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Research Article

Input Stimuli and Output Signals for LENR Experiments

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Abstract

One purpose of this paper is to draw attention to particular past LENR experiments and suggest some attractive future LENR experiments. Hence, we consider both past and prospective stimuli into and signals out of LENR experiments. Another goal is to provide a brief compilation of experimental data that can be used to test LENR theories. Rigorous challenges to theoretical results are needed to advance the understanding and practical applications of LENR.

Keywords: LENR, Experiments, Input stimuli, Output signals, LENR theory tests

1. Introduction

There are two primary motivations for attention to results from over three decades of both input stimuli and output signals from LENR experiments. The first is to identify empirical factors that have produced or resulted in unusual data that ought to be considered for future LENR experiments. That is a matter of looking backward in preparation for looking forward. The second motivation is to accumulate a diverse data set against which to test various theoretical ideas, if they are developed adequately for such tests. Many concepts about how LENR occur, that is, the mechanism that leads to LENR, are poorly developed. They are only ideas, without accompanying equations and numerical evaluations based on them. However, some concepts for LENR mechanisms have been reduced to equations that were evaluated to obtain numbers for comparison with data. The various types of parametric variations and measurements discussed in this paper serve to challenge the concepts, equations and numbers from diverse LENR theories.

LENR experiments usually consist of three parts, the central experiment, and the means to excite and monitor the experiment. These are shown in Figure 1. LENR experiments have been highly varied, usually to explore various ideas and sometimes to test theories. Many past experiments deserve review and additional consideration. We provide a short review of loading methods in the next section. The third section reviews the ranges of various quanta that are either input to or measured from LENR experiments. Their ranges and characteristics determine their uses. Then, Section 4 presents and discusses a framework for considering stimuli and signals in LENR experiments. This paper primarily focuses on the diverse inputs and outputs from LENR experiments. It essentially has major two parts, one

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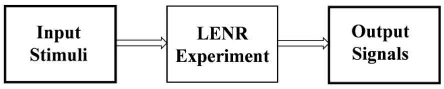

Figure 1. The three parts of almost all LENR experiments.

on input stimuli (Section 5) and the other on output signals (Section 6). Section 7 deals with quantities that have served as both inputs and outputs. Those three sections all look backward and forward. Section 8 discusses some factors that have not yet been used in LENR experiences, so it looks ahead. The conclusion highlights four topics. One involves parametric LENR experiments, which can be of great value scientifically and maybe practically. The second is on the testing of LENR theories. There is great need for such testing of the many concepts for how LENR actually happen. The third topic is the requirement for more analyses of LENR data. There have been too few serious analytical studies of data from LENR experiments. Data commonly contain additional useful information which can be extracted. Finally, we have a short discussion of engineering design of LENR experiments. That is another topic, which has not received adequate attention in the field.

2. Loading Methods and Materials

The core requirement for the production of LENR is to bring together either protons or deuterons on or in materials, usually metals or alloys. The methods for doing that are commonly called "loading", since they involve loading the hydrogen isotopes onto or into materials. That is, LENR experiments almost always involve two matter inputs, the materials and the sources of the protons or deuterons. As will be clear below, this paper is on inputs other than those needed to satisfy the basic loading requirement for production of LENR. So, in this section, we provide a short review of loading methods and materials as background for the rest of the paper.

Many ways have been used to perform loading over the decades of research on LENR. However, there have been three primary approaches, which are summarized graphically in Figure 2. Each of the three approaches has variations. Aqueous electrochemical loading is the original method of Fleischmann and Pons [1]. It has been done using both light and heavy water from the earliest days of the field. In most cases, the metallic cathode material was placed into an electrochemical cell at the start of an experiment. However, in many experiments, the palladium or other metal has been simultaneously deposited with deuterium from heavy water during the experiment. That method, called co-deposition, was introduced to the study of LENR by Szpak [2]. Molten salt electrolytes have also been tried with success. Electrolytic loading involves relatively low powers, and is a good tool for scientific research on

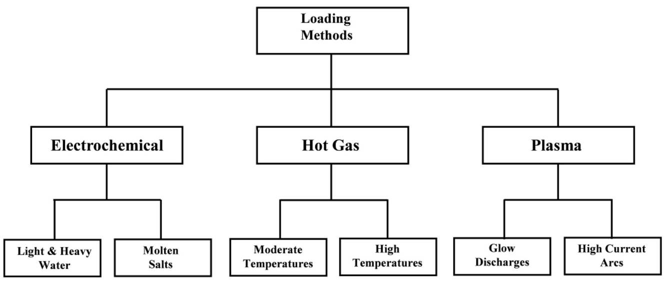

Figure 2. The three primary methods for loading protons or deuterons onto and into materials.

LENR. However, without pressurization of experiments [3], it is limited to the boiling point of water, a temperature too low for efficient production of electrical power.

Hot gas loading has involved higher input powers, which are sufficient to produce moderate (about 300 deg C) and high (up to and even beyond 1200 deg C) temperatures. High temperatures can also be generated in lower-power glow discharge plasmas and higher-power plasma arc experiments. Both hot gas and plasma methods of loading involve temperatures sufficient for efficient electricity generation, so they are the two most promising loading methods for commercial LENR generators.

As noted, loading involves two types of matter, (a) the hydrogen isotopes to be loaded and (b) the materials being loaded. Both determine the dynamics and results of loading processes. The paragraphs above in this section dealt with the sources of protons or deuterons. Logically, we would now turn to details on the materials part of loading. There have been many studies of materials before, during and after LENR experiments. They have dealt with both the composition and structures of materials, that is, what atoms are present and how they are arranged. Elemental materials, alloys and compounds have been considered. The majority of LENR experiments have involved palladium or nickel of various purities, and also alloys and compounds including them. Many LENR studies have focused on processes involving such materials before and during experiments.

The occurrence of LENR depends on the composition and structure of the materials in an experiment. Those characteristics depend both on the starting materials and on changes that occur during an experiment due to loading. It is known that success in producing LENR depends on the starting materials, especially for palladium. Variations in composition or structure from batch-to-batch, and even from sample-to-sample within one batch of materials, often makes a difference in the results obtained. Loading can lead to two beneficial changes in materials, (a) the production of regions conducive to the occurrence of LENR and (b) population of those regions with adequate concentrations of reactants. A recent example of changes in materials during loading is Storms' measurements of variations in the enthalpy of formation of palladium hydride as a function of H/Pd ratios for six loading and deloading cycles [4]. A more detailed consideration of LENR materials here would not contribute significantly to the main thrusts of this paper. Hence, we will not review materials issues further, due to a focus on input stimuli and output signals for LENR experiments. Such stimuli into materials and signals out of materials have different ranges, which are important, so they are considered next.

3. Ranges of Photons and Particles in Matter

What quanta can be put into or gotten out of LENR experiments depends on three primary factors, the particular quanta (photons, neutrons, electrons and particles), their energy (from small fractions of one electron volt to over millions of electron volts), and the materials through which they pass (both their chemistry, and their density ranging from high vacuum to dense condensed matter). The type of quanta and the energy of the various quanta are especially important in determining what can be done in LENR experiments. A thorough examination of all of these factors would be long, and is not needed in this paper. Rather, we will cite some of the factors and dependencies most relevant to understanding stimuli into and signals out of LENR experiments. It is not necessary to consider unusual particles like muons. A useful diagram relating energy and momentum transfers for various quanta and techniques is available in a review on Mossbauer spectroscopy with nano-eV resolution [5].

Photons have been widely used for LENR research, and there have been thousands of electrochemical LENR experiments involving water-based electrolytes. Figure 3 [6] shows the attenuation lengths of electromagnetic radiation in water from the UV region through the high frequency part of the radio-frequency region. High inverse length (1/m) values mean that the radiation with certain wavelengths will be able to penetrate into or escape from only small thicknesses of water. Since LENR electrochemical experiments have dimensions in the range of 1 to 100 cm (0.01 to 1 m), cells will transmit only photon radiation in range from 0.2 to about 1 micron for the wavelengths shown in

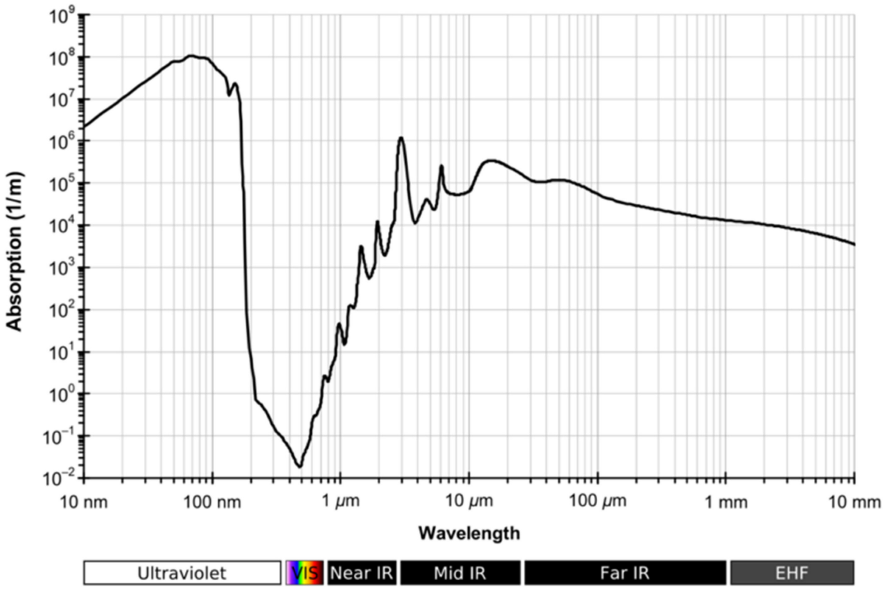

Figure 3. Inverse absorption length (1/meters) of electromagnetic radiation in water from the UV through the Visible (VIS)and Infrared (IR) to Extremely High Frequency (EHF) spectral regions. The peak of the solar spectrum is near 500 nm, very near the minimum in the absorption of water.

Figure 3. Very high energy gamma rays and hard x-rays, and very long wavelength radio waves, will also penetrate LENR cells.

Electromagnetic radiation can be made to access or escape most chambers for hot gas or plasma loading LENR experiments. That can be accomplished by using thin and low-absorption materials for most spectral regions, except for the ultraviolet range from about 10 to 100 nanometers. Internal antennas and waveguides are needed for input or detection of long wavelength photons in experimental chambers for hot gas and most plasma experiments.

Neutron energies fall into about ten classes in one accounting [7] and six classes in another [8]. They have ranges in different materials that can vary widely and rapidly with energy. Energetic (MeV) neutrons have long ranges in most materials, so they can be put into LENR experiments, but might be little absorbed within such experiments. They will also escape readily even from metallic reaction chambers. We will note below that few LENR experiments involved input neutrons, and most LENR experiments do not emit significant neutron intensities.

Electron beams are rarely put into or measured from LENR experiments. Their ranges in matter for energies up to a significant fraction of 1 MeV are relatively small. That is also true for ions, from protons to alpha particles (helium nuclei) to heavier particles, even for multi-MeV energies. Hence, it is necessary to use vacuum techniques for input or measurement of electrons or ions to or from LENR experiments. That means that only low-pressure hot gas or plasma LENR experiments are amenable to the use or measurement of electrons or ions. A very useful capability for obtaining data on electron, proton or alpha particle ranges in a wide variety of materials over many orders of magnitude for their energy is on the internet [9]. The available graphs show that the ranges for charged particles in materials vary smoothly with energy, unlike those for photons in and below the x-ray range or for neutrons.

