjected to simultaneous super-wave and ultrasonic excitations [23].

Recent papers have provided analyses of the characteristics of craters. The first, which reviewed the literature on craters, determined that the energy required to form craters varies from 1 nJ (for 1 μm diameter) to 1 mJ (for 100 μm diameter) [24]. The next advance was by Ruer, who provided an analytical model for the dynamics of crater formation [25]. He found that crater formation times in the range of nanoseconds to microseconds.

It is instructive to consider a crater with an intermediate diameter of 10 μm. The energy required for formation of such a crater is about 1 μm J, and the eruption time is near 100 ns. These values give an averaged power density of 8×10^{10} W/cm^3. This is about one order of magnitude greater than the power density due to the explosion of TNT, namely 7×10^9 W/cm^3 [26]. It must be noted that the size of the power release volume could be *much* smaller. That is, using the entire volume of the final crater gives a very low power estimate. Taking the eruption time rather than the (unknown) energy release time gives a very conservative (low) estimate of the power density. More realistic estimates of the geometries, energetics and dynamics of crater formation can only be made using modern materials simulation tools.

The first full dynamical simulation of crater formation was conducted using the CTH Shock Physics Code [27] from Sandia National Laboratories. In the simulation, 680 μJ were released in 10 ns within 0.5 μm radius sphere 10 μm beneath a Ag surface. The simulation was conducted on a Dell Z800 high performance computer using 22 cores. A simulation spanning 520 ns in time took 115 h of computer time to complete. The results of the simulation for three times are shown in Fig. 5. The images show that it took almost 40 ns for the effect of the energy release to propagate to the surface of the material. The event was far from complete by 360 ns. Pressures as a function of location and time can also be obtained from CTH calculations. It is also possible to determine the ultimate disposition of the initially released energy using that code.

Simulations using the CTH code should be done as a function of several parameters. They include the amount of energy and the release time, that is, the initial power. The size (volume) of the energy release region is an important parameter since it determines the initial power density. Probably, the precise shape of the initial energy release volume is not important, as long as it is relatively equiaxed. That is, long and thin, or else flattened, energy release volume shapes could lead to different simulation results, but might not be physically realistic. The location of the release

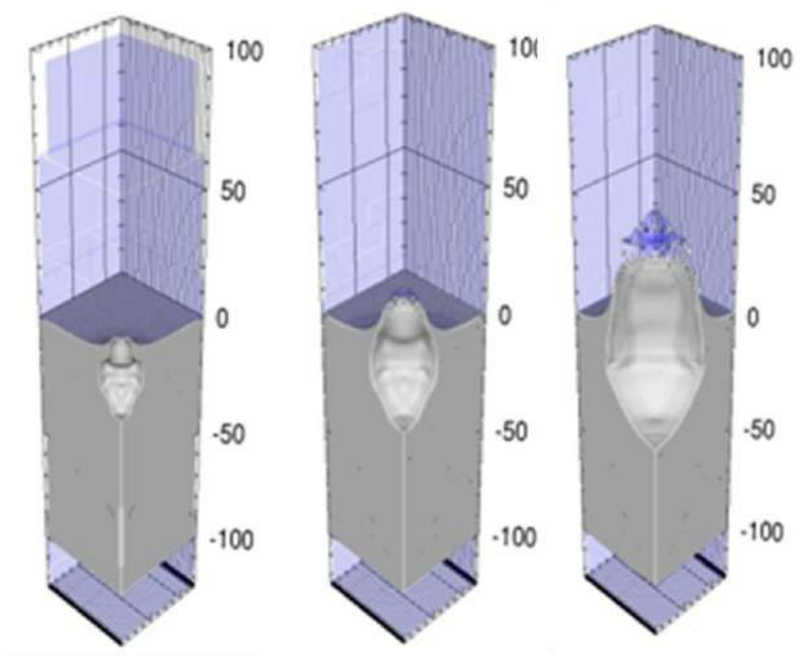

Figure 5. Three snapshots at 40, 120 and 360 ns during the evolving dynamics after release of energy in a small volume under the surface of a sample of silver. Only one-fourth of the entire simulation volume is shown for clarity. See text for details and discussion.

volume, either on the surface of the material or at some depth into the material, is an important variable. A basic issue in LENR remains whether energy is released only on the surface of materials, or only in the bulk, or in either type of location. It is hoped that comparison of the results of simulations with the energy release depth as a parameter, might contribute to the solution of that question. Clearly, several parameters should be exercised with CTH simulations, most of them over quite wide ranges of values. Variables include the material in which the craters are formed.

