Questions About Lattice Enabled Nuclear Reactions: Experiments, Theories and Computations

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Abstract — Technical questions about the science of Lattice Enabled Nuclear Reactions (LENR) are posed and addressed. Factors relevant to the experimental study of LENR are dealt with first. They include the variety of stimuli applied to, and results measured from, LENR experiments. Experimental reproducibility, controllability and reliability are considered, as are new parametric studies and the use of new laboratory tools. Theoretical and computational opportunities, which are closely related, are discussed. An approach to assessing existing LENR theories is outlined. Computational tools to evaluate rates and energies from LENR theories, and to quantify the characteristics and properties of materials for LENR are surveyed. Analysis and mining of data from LENR experiments are touted.

1. Introduction

This is the second of three papers on scientific and practical questions about Lattice Enabled Nuclear Reactions (LENR). The first dealt with questions on LENR mechanisms and materials.[1] The third paper will focus on engineering, commercialization and applications of LENR. This paper deals with a dozen questions on LENR experimental, theoretical and computational science. Again, motivations for the questions, references to related work and comments on how to address the questions are provided. As noted in the first paper, questions are numbered solely for identification, and are not in priority order. The next section deals with questions about LENR experiments. Questions about the theoretical and computational science of LENR are in the following section. Some general comments appear in the concluding section.

2. Experimental Considerations

Several experimental opportunities were already discussed, when considering the questions on mechanisms and materials in the first paper. However, those did not exhaust the questions that can be raised about laboratory aspects of LENR. More basic questions about what happens in an LENR experiment can be posed and addressed. Hence, this section lists and discusses questions about the laboratory science of LENR. We will discuss two general aspects of LENR. The first deals with the roles of diverse stimuli applied to experiments and generators, and related emissions that come from such LENR laboratory and prototype devices. The second considers resonances of various types that are or might be relevant to the production of LENR. Then, we turn to three critical aspects of LENR. They are reproducibility, controllability and reliability. Parametric experiments, and the use of new measurement tools for LENR experiments, are also considered in this section. There are numerous other general and operational questions about LENR experiments. But, the following questions touch on many of the major experimental issues regarding LENR.

Q13. *What are the roles of various stimuli applied to LENR experiments?*

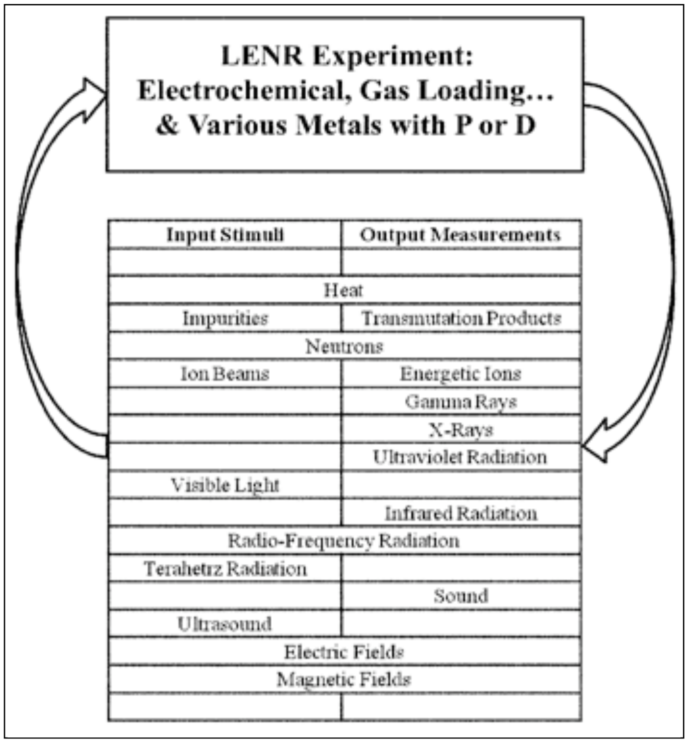
There is an interesting reciprocity regarding the application of stimuli to trigger or enhance the rates of LENR in experiments. As noted in the first paper, many types of effects have been measured in LENR experiments. They include heat, reaction products (notably tritium, helium and elements across the periodic table), particles (neutrons and fast ions), electromagnetic radiation in the gamma ray, X-ray, infrared and radio-frequency regions of the spectrum, sound, and electric and magnetic fields. Most of these entities have also been applied to LENR experiments, some of which have been heated to run at high temperatures. Impurities in materials or the ambient regions near active materials are the flipside of production of nuclear reaction products. Neutrons have been sent into some LENR experiments. And, electromagnetic radiations in the visible and terahertz regions of the spectrum were employed to stimulate experiments. Ultrasound has been used in several electrochemical and other experiments. Finally, both electrical and magnetic fields have been applied to LENR experiments.