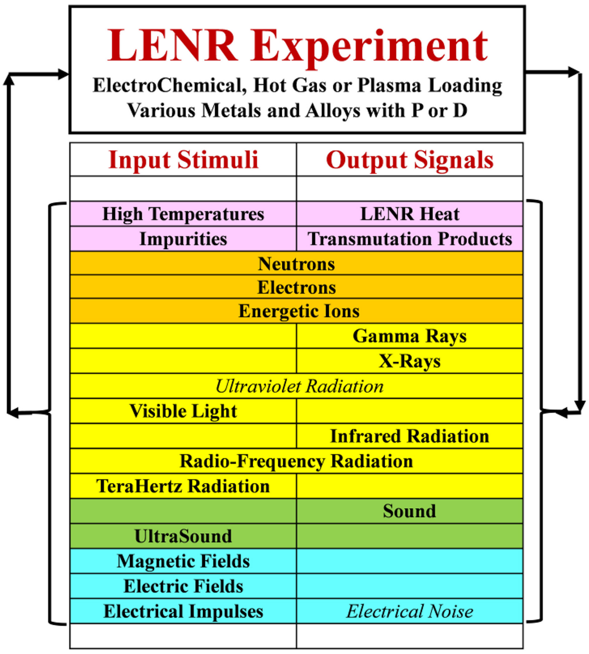

Figure 4. Schematic relationship between varied LENR experiments, the diverse input stimuli that have been applied to them (left column) and the many output measurements from them (right column). Blanks in the columns are possibilities that have not yet been applied or measured in actual LENR experiments. Ultraviolet Radiation has yet to be explored by LENR scientists, and Electrical Noise has not been measured from LENR experiments.

4. Inputs and Outputs

Experimental papers on LENR now numbers in the thousands. They raise many questions. Of all the published inputs and outputs, which might be most valuable to emphasize in future experiments? What other stimuli or signals might be used to further the understanding and commercialization of LENR? Considering such questions requires having some overview of what has already been done and found in LENR experiments. Figure 4 gives a way to organize much of the laboratory work on LENR. The LENR experiments might involve any type of loading, and any materials with either protons (P) or deuterons (D). It is seen that there are many cases in which particular entity can serve as either an input stimulus or output signal. The various stimuli and signals fall into classes. At the top, those that involve energy and matter are shown in pink. The orange grouping deals with particles, including neutrons, electrons and ions. Several regions of the electromagnetic spectrum, shown in yellow, have played input or output roles in past LENR experiments. Sound has been measured from one LENR experiment, and ultrasound put into a few experiments, as shown in green. Fields have played roles in many LENR experiments, as shown in the blue area in the bottom of Figure 4. The blanks in the diagram, as well as Ultraviolet Radiation and Electrical Noise, indicate cases where no LENR experiments are known. They are worth examining as new opportunities.

With this systematic way to classify the inputs and outputs for LENR experiments, the next section deals with most of the inputs. Section 6 involves many of the outputs. Factors that have or can serve as both inputs and outputs are the subject of Section 7. Section 8 considers the blanks in Figure 4. The concluding section provides additional comments on the various inputs and outputs, plus some discussion of parametric experiments, testing LENR theories, opportunities for more thorough data analyses, and the use of the tools of Systems Engineering.

5. Input Stimuli

This section will briefly review eight means of inputting stimuli into LENR experiments. The amount of work on each of them varies widely. However, many of the methods and results are worth consideration for future experiments.

High Temperatures. The question of the effects of temperature on LENR experiments arose early in the field for two reasons. First, it is a basic consideration for any reactions taking place on or in materials. Second, some alternative approaches to the aqueous electrochemical method of Fleischmann and Pons required high temperatures. One early example of the latter was the use of electrolysis experiments in which the electrolyte was a molten salt at 250 deg C by Liaw and his colleagues in 1991 [10]. They reported significant, albeit irreproducible power gains of 1.2 to 1.4 (after subtraction of heater power). The power gain at any specified time is the ratio of the output thermal power to the input electrical power. They report producing as much as 25.4 watts at about 460° C. Anomalous helium was also reported in a later paper by the group [11]. Another example was the use of a glow discharge by Karabut in 1992 [12], who got power gains of as much as 5. Lonchampt and others [13], in a 1996 reproduction of the Fleischmann and Pons electrochemical experiments, showed that higher temperatures favor excess power. They stated "Our results concerning the relative excess heat (percentage of excess heat to enthalpy input) can be summarized as follows: -below 70°C, between 0 and 5%, -between 70°C and 99°C, about 10%, and -at boiling, up to 150% especially in the final phase which appears as the best condition to get a large amount of excess heat." In 1998, Mengoli and colleagues [14] varied the temperature of aqueous LENR electrochemical experiments to near the boiling point. They reported "After prolonged electrolysis the loaded electrodes were found to continue heat generation in open circuit conditions." and "The major achievement of this work is to have devised a temperature range in which the generation of excess power is a totally reproducible phenomenon." In short, the benefits of using elevated temperatures in LENR experiments were well established within the first decade after the 1989 Fleischmann and Pons announcement.

Scientists at Tsinghua University have compiled useful summaries of the temperature dependence of six diverse LENR experiments [15]. Their results are summarized in Figure 5. All the plots show that (a) high temperatures favor production of LENR, and (b) the data fit an exponential variation with an activation energy (the Arrhenius equation) [16]. While clear and agreeable on those two points, the data raise two questions: (1) why do LENR obey such an activation equation, and (2) what determines the values and varieties of the activation energies, which range from 0.14 eV to 0.95 eV? These questions challenge theoreticians for explanations of the relatively simple and well-established behavior. Besides such clear scientific importance, the issue of the temperature dependence of LENR has strong practical implications for potential future commercial power generators. The temperatures at which LENR generators will operate will determine the materials for their construction, and influence their longevity.

Very recently, Storms [17] reported temperature variations experiments for both electrochemical and hot gas loading of palladium and nickel with deuterons. His data also exhibited behaviors similar to those shown in Figure 5, that is, Arrhenius variations with activation energies. He found two regimes with different temperature dependence in experiments with both Ni and Pd, some with electrolytic loading and others with hot gas loading. The behavior at lower temperatures was ascribed to the filling of active sites, in which LENR can occur, with deuterons. The high temperature behavior was thought to be controlled by the diffusive resupply of deuterons to the active sites to make up for deuterons consumed during nuclear reactions.

Impurities. In the early days of the semiconductor industry, sodium impurities led to irreproducible behavior of silicon-based integrated circuits, and control of sodium remains a challenge during modern chip production [18]. Impurities could also play a role in LENR experiments in a few different ways [19]. If impurities are a cause of LENR, they can improve the rates of LENR, or result in lower LENR rates, as they are consumed or move within

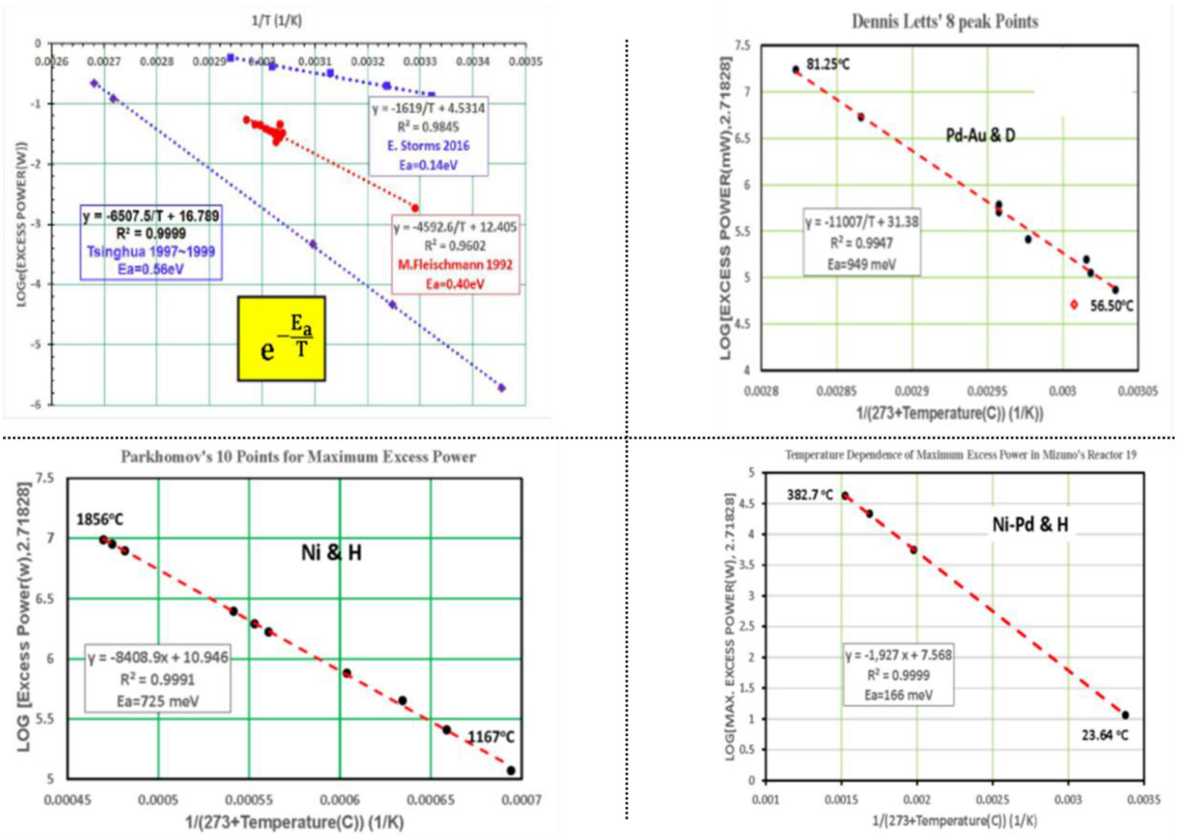

Figure 5. Four plots with data from six experiments, all having the log of LENR power vertically vs the inverse of the absolute temperature horizontally. All plots obey the Arrhenius activation equation, the main factor of which is in the yellow box.

materials. If materials are a result of the occurrence of LENR, they can similarly increase or decrease LENR activity. Impurities might create or destroy needed conditions, for example, the attainment of very high ratios of D to Pd in some locations within a lattice. Segregation of impurities to grain boundaries could impede the motions of reactants (protons or deuterons) along grain boundaries, which normally have high diffusion coefficients. That is, impurities might alter the rates for diffusion of hydrogen isotopes to LENR active sites. And, they might even change the number of such sites. Impurities could conceivably promote or retard reaction rates without participating in the reaction, much as do catalysts or inhibitors for chemical reactions. And, impurities could actually participate in the reactions. The numbers involved in this last possibility are especially interesting. If 1 part-per-billion of an impurity in a typical LENR cathode undergoes a nuclear reaction which yields 1 MeV each second, a power of about l W is produced. One watt is a nominal excess power from many LENR experiments that produced excess heat. If 10 or 24 MeV resulted per reaction, also normal sorts of nuclear reaction energies, correspondingly less material or a lower reaction rate would be required, or a higher excess power would result for the same rate. It should be noted that the large positive charges on most impurity nuclei argue against their being participants in LENR.

The important point is that few LENR experiments have been analyzed for impurities to the parts-per-billion level in the various phases within the experiments before, during or after runs. Some experiments seeking to quantify the appearance of transmutation products after LENR reactions have included such analytical work. Two famous examples are the studies of reaction products across the periodic table by Miley [20] and by Mizuno [21]. Although very different experiments, their results strongly support each other. Data from both Miley and Mizuno show peak LENR transmutation rates at the same values of the atomic mass across the entire periodic table. In these experiments, the impurities that were produced were apparently the result of LENR. It is not known if the increasing concentrations of such LENR products (a) influenced the rates of further LENR or, (b) if there was some feedback, whether it was positive or negative. Impurity levels in materials generally vary on the parts-per-billion level from batch to batch and, even, from sample to sample within a batch or single piece of material, or from centimeter to centimeter along a wire or rod of material. It is possible that, if there are unknown processes at work in LENR experiments that involve impurities, the reproducibility and controllability riddles will be explained on the basis of inadequate knowledge and control of impurity levels before and during experiments.