This completes the review of high energy and power density events in LENR experiments and prototype generators, and some work on their computational simulation. We now turn to the implications of these events for the LENR science, commercialization and potential weaponization.

6. Scientific Considerations

The scientific implications of fast LENR energy releases can be considered on the basis of some simple calculations. We start with crater formation. For a 10 μm crater, 1 μJ = 6×10^{12} eV or 3×10^5 20 MeV LENR events. Consider 10^6 LENR events on a cubic grid, 10^2 events on a side. The density of energy and power depend on the spacing between events, which can be measured in Pd lattice constants. Results for a wide variation in spacing are given in Table 1.

It is seen that, even for widely spaced events (3.9 μm) the energy density is very high. This can be appreciated by noting that the energy density of TNT = 0.74×10^4 J/cm^3 [28]. The LENR energy density reported in the second report on E-Cat testing by the Levi et al. team about 2×10^9 J/cm^3. The LENR energy densities within craters might be dramatically high, if the energy release volumes are small, as indicated by the estimates in Table 1.

Table 1. Computed energy densities as a function of the spacing between LENR events.

Pd lattice constants between LENR	Side cube (nm)	Volume of cube(cm^3)	Energy density (1 μ J) (J/cm^3)
1	0.39	6×10^{-23}	1.6×10^{16}
10	3.9	6×10^{-20}	1.6×10^{13}
100	39	6×10^{-17}	1.6×10^{10}
1000	390	6×10^{-14}	1.6×10^{7}
10 000	3900	6×10^{-11}	1.6×10^{4}

One of the most fundamental questions about LENR is whether or not they can occur in “chain reactions”, similar to fission reactions, where one reaction induces others. If not, then the fast, high-density release of LENR energy implied by crater formation and other events must be due to many reactions being nearly simultaneous in space and time. Curiosity about LENR chain reactions is old. In 1989, P.K. Iyengar wrote “Occasionally, nuclear events do appear to take place wherein over 100 neutrons are generated in a single sharp burst…this leads to the intriguing conclusion that a chain reaction involving as much as 10^{10} fusion reactions occurs within a time span of 100 μs”[29]. In 1996, Arata and Zhang provided a schematic sequence for nuclear reaction processes in solids [30]. It included “Generation and Propagation Process (‘chain reaction’)”. At ICCF-15, Srinivasan reviewed the early work on “cold fusion” at the Bhabha Atomic Research Center, including “chain events” [31].

The core question about LENR chain reactions is simple: does the occurrence of one LENR at a specific point in space and time make it more or less likely that other LENR will occur nearby in both space and time, or are all LENR independent of each other? A cartoon relevant to this issue is given in Fig. 6. It indicates how the energy released from a LENR event in an array of unit cells in a Pd lattice would propagate outward. The distance (3.9 nm) at the bottom is determined by the Pd lattice constant. The time (0.13 ns) is gotten using the speed of sound in Pd. At issue is what happens in the cell labeled with ? when the results of the initial LENR event reach that cell. Does the passage of the energetic wave increase or decrease the likelihood of a LENR event at that location, assuming conditions favorable to such an event are otherwise satisfied.

7. Development of Safe Products

It is clear that, if LENR generators for heat and electricity are to be commercially successful, they must be safe to use. So, there has been a lot of attention to the safe operation of such potential units. Can commercial LENR generators be made safe, maybe even fail safe? If early LENR products are not highly safe, there will be regulatory intervention and the widespread adoption of LENR technologies could be long delayed. An extended discussion of the safety of LENR products is available [32]. The possibilities are widely varied.