Figure 1 is a simplistic graphical listing of the various entities that have been either applied to or measured from LENR experiments. It is seen that there are still many blanks, which are opportunities for other input stimuli and output measurements. This is especially true because of the many combinations of stimuli and measurements that are possible. And, those combinations can be applied to experiments with different loading methods and various combinations of materials and hydrogen isotopes. Most LENR experiments, which already involved various stimuli, used electrochemical loading of deuterons into palladium. There are many possibilities for application of stimuli to other electrochemical experiments, for example, proton loading onto nickel, and to the possible diverse gas loading experiments.

In the following paragraphs, we will note several, but not all, of the experiments in which stimuli have been used to provoke production of LENR and, commonly, excess power. Examples of the measurements of the various types of outputs will also be cited. The sequence of inputs and outputs in Figure 1 will be used to order the presentation.

Control of temperatures has been done in a relatively small number of LENR experiments. Mengoli and his colleagues ran some experiments near the boiling point of D_2O and measured excess power.[2] Storms did an important series of LENR electrochemical experiments with varying temperatures, which enabled him to compute the activation energy for power production.[3] He showed that LENR can be triggered with the low activation energy of 0.6 eV, a value on the chemical scale, and not on the nuclear scale, of energies. Liaw and his coworkers used molten salts at 350°C, rather than aqueous electrolytes.[4] They measured as much as 25 W of excess power.

There are many reports of power production in LENR experiments. Tables of dozens of them are in the two books by Kozima[5] and the two books by Storms.[6] Such papers will not be summarized here. Suffice it to say that output thermal



Input Stimuli	Output Measurements
Heat	
Impurities	Transmutation Products
Neutrons	
Ion Beams	Energetic Ions
	Gamma Rays
	X-Rays
	Ultraviolet Radiation
Visible Light	
	Infrared Radiation
Radio-Frequency Radiation	
Terahetz Radiation	
	Sound
Ultrasound	
Electric Fields	
Magnetic Fields	

Figure 1. Schematic relationship between LENR experiments, the various input stimuli that have been applied to them (left column) and the diverse attempted output measurements from them (right column). Blanks in the columns are possibilities that have not yet been applied or measured. P stands for protons and D for deuterons.

powers in excess of the input electrical powers by tens, hundreds and even thousands of watts have been reported. Reproducibility and controllability of the LENR powers was a problem in almost all of the experiments, and will be addressed below in Questions 15 and 16.

There are many LENR papers that report measurements of impurities in cathodes and other materials. Analyses of the elements and, in some cases, isotopes both before and after LENR experiments have produced information on the rates of nuclear transmutations. That work has been reviewed by Srinivasan and his colleagues in recent papers.[7] Measurements of mass spectra during gas or plasma loading experiments apparently remain to be done.

Application of neutrons to LENR experiments is straightforward because of the long ranges of neutrons, even in condensed matter. There have been numerous reports of neutron emission from LENR experiments.[5,6] It is well known that the overall neutron intensity is far below amounts expected, if conventional fusion between deuterons occurred. However, some experiments have produced high neutron count rates, generally in bursts.[8]

Ion beams could be used to irradiate specially designed LENR electrochemical experiments. However, such experiments are difficult due to short ion ranges. No experiments in which ion beams have been used to stimulate gas loading experiments are known to this author. In contrast, there have been several experimental reports of fast ions escaping from LENR experiments. The books already cited have tabulations of such papers.[5,6] Ion energies in excess of 10 MeV have been reported. These are significant because chemical reactions cannot produce such products. That is, measurement of even weak emissions of energetic ions is solid evidence for occurrence of nuclear reactions.

Various regions of the electromagnetic (EM) spectrum have played a role in LENR experiments, both as stimuli in a few cases and as emissions in many cases. They will be briefly noted here and in the following paragraphs. Apparently, neither gamma rays nor X-rays have been applied to stimulate LENR experiments. However, both types of emissions have been measured from some experiments.[5,6] They are significant because chemical reactions cannot produce either of those radiations. There are no conclusive measurements of ultraviolet emission from LENR experiments yet. The very short ranges of UV radiation in both liquids and solids make such measurements difficult. However, successful UV measurements could be valuable because they might evidence processes occurring only on or very near to a surface. It is likely that gas loading experiments will provide the best chances for obtaining data in the UV region, either spectra or frequency-integrated intensities.

The incidence of visible EM radiation was shown to be beneficial in several LENR experiments. Letts and Cravens found almost ten years ago that excess power production could be increased by illuminating the cathode with laser light.[9] The intensity of the light acted as a control parameter. Others did subsequent experiments to verify and assess the effects of optical electromagnetic radiation on LENR. Violante and his colleagues showed that application of laser light to electrochemical experiments lead to an improvement in their reproducibility.[10] It is interesting that visible light has yet to be measured in electrochemical or other LENR experiments. There are many detectors, imagers and spectrometers for such light, so searching for emission in the visible region of the EM spectrum would not be difficult.