Given the potential roles of impurities in determining the outcomes of LENR experiments, and the dearth of quantitative studies of impurities, it would be reasonable to prepare materials for LENR experiments with a range of types and concentrations of impurities. That would be challenging, given both the wide variety of possible impurities, and the many combinations and concentrations that could be relevant. However, such parametric experiments could be useful both scientifically and practically. They might increase the probability of producing LENR. Also, they could have a major impact on the longevity of materials in LENR generators. The best strategy for such experiments with impurities is uncertain. Possibly, it would be good to start with the impurities normally found in palladium or nickel, since those metals are often used to produce LENR. A common approach to screening for impurity effects is to introduce only a few impurities, say six or less, into each sample. Then, if any sample with multiple impurities shows interesting behavior, the impurities in it can be put separately into further samples. That approach works if multiple impurities in one sample do not interact with or influence each other.

Low levels of materials dissolved in electrolytes have played a role in some electrochemical LENR experiments. In these cases, the impurities might be restricted to the surfaces of the cathode materials. Examples of such work were done by the groups in the Sydney Kimmel Institute for Nuclear Renaissance [22] and the company Coolescence [23].

Visible Light. Letts and Cravens presented a paper in 2003, which stated they had been exploring the effects of stimulation of LENR experiments by visible laser radiation for over a decade [24]. Figure 6 is one of the graphics in that paper. It shows that shining a 30 mW laser onto a gold-coated palladium cathode in an electrochemical LENR experiment within a calorimeter caused a 500 mW increase in LENR power over the course of about 15 hours. Removal of the light then caused a drop in the LENR power. The fraction of the laser power actually absorbed was not reported. The increase in LENR power was stated to be 5 to 30 times the laser input power. The paper reported on the polarization dependence of the 257 nm laser light, but did not involve variation of the wavelength. The Letts-Cravens paper has been cited about four dozen times due to both replication experiments and the overall importance of the work.

Another early study of the beneficial effects of laser light on LENR output was reported by Swartz and his colleagues [25]. Their abstract included these statements: "There is a positive photo-thermoelectric response for optically-irradiated [670 nm laser, 3.5 milliwatts] spiral-wound, electrically-polarized palladium cathodes in very low electrical conductivity heavy water. An incremental photoinduced excess heat of $\sim$89 milliwatts results from a $\sim$3 milliwatt incident optical beam, but only in the presence of a functioning active loaded cathode." Later, Violante and his team showed that application of laser light to electrochemical experiments led to an improvement in their reproducibility [26].

The use of incident visible light to stimulate and control the generation of LENR power calls for much more research. The variation of LENR production with the wavelength of the incident light is an open and important question. Similarly, how LENR varies with incident and absorbed intensities, angles of incidence and surface characteristics

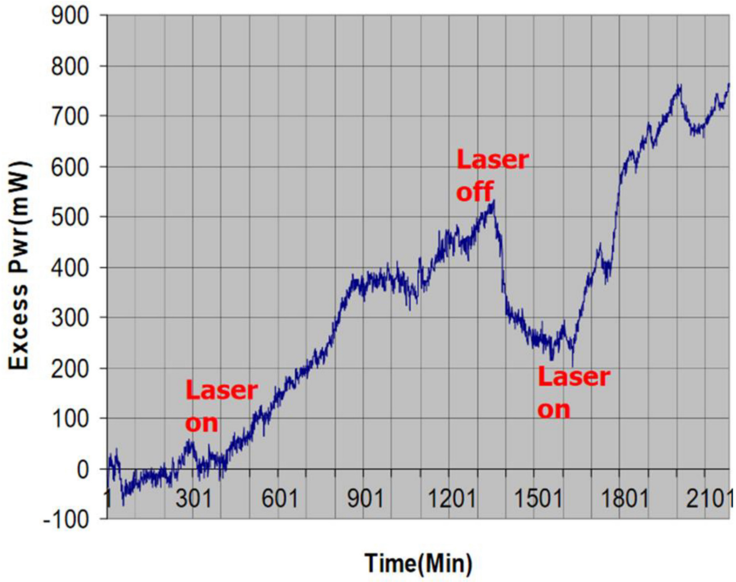

Figure 6. Time history of LENR power showing responses to laser light shined onto the cathode by Letts and Cravens.

should be determined. It would not be difficult to make a setup where light emitting diodes (LEDs) surround a cell, either on the outside or even in the electrolyte, to provide uniform and intense illumination of a cathode. Variations in LENR output with intensity could be studied with such an arrangement. The size of the area affected by focused laser light is unknown, and also calls for further experiments. Does the light affect only material that is illuminated, or is a larger area outside of the illuminated region induced to produce LENR?

Terahertz Radiation. Electromagnetic radiation of a very different wavelength was used to stimulate LENR in another experiment by Hagelstein, Letts and Cravens [27]. Beams from two lasers were beat against each other to produce terahertz radiation, which was again put onto the cathode in an electrochemical experiment in a calorimeter. The main graphic from that work is in Figure 7. It shows that the LENR power varies strongly with the frequency of the THz radiation. The abstract of the paper reads in part: "The cell responded to three difference frequencies in the THz range at 8.2 THz, at 15.1 THz, and at 20.8 THz. The first two of these frequencies can be associated with optical phonon frequencies of PdD with zero velocity." Those data were taken as evidence that phonons are important in the production of LENR. That is, it is possible that THz optical absorption produces phonons, and phonons contribute to the production of LENR. It should be noted that Vysotskii and his colleagues offered alternative interpretations of the peaks in Figure 6 in terms of coherent correlated states [28].

A later paper by Hagelstein and Letts [29] dealt with the temperature dependence of the experiment that produced Figure 7. Interestingly, it concluded "A picture for the temperature dependence is described in terms of the elimination of ^{4}He which blocks active sites when the excess power is high." The effects of reaction products on further LENR reactions have received some discussion in the LENR literature. Helium can become trapped as gas bubbles in grain boundaries as result of its low solubility [30]. However, that might not affect further LENR production. Wang and Arata addressed the problem of He piling up in nano-particles [31]. The nano-scale particles are expensive, so it would be economically beneficial to have a way to resuscitate them for further use by processing them to remove LENR products. The presence of the He might reduce the rates for H and D diffusion within the materials, and hence cut

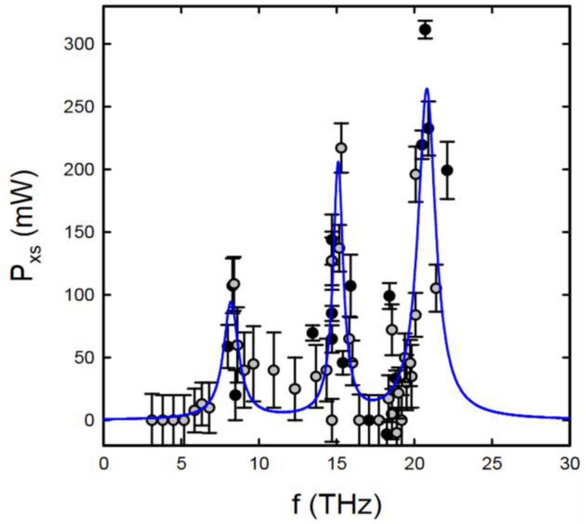

Figure 7. LENR power as a function of THz frequency put onto the palladium cathode in an electrolytic experiment.

down on the availability of the fuels for the LENR. Storms found that the diffusion of deuterium to reactions regions was the rate limiting step in LENR production.

The Thz experiment described above apparently has not been repeated in another laboratory. It seems like another good candidate for additional attention. The same variables noted above for visible light (polarization, geometry and intensity) are germane to LENR experiments with THz radiation. It seems particularly attractive to see if the effect observed with palladium, shown in Figure 7, could be seen also with other material systems, especially nickel.

Ultrasound. Several LENR experiments have involved ultrasound, which is defined as sound with frequencies greater than 20 kHz. One ultrasound experiment reportedly produced conventional deuteron-deuteron "hot" fusion within liquid media. That topic has been very controversial [32]. It is commonly called bubble-fusion or sonofusion. Such experiments probably have nothing to do mechanistically with LENR. The reported nuclear reactions do not occur on or in a solid medium, but rather in very small and very transient hot plasmas formed inside of collapsing bubbles within liquids.

Ultrasound has been used in two ways in actual LENR experiments. In one case, it led to the deuterium loading of solids and production of excess heat. Stringham used ultrasound for about two decades to stimulate LENR on and in thin foils of various metals. He reported producing nuclear reactions using both kHz and MHz excitations, with 40 W of excess power reported for one experiment [33]. In the second case, ultrasound was used as an adjunct to electrochemical LENR experiments. Energetic Technologies employed ultrasonic irradiation in addition to "superwave" electrical excitation. They reported a very high energy gain of 26 in one well-known experiment, which is discussed later in this section. That group also published an extensive paper on the application of ultrasound to the cathodes in electrochemical LENR experiments [34].

The situation for ultrasound inputs to LENR experiments is quite like that for putting electromagnetic radiation into such experiments. There is a similar large number of variables, again including frequency, intensity, and how the inputs do or do not vary with time. Here again, thorough experiments to address the effects and possible values of various sonic inputs would require (a) a major systematic research program and (b) a reproducible LENR experiment, so that the effects due to input parameter changes could be separated from other measured variations.

Magnetic Fields. The intersection of magnetic fields and LENR experiments is asymmetric. There have been many more experiments in which such fields have been applied as input to LENR experiments than situations where magnetic sensors have been used to monitor output fields. So, we first consider the application of magnetic fields to LENR experiments. The following is a sampling of papers about magnetic field effects on LENR, not a thorough review.

Letts reported results in 2011 from an experiment done in 2002. He showed that the orientation of a DC magnetic field from a permanent magnet directly influenced the production of excess power [35]. He used a 500 Gauss (0.05 T) magnet external to an electrochemical LENR cell which contained palladium co-deposited with deuterium onto a planar copper substrate. The variation of the LENR power with magnetic field orientation is shown in Figure 8. Moving the magnetic field direction from parallel to orthogonal to the cathode foil increased the excess power by a factor of about three. Then, returning the magnet to the initial position led to a decrease in the rate of LENR power production. That is, the LENR power was highest when the magnetic field was parallel to the electric field between the electrodes.

Swartz also studied the effects of magnetic fields on LENR (LANR) in electrochemical cells [36]. The cathode was a coil of palladium. He found that the field increased the electrolyte resistance, which limited unwanted gas evolution and improved loading of deuterons into the Pd cathode. That led to a higher rate of LENR occurrence. He wrote, also in 2011, "An applied magnetic field $\sim$0.3 T increases the LANR solution's electrical resistance $\sim$10 –17% with a time constant in minutes. The incremental resistance increase from an applied H-field is greatest with the applied H-field perpendicular to the driving electrical field (E-field) intensity."