Two types of unsafe operation are possible: (a) failure of critical LENR generators, which is a matter of their reliability, and (b) failure due to loss of control of the rate at which energy is produced. The high energy gains that are possible with LENR generators make loss of control a significant concern. Meltdowns and explosions are possible. LENR generators might be made fail-safe, so they automatically stop if over-heated. Rossi has stated that his units will be fail-safe. If they start of overheat, the high temperatures will destroy the efficacy of the fuel and shut them down automatically [33]. LENR units might also be engineered to prevent catastrophic runaway operation by some method, including venting of hydrogen gas, poisoning or by quenching by an auxiliary cooling system. However, it is more likely that LENR generators will be designed with active control systems, including feedback loops, to insure that they operate within bounds [20]. Such control is common in engineering systems. It might require the inclusion in the overall system of batteries to insure maintenance of positive control in the event of interruptions of power from the grid.

It is noted that nickel nano-materials pose health hazards [34], so if they are part of LENR generators, it will be necessary to insure that they are properly contained.

8. Weaponization of LENR

Historically, mankind has generally used new sources of energy for military purposes. This includes operations such as heating and transportation as well as production of weapons. It seems certain that LENR generators of heat and electricity will be used by the military for operational purposes. But, will the energy from LENR be used also in weapons? The central issue here is whether or not LENR explosions can be induced on demand.

There has been significant, albeit unpublished work on the possibility of using LENR in weapons. Experiments were conducted in the mid-1990s at a testing range in the desert west of the US to see if hydride materials imploded by conventional explosives would undergo nuclear reactions. The work was not conclusive. This author and his colleagues discussed impacting heavily hydrided materials, such as TiH_2 and TiD_2, onto targets at hyper-velocities in the early 1990s, but those experiments were never done. Possibly, the use of hydrided bullets has not been explored yet. Oddly, there was a publication on a “Metal Hydride Explosive System” in 1988 [35].

9. Conclusion

The meltdowns and explosions that have happened in LENR experiments and tests are important for three reasons: (a) they impact theoretical explanations of LENR mechanisms, (b) they must be controlled, even if not understood, for development of safe products, and (c) they raise questions about the potential weaponization of LENR.

There are two main questions. The first is: can the power density of LENR systems be turned up controllably? More pointedly, can explosions caused by LENR be willfully initiated? And, the second is: are there ways to limit and turn down LENR power output densities by use of either intrinsic effects like internal melting or by use of automatic external control systems?

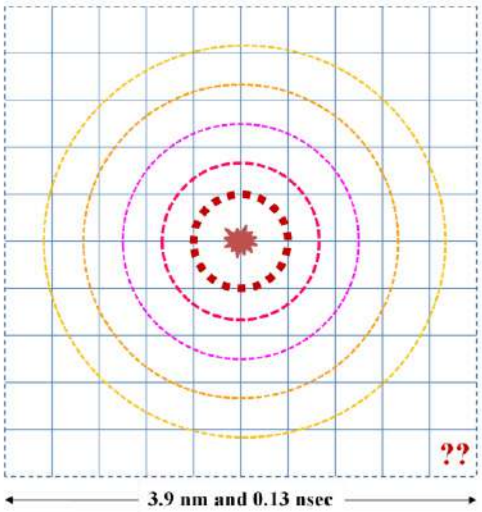

Figure 6. Schematic of a 10 × 10 of Pd lattice constants, where a LENR event occurs near the center. This array could be either on the surface of Pd or in its bulk.

Experimental research programs to address these questions would be expensive. For example, replication of the Fleischmann–Pons meltdown with at least four full electrochemical setups with significant amounts of Pd in an adequately safe laboratory might cost considerably more than \$100K. Research on the controllable production of craters, and on their scaling to larger sizes is desirable. However, it will probably be difficult due to reproducibility issues, as is much of the experimental research on LENR even to this day.

Theoretical research on fast releases of LENR energy would not be so costly, but would be very challenging. Each of the concepts for mechanisms that cause LENR can and should be examined for whether or not it is compatible with the possibility of LENR chain reactions.

Acknowledgement

David Knies performed the initial CTH simulations of crater formation, which lead to the work reported in this paper. Comments by the reviewer are appreciated.

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