Radio-frequency excitation was applied to electrochemical experiments by Bockris and his team early in the field.[11] A coil was wrapped around the cell and excited by an RF generator. Peaks in the excess power were seen at frequencies of 81.9 and 365.6 MHz. Radio-frequency signals have also been detected within 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.[12] RF emissions in the 400-800 MHz and 79-81 MHz ranges were seen by scientists at ENEA.[13]

Letts and his colleagues did experiments in which tunable terahertz EM radiation was shined onto a Pd cathode foil loaded with deuterons.[14] It was created by heterodyning two lasers. The THz frequencies spanned the band in which the optical phonon frequencies for palladium hydride occur. Peaks were found in excess power production, when the THz illumination had the known frequencies for two of the optical phonons. They also observed one peak in power production that was not matched to such a phonon frequency.

Ultrasonic irradiation has been used in several LENR and other experiments. One ultrasound experiment reportedly produced conventional deuteron-deuteron "hot" fusion in liquid media. That topic has been very controversial.[15] 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 transient hot plasmas.

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 to stimulate LENR on and in thin foils of various metals for about two decades. He reported producing nuclear reactions using both kHz and MHz excitations with 40 W of excess power in one experiment.[16] 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.[17]

The emission of acoustic radiation was measured in only one experiment. Szpak and his colleagues co-deposited Pd and deuterium onto a piezoelectric disk.[18] Such a disk is a reciprocal transducer for sound and electrical signals. In the LENR experiment, deflection of the disk produced voltage signals indicative of the emission of sound in the experiment.

Electric fields have been applied to the active materials in many electrochemical and gas loading LENR experiments. For gas loading, the fields (voltages) usually have been employed 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 fields 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.[19] The morphology of the co-deposited Pd-D materials varied greatly with the strength of the fields. Letts showed more recently that the orientation of a DC magnetic field directly influences the production of excess power.[20] He used a 500 Gauss external permanent magnet. Moving the field direction from parallel to orthogonal to the cathode foil increased the excess power by a factor of about three. Swartz also studied the effects of magnetic fields on electrochemical cells.[21] He found that the field increased the electrolyte resistance, which limited unwanted gas evolution and improved loading of deuterons into the Pd cathode.

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 and other theoreticians involves phonons within cathode materials. That theoretical research might explain the role of incident electromagnetic fields. However, it is likely 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.

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? So, we next consider resonances and resonant interactions in LENR experiments. In the process, we necessarily consider the natural frequencies of atoms, molecules and materials that are a part of LENR experiments, in addition to applied and emitted oscillatory entities.

Q14. *Do resonances of any kind play a role in occurrence of LENR?*

Many physical systems, numerous chemical systems and even some biological systems have characteristic time constants. Hence, they often have characteristic frequencies, if there is the possibility of shifting energy back and forth within the systems. A technically important example is an electrical circuit where energy flows reciprocally between a capacitor and an inductor. A more familiar mechanical example is the pendulum, in which energy oscillates between kinetic and potential forms.

The generation and emission of electromagnetic and sonic waves involves the operation of resonant systems. A resonance is the tendency of an oscillatory system to move with greater amplitude at specific frequencies.[22] There is usually a fundamental resonant frequency for a system, plus resonances at higher (harmonic) frequencies associated with more complex motions within the system. There are reasons, which are rooted in both theory and experiment, for attention to resonances when seeking to understand and control LENR power generation. It is noted that harmonics of frequencies, which may be beneficial to the production of excess power, remain to be studied.

All nuclei, atoms and molecules have characteristic frequencies. They have specific energy levels, the differences between which can result in the emission or absorption of electromagnetic radiation at specific frequencies. Energies associated with nuclear levels span the range from about 1 keV to 10 MeV and beyond. Hence, gamma ray energies up to several MeV have been observed. Energy levels in atoms and molecules are the basis for photon absorption, emission and laser action over the X-ray, ultraviolet, visible and infrared regions and for maser action in the microwave region of the EM spectrum. Vibratory motions of the atoms within molecules commonly fall in the 10^{11} to 10^{14} Hz frequency range. Molecular rotary motions in gases have lower frequencies in the range from 10^9 to 10^{11} Hz.

Most electrical systems and virtually all mechanical systems have resonances. Electronic filters that permit efficient use of the radio-frequency spectrum for mobile phones and other communications applications are resonant systems. Elastic mechanical systems of all sizes have resonances, if the damping of vibrations is not too great. The need for small damping is important. A bell struck in air will ring, but a bell struck under water will be damped too fast to generate a ringing sound. The resonant frequencies of mechanical objects can be affected by varying their size as well as their loading.

Examples of mechanical resonances are common. Movements of structures, as in loudspeakers, can generate sonic and ultrasonic waves, which are one type of mechanical vibration. Smaller and stiffer mechanical systems have higher frequencies. Think of the wing frequency of a hummingbird compared to that of an eagle. Very small resonators in MicroElectrical Mechanical Systems (MEMS) can have high resonant frequencies extending even to GHz frequencies. Objects of ordinary sizes, like bells, have resonant frequencies in the audible range. Tall buildings have low resonant frequencies, and large damping mechanisms are built into them to minimize their bending due to wind and earthquakes.