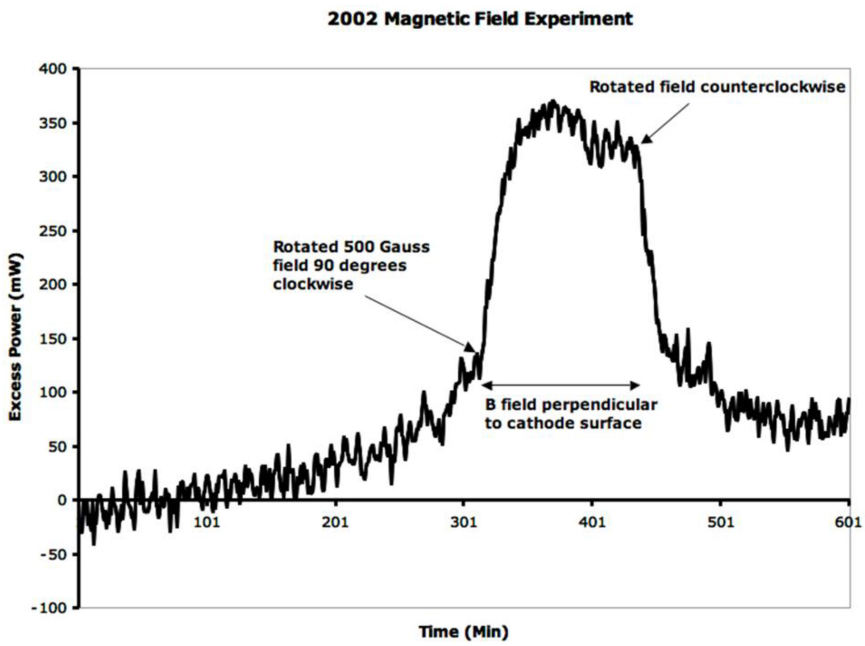

Figure 8. Dependence of the LENR power on the orientation of the magnetic field from a permanent magnet relative to the plane of a palladium cathode foil.

Letts and Swartz reported opposite orientation effects for a magnetic field on LENR rates, both in electrochemical systems. Whether or not that variation is due to the different geometries for the cathodes in their experiments is an unanswered question. Given the observed variations and the differences in the experiments, simulation of both experiments with software like COMSOL ought to be valuable [37].

There is a very basic question about the role of magnetic fields in electrochemical LENR experiments. It is possible that the fields will directly influence the rates of LENR, as indicated in an equation produced by Letts [38]. However, it is also possible that magnetic fields will alter the electrochemistry, and hence the rates of loading or deloading of the cathodes, as Swartz reported. There is a substantial non-LENR literature about magnetic field effects on electrochemical processes [39]. It appears that no one has yet digested that non-LENR literature in an attempt to determine if magnetic fields change the electrochemical dynamics in LENR experiments in ways that might indirectly affect LENR rates. Determination of whether the effects on electrochemical LENR experiments by magnetic fields are direct (only physical) or indirect (first chemical, and then physical) should be a near term goal.

In 2014, Swartz and others reported magnetic field effects on the rates of LENR in an experiment without electrochemistry [40]. They studied steady and pulsed magnetic field effects on a device called the NANOR^{TM} which contains ZrO_2–PdD nanostructured components. DC and pulsed magnetic fields from three types of magnets were used. The pulsed fields were about 1.5 T with a 0.1 ms rise time, with 1 to 5000 pulses applied to the device. Energy gains were increased over a factor of four by use of DC fields. The pulsed fields produced large effects on the LENR output. To quote the authors, "The peak power gain was ranged from 22 to up to $\sim$80 times input electrical power or more beyond the control, as determined by calorimetry." It was found that the magnetic field effects could be both immediate (synchronous) and long lasting (metachronous). In both cases, the variation of LENR power with input power to the NANOR^{TM} was different from the case with no magnetic fields. A 2016 paper by Swartz provided additional data and analyses of the response of his devices to magnetic fields, including discussion of the effects of magnetic domains within the materials of his devices [41].

As noted at the beginning of this section, there are some, but very few instances of magnetic fields being measured from LENR experiments. In fact, they are more ancillary measurements, than detection of magnetic fields generated during such experiments. In one instance, a magnetic antenna was used to pick up electromagnetic radiation [42]. In another, the magnetic field within a particle detector was measured [43]. It is clear that the potential emission of magnetic fields from LENR experiments is an unexplored territory.

Future LENR experiments involving magnetic fields might be designed to determine whether the effects seen in some past LENR experiments were direct or indirect. They might include variations in the field strengths and orientations, as well as temporal variations in those parameters. In all cases, the strength of the magnetic field at the cathode should be measured. Given the magnetic field effects already observed in various LENR experiments, it seems especially desirable to measure the effects of parametric variations of magnetic field parameters for loading of both solid and co-deposited materials. That ought to be especially true for time variations of magnetic field intensity, which have not been thoroughly explored. Such experiments can be conducted without having a reproducible LENR experiment, since various diagnostic methods and calorimetry can be used to determine the effects of diverse magnetic field characteristics.

Electric Fields. There are two types of electric fields applied to LENR experiments, those within experiments that accompany the applied voltages and those that are applied externally to the setup. Electric fields are closely related to the voltages applied to LENR experiments, since the value of an electric field is the gradient of the voltage. That is, electric fields can be expressed in Volts per Meter. Since Volts give the Energy per Charge, an electric field is an expression of the rate at which the energy of a charged particle changes spatially. Charged particles in an electric field will move to minimize their energy, much like a ball rolling downhill.

Internal electric fields due to applied voltages fall into two classes for electrochemical LENR experiments. The first is the field due to the voltage difference between the cathode and anode through the electrolyte, which is used in all experiments. The second, used in only some cases, is a voltage drop along an elongated cathode. The latter leads to an effect called electromigration. That term describes the motions of deuterons or protons within the cathode, which causes two beneficial effects for LENR production. One is an increase in the concentration of reactants in the positive end of the cathode wire. The other is a flux of reactants along the wire, which induces the interactions that are often prerequisite to reactions.

Electromigration has been used in several LENR experiments, including many by the Celani Group [44]. In 1996, the remarkable results of "about fifty" LENR electrochemical experiments with electromigration were reported in two papers by Preparata and his colleagues. The first dealt with an initial experimental campaign [45]. The second reviewed those results and provided data from the second campaign [46]. That paper provided many details of the experiments. The cathode was a wire of Pd 50 μm in diameter. It was configured to have a current flowing along its length of 250 cm, as well as between it and the anode. The experiment was run for 6,000 seconds, with the maximum input power of about 87 W and maximum excess power of over 83 W. Normalizing the excess power to the volume of the cathode gave surprising power densities in the range of 50 to 100 kW/cm^3. These values exceed those of nuclear fuel rods in fission reactors. They required fast heat loss from the thin wire to the electrolyte to avoid melting of the wire.

External electric fields have been applied to LENR experiments, in addition to the normal internal applied voltages in many electrochemical and gas loading LENR experiments. For gas loading, the fields (voltages) generally have been used to produce plasmas that can initiate and even control power production. That is, their effects are necessary, but not sufficient for LENR to occur. That is not the case for the use of fields in electrochemical LENR experiments. Then, the applied external fields can directly influence the ability to produce LENR.

Researchers at the SPAWAR Systems Center did co-deposition experiments in which static electric fields were applied to the regions of the cathode from outside of the cell [47]. The morphology of the co-deposited Pd-D materials varied greatly with the strength of the fields. Figure 9 provides one illustration of the influence of electric fields on (a) the structure of the materials produced in co-deposition experiments and (b) the results of the experiment.

While electric fields have been shown to greatly affect materials in co-deposition experiments, there seems to be no data on their influence on LENR rates. If it is shown in future LENR electrochemical experiments that there are electric field effects on LENR, then there will arise a basic question: do the fields directly affect LENR rates, or do they influence the dynamics of the electrochemistry which, in turn, determines such rates.

There are many sensors for electrical fields [48]. However, there has been little or no use of such sensors inside of LENR experiments. That is, electric fields have not been measured as either input or output signals within LENR experiments. Recent advances in electric field sensors based on fiber optics might enable measurements of fields within electrochemical LENR experiments. They offer spatial resolution of the scale of 10 micrometers [49], and might be used to determine internal fields even within aqueous electrolytes.

Overall, the situation for prospective experiments with electric fields applied to LENR experiments is very similar to that for the use of magnetic fields. Whatever their motivations, future LENR experiments with applied electric fields might include variations in the field strengths and orientations, as well as temporal variations in those parameters. Given the electric field effects already observed in co-deposition experiments, it seems highly desirable to measure the effects of parametric variations of electric field parameters on atomic and particle structure of materials that are deposited *in situ*. That ought to be especially true for time variations of electric field intensity, which have not been explored. Such experiments can be conducted without having a reproducible LENR experiment, since diagnostic methods like x-ray diffraction and scanning electron microscopy can be used to determine the effects of diverse electric fields.

Electrical Impulses. Disequilibrium, especially the presence of fluxes of deuterons in palladium cathodes, has been discussed for LENR experiments since the earliest days of the field [50]. We now review another type of disequilibrium, specifically the application of impulses to LENR experiments. It is not known yet if impulses act only to change the

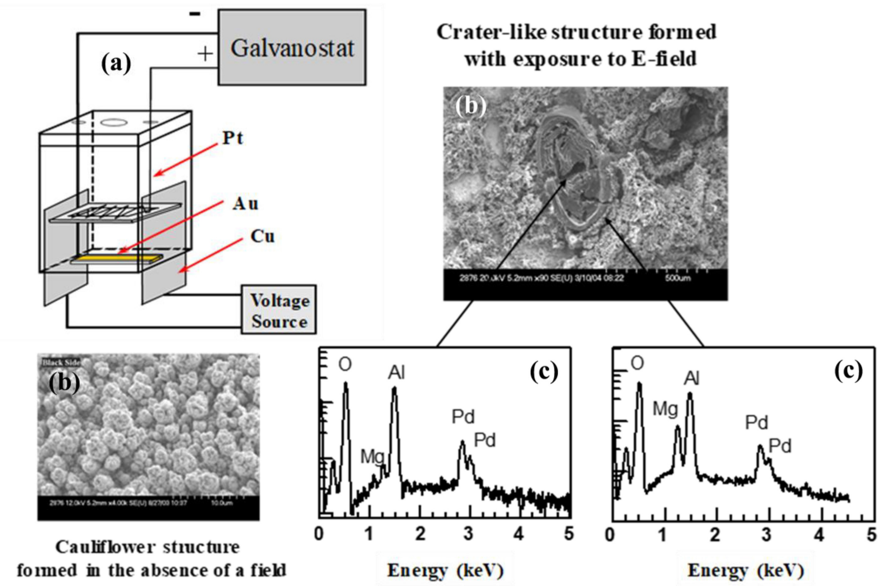

Figure 9. The experimental arrangement (a) for a co-deposition experiment with an applied electric field, (b) micrographs showing the different morphologies of the material without and with the field present, and (c) x-ray spectra showing the appearance of Mg and Al during the experiment at a crater.

chemical conditions within electrochemical LENR experiments, or if they act directly on the nuclear reactions. Two key experimental plots will illustrate the apparent importance of impulses for electrochemical LENR experiments.

The first data set is the well-known graphic from Energetics Technologies, first presented at ICCF-11 in 2004, and shown in Figure 10 [51]. The data in that figure showed instantaneous power gains as high as 35 and an integrated energy gain of 26. There are five times when the *input* power sharply decreased for a brief period. They are labelled A through E in Figure 10. At those times, the input power went to zero (once, namely D) or even apparently negative (A, B, C and E):

- A was at the start of the experiment, when there was an immediate, but small excess power.
- B marks two negative excursions, when the output power shot up from about 2 W to 18 W.
- C marks a second large jump in thermal power, from 20 to 29 W, after an apparently negative input change.
- D marks a time when the input power went to zero, which was followed closely by an increase of output power from about 13 W to 34 W.
- E notes another apparently negative excursion of the input power near the end of the experiment, which did not result in an increase in the output power.

In addition to the large increases in output LENR power following closely the small decrements in the input power, there are other correlations between input and output power. They are indicated by the green lines in Figure 10. In general, there are significant increases in output power due to most of the transient very small increases in the input power. The rise times in the output power are limited by the time constant of the calorimeter.