The earth has two sets of resonances, one electromagnetic and the other mechanical. The first exist because EM waves excited by lightning can be trapped between the surface of the earth and the ionosphere, both conductors. They are called Schumann resonances.[23] Their fundamental frequency is 7.8 Hz and they have harmonics extending to about 60 Hz. The entire earth is a mechanical object, which can deform in a variety of shapes at different frequencies. Oscillation frequencies fall in the 2 to 20 mHz range.[24] Ocean waves and variations in atmospheric pressure drive the excitations, even in the absence of earthquakes.

Our focus here is on the physical, and possibly, chemical systems that are part of LENR experiments, and their resonances. The resonances might be driven by the application of vibratory waves to experiments. Or, they can exist naturally within an experiment. So, there are three possible types of interactions with the simultaneous application of two stimuli, an interaction between those stimuli and the interaction of either of them with some resonance that occurs naturally within the LENR experiment.

It is instructive to consider all of the frequencies that might be applied to a LENR experiment, or exist within it and could interact with any external stimuli. This can be done with reference to Figure 2.[25] It shows the frequency ranges of most of the electromagnetic spectrum and mechanical motions of diverse types. The lowest mechanical frequencies are a small fraction of 1 Hz. The highest mechanical frequencies are in MEMS devices at about 10 GHz. Mechanical frequencies are possible in LENR experiments. The cathode and the entire experiment have resonant frequencies, as do any mechanical object or system. Cathodes can oscillate in several modes with different mechanical excitations and motions. They include bending, twisting and volume changes. Such variations generally occur at very high frequencies, depending on the geometries and materials of the cathode. For example, the mechanical resonances of a small metallic object, like the cube of Pd 1 cm on a side that melted in a Fleischmann-Pons experiment in 1985,[26] fall near 100 kHz. It has not been determined whether any such mechanical oscillations occur in LENR experiments.

Other mechanical mechanisms might also be important. The audio range extends from 20 Hz to 20 kHz, with the ultrasonic range reaching more than three orders of magnitude to higher frequencies. Phonon frequencies, the collective motions of atoms and molecules within solids, can have frequencies as high as about 10^{14} Hz. In principle, they can extend to very low frequencies, but most of their features are in a range of about three orders below the maxima. The atomic and molecular motions within solids are different than the oscillations at their surfaces. Vibrations within molecules have similar frequencies, mostly in the THz range. The rotations of molecules in gases exhibit frequencies spanning a range of about 100 below the range of molecular vibration frequencies. They might have little to do with mechanisms in the solids or liquids of electrochemical experiments. However, they could play some role in gas loading experiments. There are other possible resonators not shown in Figure 2. Non-diffusive phase transformations, such as Martensitic Transitions, can occur quickly in some solids. Very little energy separates the two phases, so it is possible to have oscillatory lattice structures over a range of frequencies, depending on heat transfer.

In principle, resonances relevant to LENR experiments, and to future commercial power generators, can occur at any of the frequencies shown in Figure 2. The highest frequencies involve nuclear energy levels. Hence, insofar as LENR truly involve nuclear reactions, either in one- or two-step processes,[27] those energies are relevant to understanding LENR. X-rays have been observed in some experiments. But, X-ray and ultraviolet frequencies have yet to play much of a role in LENR experiments. Visible laser radiation and THz radiation from heterodyning two lasers with similar frequencies have been found to stimulate the production of excess power. Phonon frequencies play a role in several theories about LENR, as already noted. Ultrasound has been applied to several electrochemical experiments, and sound has been measured in one experiment. There has been little attention to the possible high-frequency mechanical vibrations of the cathodes in electrochemical experiments. It is noted that Letts and Cravens, and also Mizuno, found evidence for diurnal variations in the excess power from LENR experiments.[28] They occur at a frequency far below those shown in Figure 2, specifically at 12 microHz.

A fundamental point, evident from Figure 2, is that, at most frequencies below the THz range, there are two or more vibratory mechanisms. That raises the possibility of their interactions, which might influence the production of LENR or the redistribution of products from such reactions. If there are sharp frequencies within an LENR experiment, whether applied or natural, they will interact strongly when their resonant frequencies overlap. If a system is driven at one of the resonant frequencies, even small excitations (pushes) can build up large amplitudes (as with a child on a swing). In that case, large oscillations could be produced.

The interaction of two resonances at specific frequencies can be very large. If either of the oscillations influence the production of LENR, the achievement of a resonance might be important in triggering and maintaining excess power production. If one or the other of the resonant frequencies varies with time during a LENR experiment, and their interaction is important to the production of excess power, the time history of the output power will be erratic. This has frequently

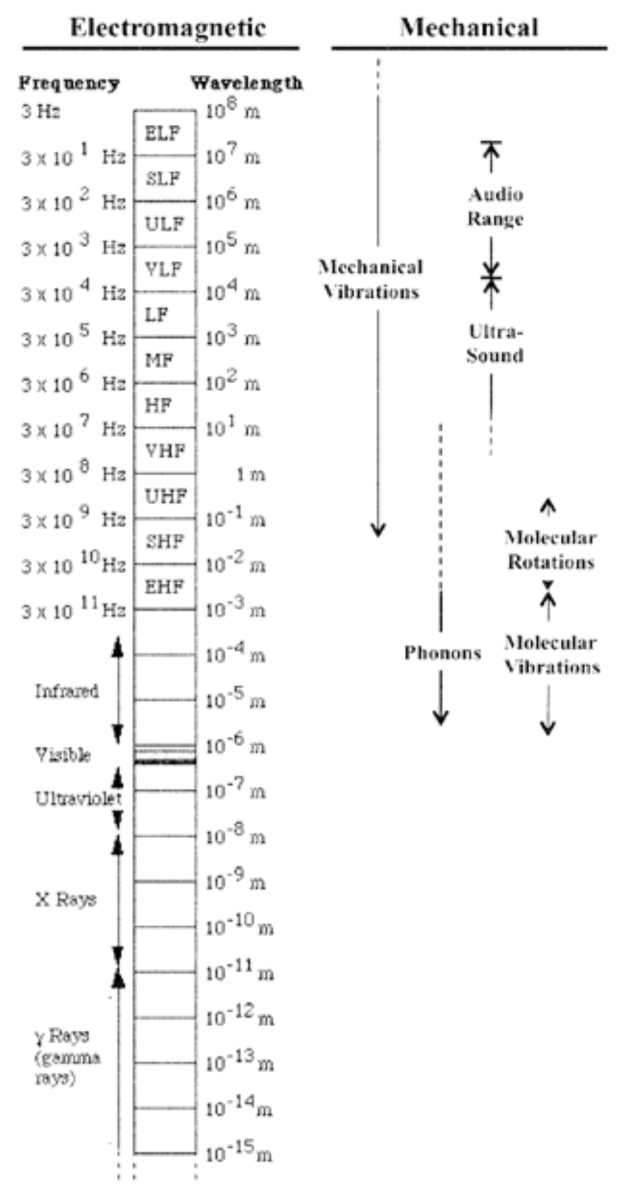


Figure 2. Frequencies of the electromagnetic and acoustic spectra, and the range of mechanical vibrations of various types.

been observed. The often-wild variations in production of excess power might be explained qualitatively by the need to match oscillations to produce a required resonance. If one of the oscillation frequencies were constant, but the other one varied due to some change within the experiment, achievement of a matched resonance and production of LENR would change, either improving or becoming worse. If both oscillation frequencies were variable, staying on resonance would be problematic, possibly hit or miss. If a resonance is driven by an effect spanning a broad frequency band, then there will be less sensitivity to changes in its frequency. Variations in loading would influence mechanical resonances within cathodes. The main point is, if production of LENR depends on existence or overlap of resonances, their variation with loading or any other factor, might lead to irreproducible, uncontrollable and unreliable power generation.

Whether there are one or two resonance conditions operating in any LENR experiment, each has associated with it a wavelength. It should be remembered that unusual phenomena occur in physical systems when wavelengths match the dimensions of some part of an experiment. That is a basic reason why the properties of nano-materials are different, and often more useful, than the same materials in larger pieces. Whether or not matching of wavelengths and geometrical dimensions plays any role in LENR experiments remains to be determined.

Another fundamental consideration about resonances in systems concerns the possibility of reciprocal actions. An antenna resonant at some electromagnetic frequency will both emit (transmit) and absorb (receive) the frequency efficiently. So, it can be asked if such a situation can arise in an LENR experiment. Specifically, would efficient absorption and enhanced production of excess power at some radio frequency, as Bockris and his colleagues found,[11] indicate that emissions at the same frequencies ought to be sought as a measure of how excited the system is at any point in time?

There has been much concern over impurities in LENR experiments, and whether or not they can be detrimental or beneficial. They might do anything from poison the materials to prevent them from hosting LENR to enabling the production of nuclear active regions to actually participating in LENR. In a somewhat similar fashion, there are "impurities" on the signals into and out of any LENR experiment. Noise signals of small amplitude ride atop virtually all electrical and other signals. Generally, they span a broad frequency range. Although small, they can, in principle, drive resonances that occur within the noise spectrum. The noise in electrochemical systems has rich features,[29] but these have yet to be considered in LENR experiments.

The determination of whether or not resonances do play a role in the basic mechanisms of LENR, or in the increase of the rates at which LENR occur, or even in the control of those rates, should be a priority. If resonances are significant for any part of the production of LENR, knowledge of which resonances occur and how to control them will be important. If there are two resonators that have to be frequency matched, their determination and control will also be significant scientifically and, especially, commercially. The relative importance of oscillations intrinsic to materials and those associated with application of external fields remains to be determined.

We now turn to three features of the production of energy by LENR, all of which are fundamental to its eventual commercial viability, namely reproducibility, controllability and reliability. Their importance can be appreciated by consideration of an automobile or HVAC system without high performance in all of these areas.