Overall, the three sharp decreases in input power in Figure 10 led to three positive excursions in output power. The meaning of the apparently negative input power is interesting. During those brief periods, the experiment appeared to

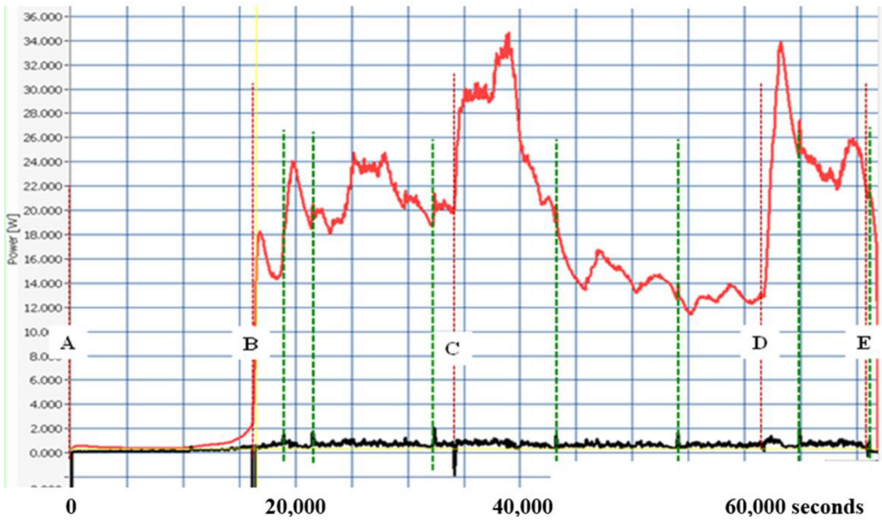

Figure 10. Time variation of the electrical power input (black) and thermal power output (red) for an experiment conducted by Energetics Technologies in Israel. Times when the input power dropped precipitously are indicated by the letters.

be acting as a battery, supplying rather than consuming power. It is not clear if the instrumentation in use to record the input electrical power was capable of detecting and properly measuring such behavior. However, it is evident that negative excursions in the recorded input electrical power resulted in positive increases in the output thermal power. Some of the half dozen brief positive excursions in input power did not produce significant changes in the output power. That might indicate that fluxes are a necessary, but not sufficient condition for the production of LENR.

A second strong LENR heat generation result, which involved small changes in input power with large effects, was obtained at the Naval Research Laboratory, as shown in Figure 11 [52]. The letters indicate the times when there were discontinuous increases in the input power. In most cases, save for times E, F and J, increases in the output power occurred at the times of, or soon after those increases in input power. Discontinuous electrical power inputs generally had beneficial effects on the LENR output power. Figures 10 and 11 both show that very small changes in input power led to much larger changes in output LENR power. However, in one case (Figure 10), sudden *decreases* in input power triggered large increases in output power. In the second case (Figure 11), it was sharp small *increases* in input power that triggered larger increases in the output power.

The natural question of why both positive and negative excursions in input power should lead to increases in output LENR power might be easy to answer. Much laboratory evidence, and some LENR theories, indicate that a flux of deuterons is desirable to produce LENR. However, there is no indication if an inward or outward flux is better. Both produce deuteron motions that can lead to higher LENR production rates.

The data in the past two figures have interesting and maybe important implications. It is possible that using either or both increases or decreases in input power, with any waveform, could provide a means to vary the output power of a LENR experiment, prototype or product that uses a LENR cell of any type. This suggests that experiments be performed in which the input electrical power is willfully changed suddenly. Figure 12 shows one possibility. It is also possible to input pulses by the use of coils around the leads to the electrochemical cell. There are many choices to be made in such experiments in addition to picking either an increase or decrease in the power. The magnitude and time duration of the changes have to be chosen. The frequency with which changes are made is another variable. By

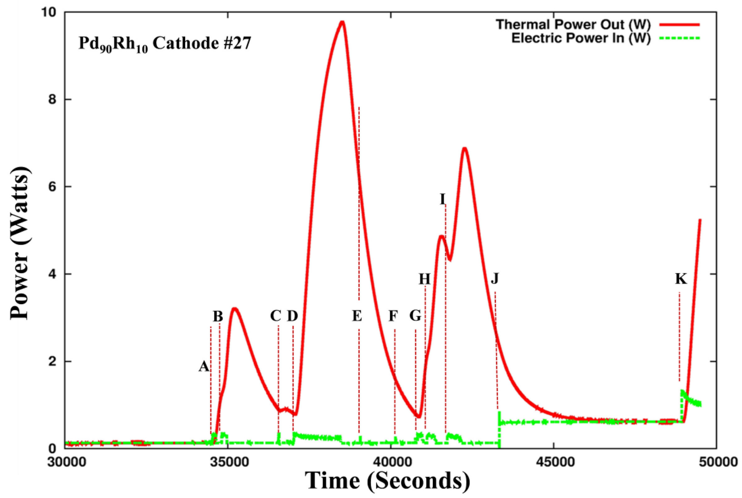

Figure 11. Time variation of the electrical power input (green) and thermal power output (red) for an experiment conducted by the Naval Research Laboratory in Washington DC. The letters indicate times when the input electrical power increased suddenly.

themselves, those four variables of direction, magnitude, duration and frequency, present a large experimental matrix. Execution of experiments in such a matrix would be challenging, due to the large number of possibilities, even if one had a reliable means of producing LENR at will. However, the current inability to reproducibly and controllably cause LENR to happen in an experiment makes it doubtful if such parametric experiments can be done successfully now. It must be noted that input pulses are being used by Brillouin Energy Corporation in their LENR research and development [53]. They believe that the pulses directly affect nuclear reactions.

While waiting for reproducible LENR experiments to be developed, it is possible to consider the effects of sudden changes in the input power, either or both due to changes in electrolysis or the use of heater pulses. Step functions [54], and also square waves [55], contain many high frequency components. That is, the Fourier Transforms of such input waveforms contain many frequencies, some of which might be useful in producing LENR. That might be the case if there are one or more resonances that might be excited, which will improve LENR rates. It is possible that the use of "superwaves" in some productive LENR experiments produced desirable excitations [56].

6. Output Signals

This section deals with six various signals, which have been measured from LENR experiments. As with the input stimuli considered in the last section, the amount of work on the diverse signals varies greatly. The difference is that input stimuli can be controlled, but it is rarely possible to completely or even significantly control what comes out of a particular LENR experiment. It is interesting that a list of 11 different types of output observations appeared as early as 1990 in a paper by Fleischman [57]. He listed separately steady and burst observations.

Heat. Thermal energy is probably the most measured variable from LENR experiments. One reason might be the fact that it was measured in the original Fleischmann and Pons experiments. The level of LENR energy is often so high that potential chemical reactions are excluded as the origin, leaving only nuclear reactions as the likely source. Another, and probably more compelling reason for interest in heat measurements, is the possibility that commercial LENR generators will be developed to produce at least heat and maybe also electricity.

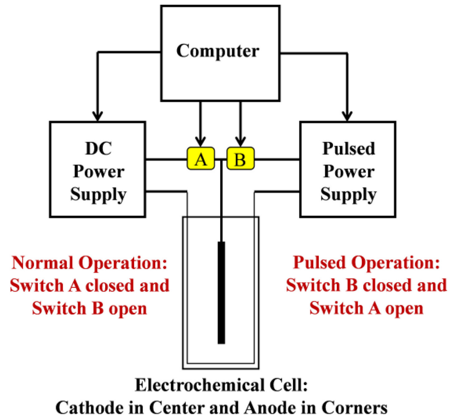

Figure 12. Circuit for putting impulses into electrochemical LENR experiments.

There have been thousands of LENR experiments in which heat production was measured by thermometry or calorimetry. Searching the lenr.org library [58] with the word "heat" produces a list of over 1100 papers and reports. Since this paper is focused on the less common inputs to and outputs from LENR experiments, we will not consider heat measurements further here. Thermal power measurements were part of the discussion in the last section of the effects of impulses on LENR experiments.

<u>Transmutation Products.</u> The situation for LENR reaction (transmutation) products is similar to that for heat measurements. There has been great interest in products from LENR, since they provide much information on what happened in an experiment. Another search of the lenr.org library with the word "transmutation" produced over 400 hits. As with thermal measurements, there is much further work on LENR products that could be done. One motivation is the fact that some really unusual transmutation products have been reported. The papers by Miley [20] and Mizuno [21], already noted above, both show the same peaks in LENR rates as a function of atomic mass. The reasons for the existence of those peaks remains to be explained, which calls for further measurements of transmutations, as well as additional theoretical considerations. Similarly, Iwamura reported transmutations that apparently involved as many as six deuterons [59]. There is no theoretical explanation for those results. And, there are several reports of isotope anomalies after LENR experiment, which are not understood [60]. The variety of transmutation results raise the question about whether or not there is only one mechanism for LENR. That is possible, but there might be multiple mechanisms by which to produce LENR. This is one of the more fundamental open questions in the field.

<u>Gamma Rays.</u> Interest in measuring gamma rays from nuclei in LENR experiments immediately followed the 23 March 1989 Press Conference by Fleischmann and Pons for two reasons. One motivation was the known gamma ray emission from ordinary deuteron fusion in one out of ten million events. Although relatively rare, the gamma emission from deuteron fusion is readily measured. The other reason was reports of gamma ray measurements by Fleischmann and Pons, as documented in their 1989 initial paper [61], which was submitted ten days prior to their Press Conference, and in another paper the same year [62]. Searching the lenr.org library with the word "gamma" produces about 230 hits. There are reports of gamma ray spectra from various LENR experiments, but they are relatively rare. One early example is from a glow discharge experiment [63]. The spectrum contained 25 gamma ray lines from 51 to 335 keV, nine of which were identified with isotopes of Sr, Rh and Pd. It is noted that gamma ray emission can originate from radioactive decay, as well as from the decay of nuclear excitations. The

low levels of radioactive products from LENR experiments are challenging scientifically and potentially important commercially.

It is now known that LENR experiments do not generally emit significant gamma ray intensities. That is true both during and after experiments. LENR experiments do not usually produce significant residual radioactivity. That is good, of course, since there is no radioactive waste problem for LENR, as there is with existing fission and anticipated fusion power systems.

X-Rays. There are two classical sources of x-rays. One is line radiation from electrons filling vacancies in atomic orbitals and the other is continuous radiation called Bremsstrahlung from deceleration of energetic electrons by nuclear fields. The situation for x-ray emission from LENR experiments is a lot like that for gamma ray emission from such experiments. There are about 200 papers in the lenr.org library that contain the word “x-ray”. However, many of them have to do with using x-ray diffraction to probe the lattice parameters of materials in LENR experiments, rather than measurements of x-ray emission during or after experiments.

Similar to the case for gamma rays, some examples of x-ray emission and spectra can be found in the LENR literature. One of the early cases, Iwamura and his colleagues [64] measured x-rays from an electrochemical LENR experiment. They observed a clear peak in the x-ray emission near 75 keV during the run. Spectrochemical analysis of the palladium cathode after the run showed the presence of lead. The strongest Kα x-ray emission line of lead is at 75 keV.

Much lower energy x-rays were measured by Storms and Scanlan in an experiment with a glow discharge in deuterium gas [65]. The conclusion of that study contained the following statements “Anomalous radiation is produced when a glow discharge is produced in deuterium gas. This discharge consists of low-energy X-radiation and occasional energetic particles. The energy of the X-radiation increases as voltage applied to the discharged is increased, with an energy equal to applied voltage at 600 V. Intensity increases with applied voltage and with increase in O/D ratio. The source does not appear to be K-radiation from oxygen or nitrogen. The intensity of X-radiation is at least 1000 times greater than the particle flux. Insertion of Mylar absorbers suggests the particles are deuterons with energy peaks having various values between 0.5 and 3 MeV. The energy is sensitive to voltage applied to the cell and to gas composition.”

Infrared Radiation. There are only a few LENR papers where infrared (IR) emission was reported. The first was taken from a cell in which palladium and deuterium were co-deposited on a substrate near the wall of an electrochemical cell [66]. One of the images from a video [67] of that experiment is in Figure 13. The red area from the cathode is warmer than the surroundings. Within that region, there are small white spots that are even warmer. The video showed

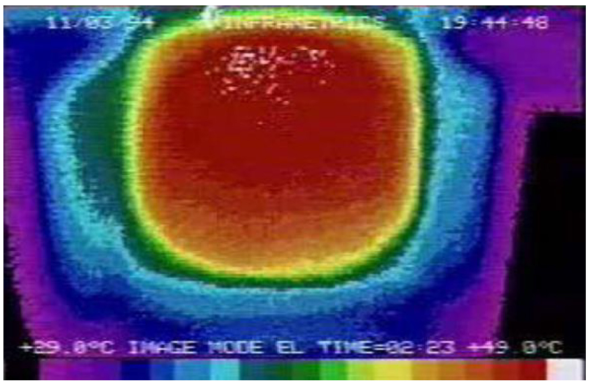

Figure 13. Infrared image of the cathode in an electrochemical LENR co-deposition experiment.

that the hotter regions occurred at different locations and lasted for only short times. The behavior is consistent with fast heating due to the release of LENR energy in small regions, which then cool quickly. Estimates of the temperature increases based on the particle sizes in the co-deposited materials are consistent with nuclear levels of energy: release of 1 MeV in a cube of Pd 100 nm on a side gives a temperature (T) rise of $\Delta T = 380$ K using $(3 \text{ k } \Delta T)/2$ as the increase in vibrational energy, or $\Delta T = 55$ K using the specific heat for Pd = 26 J/K mole [68]. Additional experiments of this type should be very valuable, especially if the infrared imaging were augmented with time-resolved infrared spectroscopy.

In 2008, Swartz reported the measurement of non-thermal IR radiation from different LENR experiments [69]. To quote from that paper, "Non-thermal near-IR electromagnetic radiation is emitted from LANR active electrodes when excess heat is observed at their optimal operating point. The appearance of excess energy in several types of high impedance and co-deposition Phusor®-LANR (lattice assisted nuclear reaction) devices [Pd high impedance, Pd co-deposition, and possibly Ni with light water] was simultaneously detected from loaded, active nickel and palladium devices, by *in situ* monitoring."

The only other LENR experiment involving IR measurements was reported in 2019 [70]. It involved multiple layers of hydrogenated copper–lithium–boron alloy electrodes separated by a liquid dielectric containing fine graphite particles in a capacitor configuration. Infrared imaging was used to view the edges of the stacks of electrodes through an IR transmissive window in the cell.

Infrared imagers, which can be attached to smart phones, are now available for modest costs [71]. That fact, and the likelihood that IR imaging of hot gas and plasma loading experiments would be valuable, indicates that their use might be relatively productive in some future LENR experiments.

Audible Sound. The range of audible sounds has frequencies from 20 Hz to 20 kHz. The emission of acoustic radiation was measured in only one known LENR experiment. Szpak and his colleagues co-deposited Pd and deuterium onto a piezoelectric disk [72]. Such a disk is a reciprocal transducer for sound and electrical signals. Deformations due to sound produces voltages, and application of voltages causes deformation in piezoelectric materials. In the LENR experiment, deflection of the disk produced voltage signals indicative of the emission of sound in the experiment. That experiment, which is relatively easy to perform, has not been replicated.

Unlike heat, reaction products and photons, there is likely to be sound from all LENR experiments. That may be most certain for electrochemical experiments due to the bubbles that form on the electrodes. It might also be true of both hot gas and plasma experiments. Sounds can arise from both chemical and nuclear processes. If sound can be attributed to episodes of LENR heat release, [73] the intensity and frequency of acoustic emission will provide data on a time scale much faster than that offered by calorimeters. Microphones are small and cheap, and the circuits for capturing sound signals are simple. Listening for sounds ought to be done in many more LENR experiments.

7. Inputs and Outputs

We now turn to four entities that have served as both inputs and outputs for LENR experiments.

Neutrons. Since ordinary deuterium fusion results in the production of neutrons, there were many early attempts to measure neutrons from LENR experiments. They produced varied results. There have been very few cases where neutrons were used as input to LENR experiments. Motivations for such experiments include the fact that neutrons can lead to nuclear reactions that result in activation of some nuclei and fission of other nuclei.

One paper [74] that described neutron input to a LENR experiment stated "…..metallic deuterated Pd samples have been irradiated with partly moderated Am/Be neutrons and the resulting neutron intensity has been measured by the FERMI apparatus….. the resulting rate corresponds to several outgoing neutrons for every neutron impinging on the Pd-D sample……. The underlying process can be interpreted as D-D fusion in a Pd-D lattice perturbed by neutrons. The excess, predominantly due to thermal incident neutrons, demonstrates that the Palladium lattice strongly increases the probability for D-D fusion even almost at rest."

The literature on neutron measurements from LENR experiments is quite extensive in both the number of papers and the sophistication of the experiments, which were described. In the next paragraph, we give one example from that literature to illustrate the complex efforts made to measure very low levels of neutrons from LENR experiments. The challenge was born of the fact that low numbers of neutrons come out of most LENR experiments, much smaller than would occur if ordinary deuterium fusion were happening. Hence, it was necessary to achieve low noise and low background performance of the neutron detection systems, including going underground to avoid cosmic ray neutrons.

Part of the abstract from the report [75] on a major program by scientists from the Los Alamos National Laboratory, which searched for low levels of neutrons from LENR experiments, reads "A wide variety of neutron detector systems have been used at various research facilities to search for anomalous neutron emission from deuterated metals. Some of these detector systems are summarized here together with possible sources of spurious signals from electronic noise. To improve our detection sensitivity, we have increased the shielding in our counting laboratory, changed to low-background ^{3}He tubes, and set up additional detector systems in deep underground counting stations." That paper reported on the results of exposing titanium to various pressures and temperatures of deuterium gas.

It must be noted that a few non-electrochemical LENR experiments did provide substantial neutron emission rates. Early in the field, an Italian group subjected titanium samples to rapid temperature changes, and observed neutron emission [76]. The results of similar experiments were reported 25 years later, again with stronger neutron measurements [77]. Reports such as those raise a question: do different types of LENR experiments cause major variations in both rates and branching ratios?

Another question involving neutron measurements from LENR experiments concerns the origin of the neutrons. Are they the result of LENR, however stimulated, or do they come from deuterium fusion reactions caused by energetic processes that arise during stress-induced cracking of materials? The latter process is called fractofusion. Charge separation during cracking can produce potentials high enough to accelerate charged particles, like deuterons, to energies sufficient to cause nuclear reactions. Attention to fractofusion began soon after the Fleischmann-Pons announcement [78]. Reports of fractofusion are in the 2015 book by Carpenteri [79]. Determining the source of the neutrons measured in various LENR and related experiments is another of the old challenges in the field.

Finally, we note that, like issues with magnetic fields and other LENR variations, there remains the question of what influences and determines neutron production from LENR experiments. Is it a direct effect, or the result of some prior, possibly chemical effect, which is active?

Electrons. The use of electron beams in LENR experiments has been rare, with only a few studies.

Lipson and his colleagues did experiments in which an electron beam with a current of 100-300 nA and energy of keV was used to irradiate samples with high concentrations of deuterons [80]. The targets were Pd/PdO:D_x and TiD_x. Passive plastic CR-39 detectors covered with absorbing foils were used to detect and measure the types and energies of emitted particles. It was found that protons with energies near 3 MeV and alpha particles with energies in the range of 11 to 20 MeV were emitted only when the electron beam was active. Otherwise, the targets did not emit the protons or alpha particles.

Reports of electrons emitted by LENR experiments have also been infrequent. In a series of studies with a glow discharge plasma in a deuterium gas atmosphere, Storms and Scanlan reported electrons, as well as heavier particles and x-rays. The conclusion of their first paper [81] reads "The observations show that energetic electrons make up part of this emission and energetic particles that might be protons and/or alpha particles add to the radiation, depending on the chemical composition of the cathode and gas. The type of radiation, its energy, and the rate are all sensitive to the presence of certain elements in the environment." Later, the same authors tried to deflect the emissions with a magnetic, which was not possible. Hence, they concluded that they were measuring photons, not electrons [64]. The certain measurement of electrons emitted from LENR experiments remains another challenge.

Energetic Ions. The situation for ions into and out of LENR experiments is unusual. There are many instances of such stimuli and measurements. However, they involve very different experiments. The relatively short ranges of energetic ions in condensed matter mean that it is generally not possible to put them into electrochemical LENR experiments. Injection of ions into hot gas and plasma experiments is possible, depending on the pressures used, but that does not seem to have been done during any experimental study of LENR. The experiments, where beams of energetic ions have been used, involve impacts on solid and, in a few cases, liquid surfaces within vacuum chambers.

Papers on the impact of ions with keV-scale energies have been presented at LENR conferences since early in the field [82]. They showed that the deuterium fusion cross sections are enhanced above expected levels as the beam energy is decreased. It was thought, and might still be possible, that the enhancement, which is called anomalous screening, is due to a mechanism similar to what is active in LENR at ordinary temperatures. However, there is a difference between the beam energies (keV) and room temperature (1/40 eV) of over a factor of ten thousand. It remains to be determined if the physics of fusion cross section enhancement at low ion beam energies is related to the physics of LENR.

There are some theoretical papers on the relationship of anomalous screening and LENR. In 2009, the abstract of a paper by Czerski read "The enhanced electron screening effect observed in accelerator experiments for the ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He reaction in deuterized metallic targets may be a breakthrough in understanding the phenomenon of cold fusion. The dielectric function theory enables an extrapolation of experimental cross sections determined at higher energies down to room temperature, leading to an enhancement of the fusion reaction rates by a factor of 10^{40} compared to the value predicted for the deuterium molecule. An additional enhancement can be obtained due to a $0+$ resonance which should exist in the compound nucleus ^{4}He very close to the D-D reaction threshold. Combination of both processes offers a simple explanation of high penetration probability through the Coulomb barrier and the reaction branching ratio preferring the ^{4}He channel in heavy-water electrolysis experiments.". Two recent theoretical papers by Kálmán and Keszthelyi note the potential connection between anomalous screening and LENR. In one, they wrote "The 3rd-order heavy particle assisted and the 4th-order electron assisted resonance-like double nuclear processes may partly be responsible for the so-called anomalous screening effect observed in low energy accelerator physics investigating astrophysical factors of nuclear reactions of low atomic numbers [83]." In the second, they stated "Consequently the anomalous screening phenomenon may be connected to the processes discussed here." [84] They were referring to LENR processes.

Given that ordinary deuterium fusion produces energetic protons, tritons and helium-3 ions, as well as neutrons, much early effort was devoted to measuring ions from LENR reactions. However, as noted, ions with even MeV energies have very short ranges in condensed matter, as in electrolytic LENR experiments. So, the experiments were challenging. A paper from 1998 [85], after many searches for ion emission, concluded "We searched for nuclear products in electrolytic cells in which were observed excess heat, in gas phase of Pd + D systems and in D + single crystal. The detectors were run for long period to measure background and check stability. The signals from the detectors were analyzed by the Pulse Height Analyzer and recorded in the personal computer as spectra. Having done that, we could surely identify the signals due to noise or true events. The results of experiments reported here contradict other groups' claims of finding various sorts of nuclear products. We could only obtain the upper limit of existing nuclear products in our systems." In short, measurements of ions from LENR experiments are similar to searches for neutrons in that usually only low-level emission is found.

Radio-Frequency Radiation. Frequencies in the radio-frequency range have been both applied to and measured from LENR experiments [86]. Figure 14 is a graphical summary of the specific frequency ranges used by various investigators. It includes notes about whether or not excess heat was obtained in the experiments. It can be seen that there is no clear relationship between the measurement of radio frequencies from the LENR experiments and the appearance of excess heat. However, application of such frequencies appeared to be beneficial in some cases.