Q15. *What are the reasons for the lack of reproducibility in many LENR experiments?*

Reproducibility is commonly and sensibly taken to mean that, if a particular experiment is redone properly, the results will be repeatable, that is, close to what was originally measured. Reproducing an experiment means that the equipment (in and around an experiment), protocols (procedures and practices) and materials (fuels and others) are either the same, or sufficiently similar, in the key features that determine the outcome of the experiment. Hence, achievement of better reproducibility requires careful attention to everything that goes into, and is done before or during an experiment. Reproducing an experiment is easier if it is done in the same laboratory as the initial experiment. However, the reproducibility that is most meaningful is that between laboratories with different scientists and organizations. Related questions are what most controls the reproducibility of LENR experiments, and what is needed experimentally to achieve full reproducibility?

There are two major reasons why experiments are difficult to reproduce, in general, and especially in a new field where the key variables are not known adequately. The first is the difficulty in matching the setup and input factors. The second is the natural tendency of scientists to vary these factors, either because they think they have a better idea, or because they do not have similar equipment and materials. Some of the factors already discussed above must be responsible for the early and remaining problems with lack of reproducibility in LENR experiments. Variations in seemingly identical experiments, as well as changes during an experimental run, have proven to be major problems in the field. They must be due to lack of knowledge of the conditions necessary for the production of LENR and ignorance of the details of material requirements, which are almost certainly key to LENR.

Reproducibility is so important, and so challenging for LENR experiments, that it has been continually discussed in the literature and commentaries on the subject. Reports on specific experiments have cited the percentage success rate, that is, the fraction of a group of experiments that give excess heat or some other evidence of LENR. They are widely scattered in the large literature on LENR experiments. The topic of the reproducibility of LENR experiments deserves a new study and report. Here, we will cite only one paper from a decade ago. Letts and Cravens wrote: "The thermal response of the cathode is typically 500 mW with maximum output observed of approximately 1 W. The effect is repeatable when protocols are followed and has been demonstrated in several laboratories."[9] This is one of several published assertions about the good reproducibility of some experiments.

Variations in the chemical makeup of the experimental equipment can introduce inconsistencies. However, good control over experimental equipment is usual, and it is unlikely that variations in apparatus are responsible for the irreproducibility of many LENR experiments. If the same equipment is used by the same scientist in the same laboratory, there remain two candidates to explain the lack of reproducibility, protocols and materials.

The protocols in LENR experiments include what voltages are applied at what times and which measurements are made when. It is possible to automate entire protocols, including additions or removals of electrolytes during the course of an experiment. A computer program, with no variation from run to run, could drive the entire experiment. Complete computer control is not commonly done, which leaves open the possibility that variable human participation in the protocols is responsible for variations in experimental outcomes. So, it is desirable to remove this possibility by a series of experiments without human intervention, once the experiment is set up and the computer programmed. However, it is not expected that differences in hands-on participation by scientists can account for all the experimental irreproducibility.

If it does turn out that protocols are not the main suspect for irreproducibility, materials are left as the prime candidate. The experience at SRI International is directly relevant.[30] Pd from a wide variety of sources, treated in diverse ways, was subjected to tests at various temperatures and many different additions to electrolytes for loading of either protons or deuterons. Success in loading of hydrogen isotopes and the production of excess heat varied widely. A more recent article, also from SRI International, deals with the topic of replication of LENR experiments.[31]

It is possible that low levels of impurities within the solid materials in an experiment are basic to the outcome of LENR experiments. This could be the case because the impurities create conditions needed for LENR, or because they catalyze the heat-producing reactions, or even because they participate in the reactions. It is very expensive to measure accurately the quantities of low-level impurities in the materials that go into and come out of an experiment. So, few experiments in the field have done a defendable job of assaying impurities that might influence or even determine the outcome of experiments.

The Naval Research Laboratory was unable to produce excess heat with pure Pd cathodes in over 200 experiments. However, they had some indications of heat production with old Pd materials that contained Pt and Rh as impurities. That observation led to experiments with Pd alloys, which contained 10% Rh. Those cathodes gave significant excess heat in 6% of 61 experimental runs.[32] The *composition* of cathodes is clearly important to the production of power by LENR.

Work at ENEA showed quantitatively that the production of excess power depends sensitively on fine details of cathode *structures*.[33] Violante and his colleagues discovered that Pd cathodes, which they manufactured, were more likely to give excess heat if they had surface roughness in the range of 10^6 to 10^7 m^{-1}. They also found that having dominant (100) surface crystal orientations favored the production of excess heat. These findings encourage a series of experiments in which metallurgical techniques are used to insure the correct crystal orientation, and subsequent ion bombardment or other surface treatment methods are employed to produce roughness with favorable spatial frequencies.

Even if materials with well-known composition and structure, and also uniformity, were available, reproducibility of LENR experiments is not guaranteed. Fortunately, there are systematic approaches to the problem of reproducibility. One of them is to obtain good statistics on experimental behavior by running large numbers of nearly identical experiments and using as many time-dependent diagnostics for each as is reasonably possible (affordable). Having many measurements for numerous runs would permit various types of statistical analyses. If any of the experiments gave excess power for at least some of the time during their operation, the analyses could point to what is different and useful about them. Remember the many materials tried and numerous tests made by Edison before a reliable filament for light bulbs was discovered.