Radio-frequency excitation was applied to electrochemical experiments by Bockris and his team early in the field [87]. Figure 15 shows the setup and results. A coil was wrapped around the cell and excited by an RF gen-

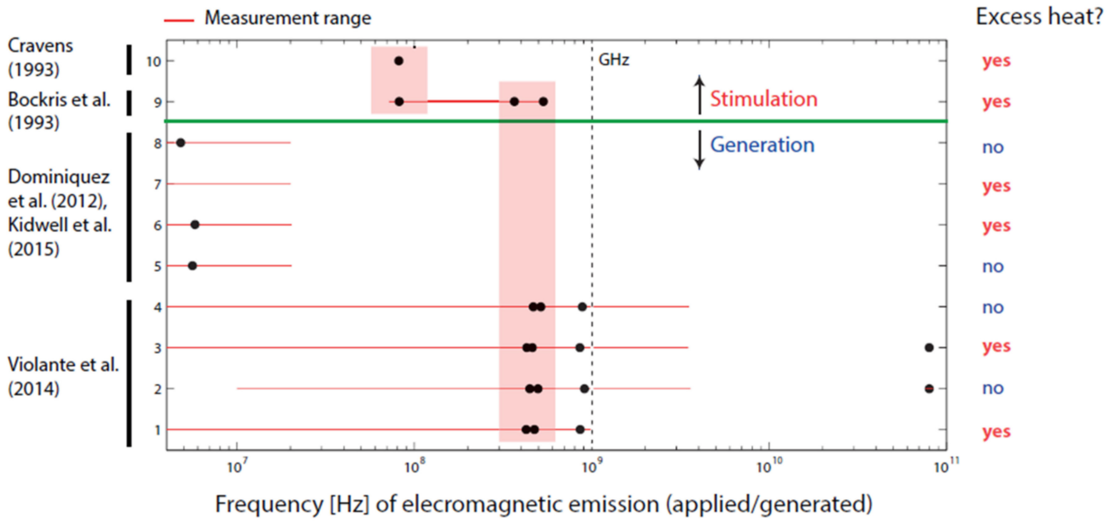

Figure 14. The ranges of radio frequencies that have been input to (above green line) or measured from (below green line) LENR electrochemical experiments.

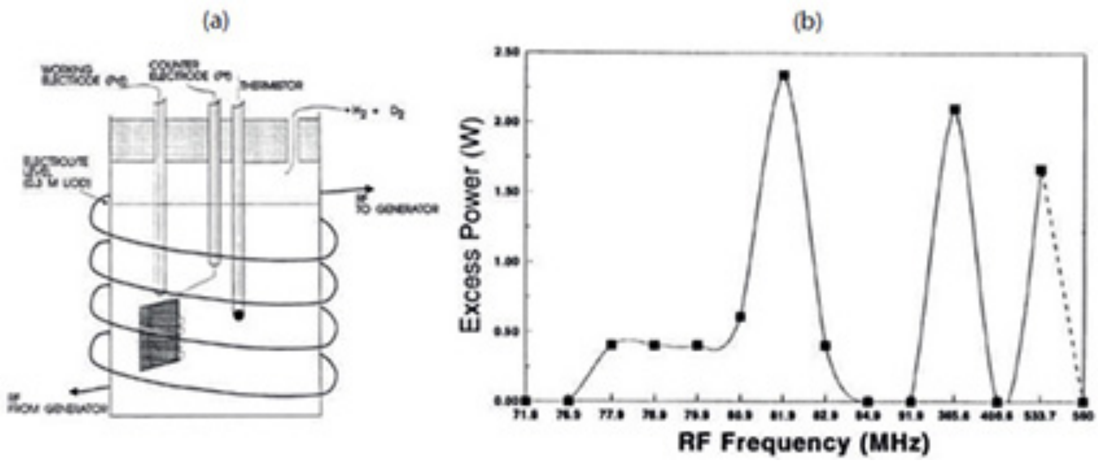

Figure 15. Left: The experimental setup in which a coil encircled the LENR electrochemical cell. Right: Variations in the excess power as the excitation frequency was tuned.

erator. Peaks in the excess power were seen at frequencies of 81.9 and 365.6 MHz. Radio-frequency signals have also been detected within and from LENR experiments. Frequencies in the range from 0.45 to 4.82 MHz were observed during the production of excess power at the Naval Research Laboratory [88]. RF emissions in the 400–800 MHz and 79–81 MHz ranges were seen by scientists at ENEA [89].

A surprising recent example of RF emission was published by Swartz and discussed in a pair of papers [90]. He found radio-frequencies were produced by two types of LENR experiments, a dry pre-loaded NANOR$^{\mathrm{TM}}$ and an aqueous system. When the NANOR$^{\mathrm{TM}}$ was driven above a voltage threshold, but below the point of avalanche operation,

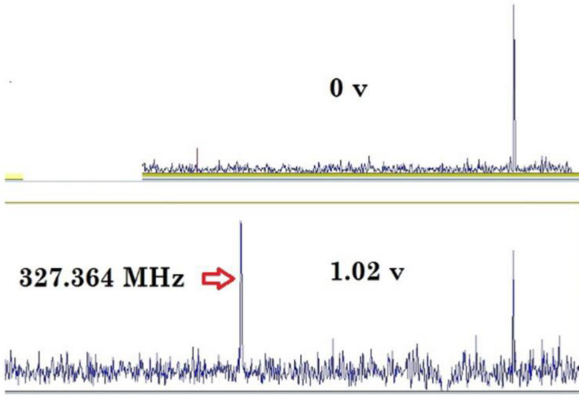

Figure 16. RF emission from a NANOR^{TM} for two applied voltages. Frequency increases to the right.

maser action at a specific frequency was measured. Figure 16 gives the spectra measured with the NANOR^{TM} off and in the maser mode, the latter showing a line at 327.364 MHz. The other line in the spectrum is of galactic origin, and serves as a fiducial. Swartz interpreted his observations as indicating that deuterons in vacancies in the Face-Centered Cubic palladium lattice are the source of LENR [91].

8. Unexplored Possibilities

The blanks in Figure 4 might exist for two reasons. One is the simple fact that no one has thought that experimenting with the missing input or output possibilities would be worthwhile. Another is the perception that such experiments are either not worthwhile or too difficult. Whatever the reason, we consider each of those blanks in this section.

Input Ionizing Radiation. We already noted that low energy (∼keV) ion beams have been used to produce enhanced deuterium fusion cross sections. We now turn to three other types of ionizing radiation that do not appear to have been input to LENR experiments. They are all electromagnetic, namely gamma rays, x-rays and ultraviolet (UV) photons. The reason for the lack in incident gamma ray experiments seems clear. There seems to be no particular scientific motivation. Further, the production, collimation and aiming of gamma rays are challenging, and relatively few gamma rays might be stopped within a LENR experiment (depending on the gamma ray energy). By contrast, it is relatively easy to produce beams of x-rays and UV radiation, if there were reasons to use them for excitations or other effects in LENR experiments. That is most true in synchrotron radiation facilities, but also applies to laboratory x-ray and UV sources. X-rays of appropriate wavelengths can get into the cathodes of electrolytic experiments and be absorbed by them. Although their absorption would produce heating and electronic excitations, it is unclear how those effects might contribute to the occurrence of LENR. X-rays would be little absorbed in hot gas or plasma experiments. X-rays have been used as probes of LENR experiments, as will be noted in the concluding section.

There are no papers in the lenr.org library on the emission of ultraviolet radiation from LENR experiments. That is understandable for the case of aqueous electrochemical experiments. UV radiation is heavily absorbed in water. Figure 3 shows that UV radiation in and near the visible region can escape from water-containing cells of the size of those used in LENR experiments. However, for wavelengths below about 180 nm, the escape depth is on the order of micrometers or smaller. Then, it is not possible to measure UV emission from aqueous cells.

The absorption of UV radiation by hot gases or plasmas, such as those used in some LENR experiments, is much less than the absorption in aqueous cells due to the lower density of the atmospheres in those cases. So, it ought to be possible to measure the UV emission from hot gas and plasma loading LENR experiments. Such data could be useful, especially for plasmas, which commonly contain many emission lines in the UV regions. The wavelengths and intensities of those lines can be used to obtain information on the temperatures and densities of plasmas, as well as whether or not their electrons and ions are in equilibrium [92]. UV might be absorbed in some hot gas and plasma LENR experiments. However, here again, there does not seem to be any motivation for using input UV radiation.

Output Visible Light. The motivation for measuring output visible light from LENR experiments seems clear and strong. Visible spectra are easy to measure with modern instruments, and can provide a great deal of information on the excitations and ionizations of materials in experiments. However, that seems not to have been done for electrochemical LENR experiments. When one looks for papers on light emission from electrochemical experiments, the topic of LECs (Light-emitting Electrochemical Cells) appears [93]. They are solid-state devices, which seem to have little in common with the wet electrochemical cells in many LENR experiments. It is possible that electrochemical experiments, in general, and LENR electrolytic experiments, in particular, do not emit easily-measured intensities of visible light. However, both hot gas and plasma LENR experiments ought to emit significant and useful visible light. It seems that there should be papers on spectra from such experiments.

Input Infrared Radiation. The situation for input non-ionizing radiation might be similar to that for input ionizing radiation, as just detailed. What is the motivation for shining IR radiation into LENR experiments? Doing that could produce localized heating. However, no other reason for shining IR radiation into any type of LENR experiment is known to this author.

Input Sound. It is easy to put sound of any frequency into almost any type of LENR experiment. We noted the input of ultrasound in Section 5. There are many sources and transducers for sonic frequencies. Consider the billions of audio systems of any kind in use in the world. The apparent lack of work on audible insonification of LENR experiments might again be due to the absence of motivations for such research. The question of what would sound do in an LENR experiment was unanswered until recently. A new theoretical paper [94] dealt with the effects of vibrations on the occurrence of LENR. It concluded: "So, the main consequences for LENR caused by the presence of classical vibration (coherent phonon field) are the following: (a) If a vibration is switched on then nuclear reactions may occur even at very low energy (in the $\varepsilon \rightarrow 0$ case), (b) If a vibration has a high enough amplitude then de-localization of nuclear reactants happens with high probability, (c) Nuclear reactions may follow delocalization, (d) The rate of nuclear reactions has strongly nonlinear dependence on the amplitude of vibration, and (e) Especially during electrolysis, accidental mechanical vibrations caused by e.g. bubble formation can be connected to accidental processes (bursts, explosions and crater formations)." That work indicates that it could be useful to input sound to LENR experiments at some yet-unknown frequencies and amplitudes. As with some of the other input effects, it is unlikely that the sound would directly affect the nuclear reactions. Rather, sound (like ultrasound) might influence prior effects that lead to conditions that might change rates of LENR.

Output Ultrasound. Running water is a rich source of ultrasound. It is possible that LENR experiments also generate ultrasound, although that does not seem to have been measured yet. The search of emitted ultrasound from LENR experiments might, like many other earlier exploratory LENR measurements, produce something of interest. The sudden release of nuclear-level energies in a small region of space and time by LENR could produce high frequency vibrations, as well as electrical noise. If LENR do generate ultrasound, it should be possible to detect the occurrence of LENR at rates well below the lower limits of calorimeters by measuring ultrasound, similar to the following discussion of electrical noise measurements.