Multiple parametric experiments can be run serially or in parallel. So-called matrix experiments, in which many experiments are run simultaneously, with one or two parameters being varied between the different experimental setups, can be very valuable. However, they are impractical (too costly) for complex experiments that require expensive equipment. Parametric variation experiments with such equipment must be done sequentially, preferentially in the same apparatus, if it is stable over time and use. Sequential experiments can also be conducted in different apparatus. At this time, operation of many small and relatively inexpensive setups with simple but adequate diagnostics should be very useful for empirically improving reproducibility of LENR experiments, even before full understanding is achieved. The prospect of running multiple LENR tests simultaneously in the same or very similar conditions is attractive. More discussion of parametric experiments, some specific to LENR, follows Question 18 below.

Understanding, that is, having a theory that is clear and well tested, should also solve the reproducibility problem. But, that approach contains a Catch-22 in that the experiments needed for adequate testing of a theory might be problematic, if all of the relevant parameters and their values are not specified by the theory being tested. The situation can be imagined as similar to a system of roads. If a person starts at a point that has no connection to the desired goal, there is no hope of getting to it. But, even if there is a connection between the starting point and the desired destination, there are many forks that will lead off to places other than the goal. Some of the "topography" is known for LENR, such as high loading for electrochemical experiments. But, key guidelines for achievement of reproducible excess power in various experiments are still missing.

Before leaving the topic of reproducibility of LENR experiments, it should be noted that there has been little attention to *quantification* of whether or not excess heat or some other evidence for LENR has been observed. The question, yes or no, is part of the important subject of "binary classification." That topic is critical to medical testing for questions about whether or not a person has cancer or some other malady. If heat, radiation or other effects occur at low levels, there is naturally a question of whether or not an experiment produced LENR. That decision is commonly the opinion of the experimenter. Usually, there are not enough runs to achieve statistics adequate to apply the common 3σ rule. Then, an effect is considered present if its magnitude is more than three standard deviations (σ) of the noise in the measurement system above the average noise level.[34] No LENR experiments have come close to being run enough to apply the detection methods that go by the name Receiver Operating Curves.[35] The classification challenge is toughest for heat data. Not only are there the normal statistical considerations, but sometimes small levels of LENR power production are not distinguishable from power due to chemical reactions. In general, there should be more attention to measures of reproducibility, beyond subjective determinations of success or not, and to distributions of those measures.

In summary, not all of the key factors for the production of LENR are known, let alone adequately controlled. Hence, it is difficult to replicate experiments, even within one laboratory and, especially, between laboratories, even if they seem to be similar in their construction and operation. Despite this fundamental challenge, the problem of imperfect reproducibility of LENR can be systematically confronted. This requires two things, a serious and adequately funded attempt to have similar equipment and procedures, and the use of very well characterized materials. Both the composition and structure of materials have to be known in detail before and after experiments.

Lack of assured reproducibility is both a scientific and practical problem for LENR. And, it still figures in the unwillingness of the broader scientific community to accept LENR as a legitimate field of science. It can be noted that, even after more than a half century of dramatic industrial success in a multi-billion dollar industry, the production of integrated circuits does not produce yields of 100%. Achievement of even good reproducibility will speed acceptance of the reality of LENR, even in the absence of full understanding. So, reproducibility remains a critically important goal. But, it alone does not guarantee the development and success of commercial LENR power generators. Control of such systems is also mandatory.

Q16. *What are the control parameters for production and variation of excess power?*

Reproducibility is a prerequisite for control of the production of power and energy by LENR. But, these two topics are not the same. Reproducibility has to do with getting the same results when the same actions are executed. Controllability deals with the ability to turn on, turn up, maintain, turn down and turn off the production of power. It is a recognized part of the commercialization of LENR.[36] Controllability requires and goes beyond reproducibility. The engine in an automobile provides a familiar example. That a car starts every time transportation is needed is insufficient. It is necessary to be able to willfully vary the speed of the engine and its output power in order to be able to drive properly.

Fine control is not required for all applications of LENR. For example, the production of warm or hot water can be accomplished for some applications by more-or-less steady power output. In this case, the ability to turn on and off the LENR power production is still needed. Most applications of LENR for production of either heat or electrical power will require more complete control, either manually or by a computer. A feedback loop might be needed to maintain constant output power from LENR generators, as is the case for some present power systems. Maintenance of the desired temperature in a room is a common example of control by feedback.

The vast majority of "successful" LENR experiments, that is, those that produced excess heat, were not controllable in the sense required for commercial products. Most of those experiments used electrochemical loading, for which small amounts of impurities can influence conditions on the cathode surface. The controllability of gas loading experiments is a central issue now that companies are striving to develop LENR systems for sale. So, controllability is simultaneously a critical scientific question, largely for electrochemical experiments, and a practical question, especially for gas loading developments. But, controllability is needed for both full understanding and commercial units.