Electrical Noise. Noise is a feature of all experiments, including those that seek to produce LENR. There are multiple kinds of noise in LENR experiments, including both the input stimuli and the output signals. The noise on the thermal power measured in an experiment limits the ability to measure small powers with calorimeters. Swartz

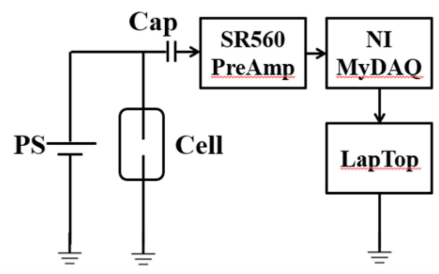

Figure 17. The electrochemical LENR circuit on the left, consisting of the Power Supply (PS) and the cell. Electrical noise is coupled out of that circuit with a Capacitor (Cap), amplified by the Stanford Research 560 unit and digitized with the National Instruments MyDAQ box.

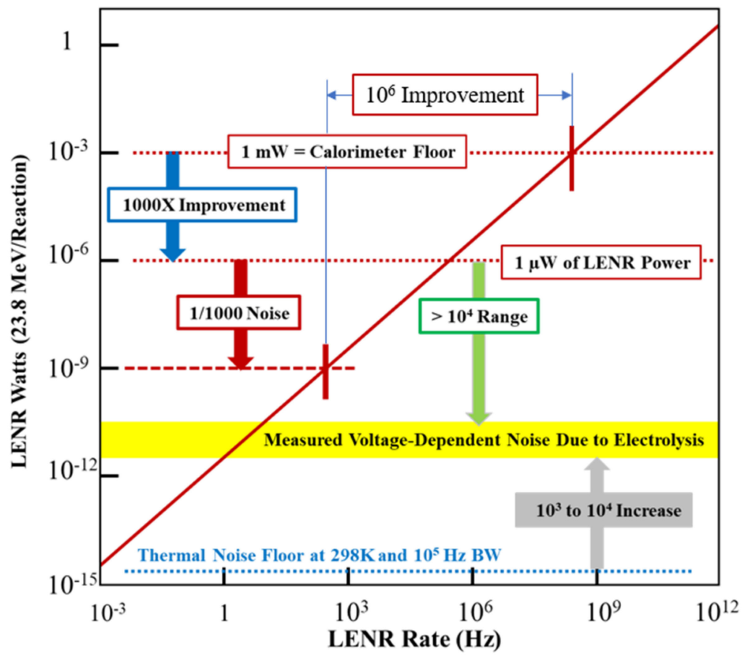

Figure 18. Plot of LENR power as a function of the rate at which LENR occur. See text for details.

discussed that type of noise in a 1997 paper [95]. There is also noise on all electrical currents within a LENR experiment, including the current that flows through electrochemical cells. Electrical noise is widely used to understand the behavior of electronic devices [96]. It could also provide a new way to detect LENR at low rates, that is, at rates below those needed for calorimetric detection of LENR heat. Such a method is being developed at the George Washington University [97]. It might offer faster determination and lower limits for detection of the occurrence LENR. The method is based on quantitative measurements of electrical noise on the cell voltage. It depends on what fraction of the energy produced by LENR goes into electrical noise.

The idea and status of using electrical noise as a sentinel for LENR can be described with reference to Figures 17 and 18. The circuit for noise measurements is easily mated by a capacitor with the circuit for most electrochemical cells, quite independent of the design of the cell and any calorimeter in use. A Stanford Research low-noise preamplifier and a small analog-to-digital converter from National Instruments are used. Noise data are sampled at a rate of 200 kSamples/sec for 100 seconds. Then, performing a Fourier Transformation on that time series gives the spectrum of the electrical noise from 1 Hz to 100 kHz. The spectrum consists of 1/frequency (Flicker) noise up to a few Hz and thermal (White) noise for most of the range to 100 kHz. With no current in the electrochemical circuit, the noise floor is set by the temperature and the input impedance of the pre-amplifier.

The red diagonal line in Figure 18 is a plot of the LENR power (assuming 23.8 MeV per reaction) as a function of the rate at which LENR occur. The horizontal blue line at the bottom is the noise floor computed from the equation for Thermal Noise: $V^2 = (4 \text{ k x T x R x BW})$, where V is the noise-induced voltage, k is Boltzmann's constant, T is the absolute temperature, R is the input resistance, and BW is the bandwidth [98]. Since electrical power P $=$ I x V $=$ V^2/R, one has Noise Power/Hz $=$ 4 kT. We measured the increase in White Noise from an electrochemical cell with both electrodes made of platinum. For voltages on that cell of 2, 3, 4 and 5 V, the noise increased by a factor between 10^3 and 10^4 above the level for zero voltage. The yellow band in Figure 3 gives the Noise Power when the cell is powered. Turning attention to the top of Figure 3, the 1 mW floor for a calorimeter is indicated, along with the power level of 1 μW. If only 1/1000 of a LENR power of 1 μW went into electrical noise, that noise would still be one to two orders of magnitude higher than the electrical noise in the powered electrochemical circuit. If the LENR power were higher than 1 μW, or a larger fraction of the LENR power went into electrical noise, this noise technique might make it possible to detect an even smaller fraction of the LENR power and rate. As indicated in Figure 18, an improvement in the ability to detect the occurrence of LENR might be as much as a factor on one million. That increase in capability could have a large impact on LENR research, especially for the screening of materials for LENR activity.

9. Conclusion

This paper has dealt with inputs to LENR experiments that are meant to influence their outcomes, and with signals, which show at least partially what happened during such experiments. Such stimuli and measurements do not have to be simultaneous. Here we make passing note of techniques used to study the conditions and dynamics of some LENR experiments that have involved simultaneous inputs and outputs. Such probe measurements are not intended to control or even influence the experiments. There are a few examples of probe measurements in the literature on LENR. X-rays have been used to determine the structure [99] and composition [100] of LENR experiments. Similarly, Raman spectroscopy (input and output laser radiation) of active LENR experiments has been demonstrated [101]. There is no evidence that such probe measurements have determined, or even influenced the course of the interrogated LENR experiments.

Input Stimuli. It is possible that the roles of incident radiations or fields in LENR experiments could be determined theoretically, at least in some cases. Work by Hagelstein [102] and other theoreticians [103] involves phonons within cathode materials. Such theoretical research might explain the role of incident electromagnetic fields. However, it is also possible that resolution of the questions regarding the effects of various radiations and fields on LENR will be decided experimentally. That could take a relatively long time due to the large number and complexity of the potential experiments, even if a reliable means to produce LENR were already in hand.

Output Signals. There is clear opportunity and need for the use of various additional measurement techniques in the experimental study of LENR. Modern laboratory tools are readily available. One example involves compact and high-resolution instruments for measurement of spectra in the UV, Visible and IR regions. Such spectrometers are relatively easy to integrate with most LENR experiments. They can produce many wavelengths and intensities of line spectra for comparison with each other and other measurements. If any two measurements are made, their comparison or correlation provides additional information on an experiment.

Both Inputs and Outputs. Some of the excitory and emitted entities discussed above involve oscillations. That is true of electromagnetic and sonic waves, of course. There are also oscillations within materials, such as the cathodes in electrochemical experiments. Phonons are a prime example. The presence of these oscillations, each with some frequency or range of frequencies, raises two types of questions. First, what role might they play in the basic mechanism(s) that produce LENR? Second, are there interactions between any of these vibrations? The second question leads to consideration of resonances and resonant interactions in LENR experiments. The natural frequencies of atoms, molecules and materials that are a part of LENR experiments require consideration, in addition to applied and emitted oscillatory entities. A discussion of potential resonances and their interactions has been published [104].

One can ask what are the best combinations of inputs and outputs for LENR experiments in terms of (a) scientific learning and (b) potential commercialization. Eventually, it should be possible to answer both of those questions on the basis of experimental results and maybe also theoretical considerations. It seems likely that the best input stimuli will be those for a given loading method that have led to the most certain, intense and controllable production of LENR. Similarly, the best measurements ought to be those that provide the most useful information on what happened during an experiment. Given the current experimental and theoretical uncertainties regarding LENR, it is unlikely that any consensus on the best input stimuli and output signals will develop very soon.

Parametric Experiments. There have been many systematic measurements in LENR experiments, in which some variable, such as temperature, is changed during a run or between runs. We have noted such experiments in a few instances earlier in this paper. They have multiple advantages. In the absence of well-developed and widely-accepted theory on the potential outcomes of LENR experiments, parametric measurements indicate which variables are important. They are invaluable in showing the importance of any variable in the outcome of the experiments. Further, they challenge theoreticians to take the variables of importance into account. Parametric experiments can now be performed with modern instrumentation, such as that available at Synchrotron Radiation and Neutron Scattering Facilities.

Testing LENR Theories. The potential inputs and measurements discussed in this paper challenge LENR experimentalists. Past and possible experiments also challenge those who have developed theories about the LENR mechanism(s). LENR theories start with a concept of the mechanism that causes nuclear reactions to happen at low energies. They next need to be developed further by deriving the equations based on the concept, and performing calculations using those equations. Only then are numbers available for comparison with past or future experimental outcomes. The development of theories about LENR varies widely from many with only concepts and nothing more, to some that have the entire range of requirements and features. For those few LENR theories that have been developed to the point of explicit equations and numbers computed from the equations, data from parametric experiments serves to test the validity of the theories. Both the input stimuli and the output signals discussed in this paper provide tests of any LENR theories. Just as LENR theories vary greatly in their development, there is great variety in the thoroughness with which the better developed theories have been compared with experimental results.

Thorough Data Analyses. There have been two chronic shortcomings in the literature on LENR. One involves reports that fail to include relevant information, which is needed to (a) fully understand what was done and found, or (b) replicate the reported experiments and their results. A recent example was published by Staker, in which cyclic loading and deloading of palladium cathodes prior to experiments was cited as beneficial, without specific information on the protocols (currents and times) used for those operations [105]. The other problem includes reports in which data are presented without clearly possible additional data analyses. A common example of the second difficulty involves time histories of measurements without subsequent Fourier Transforms, which reveal the spectral (frequency) content of the data. A search of the lenr.org library with the phrase "Fourier Transform" does not produce any papers. Another example of missed analytical opportunities is the failure to perform correlations between simultaneous measurements to see if they might be related in some fashion. As the cliché states, correlation does not prove causation. However, correlation is additional information that might be useful for empirical or theoretical insights. Only ten papers in the lenr.org library deal with correlations. One of the more notable is an experiment in which neutron emission was found to time correlate with excess heat production [106]. However, that is an observation, not the result of a sophisticated data analysis. In another example, a mathematical correlation was detailed between the time of day and unexpected (and still unexplained) variations in the loading ratio, temperature and pressure in transmutation experiments [107]. That paper does exemplify the type of data analyses that are possible and desirable after future LENR experiments.

Systems Engineering. Past and current LENR experiments, and future LENR generators, are systems. They consist of the inputs, core and outputs discussed in relation to Figure 1. It is worth noting that there have been a few examples where the tools of Systems Engineering were applied to LENR. In 2003, Bass and McKubre [108] developed a Cause (C) and Effect (E) Protocol for determination of the appearance of LENR in an experiment. They wrote "Instead of the usual eyeballing of a (C,E) plot and assigning of a figure of merit regarding linearity in a subjective manner, the experimenter may now plan to evaluate a sequence of similar experiments in a completely objective manner by computing the significance ratio derived above." Then, in 2008, Bass and Swartz [109] applied the methods of Empirical System Identification (ESID) to LENR. Systems Identification was also employed for the study of the calorimetry used in a recent Google-funded program [110]. It is expected that Systems Identification methods will be applied to both future LENR experiments and also the development of commercial LENR generators. Books on the methodology are available [111].

This paper has not been exhaustive, citing all papers on each of the topics, which were discussed. Further, it is likely that this review has missed several papers that should have been included in the discussion above. However, it is hoped that the provided organization and example papers serve to stimulate additional considerations of and experiments on LENR, as well as more thorough comparisons of theoretical results with experimental data.

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