It seems certain that the control parameters for electrochemical loading and gas loading will be different. Neither of those types of controls is in place, a major limitation on progress in the field. The electrochemical experiments with the greatest control now sometimes involve irradiation with laser light of the surface of an operating cathode in a cell. That can increase the level of excess power. However, even this control parameter is currently inadequate. That is, by itself, irradiation does not suffice to control LENR electrochemical experiments. Application of proper voltages and currents is also required.

Several parameters have been considered and exercised for triggering (initiation) and control of electrochemical and gas LENR systems. They include many of the factors shown in Figure 1. Prominent among parameters discussed for control of LENR generators are variations in temperature, pressure, electric, magnetic and electromagnetic fields, and sound. Static or continuous variations, and impulsive agitation using voltages or other means, are being considered. Combinations of stimuli might prove to be very effective. It must be remembered that control of LENR power production can be exercised at any step in a multi-step process leading to the occurrence of LENR.

It is widely accepted that the earliest commercial LENR generators will employ gas loading. Hence, we now focus on that challenge. Arata and Zhang demonstrated the ability to produce heat by simply pressurizing a chamber filled with ZrO_2-coated nanometer particles of Pd.[37] Pressurization was the only control parameter. The experiment produced excess heat for hundreds of hours when pressurized with D_2, but not when filled with H_2. He-4 was produced during the D_2 runs, but not when H_2 was used. Whether or not there was a means within the Arata-Zhang chamber to turn H_2 molecules into atoms was not revealed. The employment of catalysts, such as are used in the petroleum and related industries, to separate H_2 or D_2 molecules into atoms, might also be useful for promotion of LENR in gas loading experiments.

Considerable unpublished development work on gas loading is now in progress in small companies. It sometimes involves the generation of plasmas for both the initiation and control of power production. There is low probability of any nuclear reactions involving the protons within H atoms or the deuterons in D atoms. In those cases, the lone orbital electron does not permit close nuclear approaches. That is, only ions (protons or deuterons) might be effective for producing LENR.

The creation of plasmas with low temperatures is relatively easy with both steady and pulsed voltages. Hydrogen or deuterium plasmas with temperatures of a few thousand degrees K will consist of some molecules, some atoms and very few ions (bare protons or deuterons). At a temperature of 10,000 K, less than 1% of the particles in a hydrogen plasma are bare protons.[38] The numbers of H atoms and protons are equal at temperatures near 15,000 K. Getting almost 100% ionization of H or D requires temperatures of about 35,000 K. The potentially damaging effects of such temperatures on active materials in LENR experiments and generators are noted below. Testing of the idea that H or D ions are needed to produce LENR can be done by varying the plasma temperature. That is possible by controlling the electrical power fed to the chamber with the gas and active materials. It is likely that, if plasma properties are useful control parameters, there will be significant hardware and software associated with practical LENR generators to control plasma characteristics.

The means of control of E-CAT systems in two recent tests varied significantly. During the tests in 2012 and 2013, a varying electrical waveform was used to keep the output thermal power under control.[39] The devices were heated by electrical pulses. Figure 3 shows the time histories of the input electrical and output thermal power. A square wave was used for control, the magnitude, duration and spacing of which were specified. It is seen that, after the input power was turned on, more power was being consumed than was produced in Phase I, a situation that reversed during Phase II. Then, after the input power was stopped, the output power declined in Phase III. The shape of the output power curve is very significant. During heating, it is concave upward, opposite of the behavior of a heated resistor. That indicates a potential run away situation. The character of the output power curve during cooling is concave downward, again opposite the behavior of a normal hot object, which cools quickly at first and more slowly later. This controllability has a highly desirable feature. Failure of the input heating power system would lead to prompt shutdown of LENR power production. Hence, meltdowns would be avoided, a good feature even with the absence of radioactive materials in a LENR reactor.

In the more recent E-CAT test during 2014, the electrical input was steady, when maintenance of a fixed output temperature was desired.[40] Temperature control was achieved by electrical power variations. When the input power was increased from 800 to 900 W, the temperature rose from 1260°C to 1400°C in about six minutes. Simultaneously, the output power increased by 700 W. The speed with which changes in output power from LENR generators can be made is clearly important. Again, consider an automobile where near instantaneous responses to stepping on the gas pedal is needed for safe driving.

In contrast to the control of E-CAT systems with electrical currents, either square wave or steady, Defkalion Green Technologies achieved control of its R5 reactor by application of fast pulses to produce plasmas within their system. That is, while the E-CAT apparently has protons stored in it within compounds that are part of the fuel, the R5 system produced protons by dissociation of H_2 molecules in plasmas. The use of plasmas to trigger and control LENR generators has two worrisome aspects. Their generation is not energy efficient, since power goes into ionization and heating of the ions and electrons. Further, plasmas produce both particles and radiations, all of which might not be useful. That is, bombardment of the solid fuel within a LENR generator with ions, electrons and electromagnetic radiation might damage the fuel, and degrade long-term reliability.

The situation for controllability of LENR is somewhat similar to that for reproducibility. Neither is satisfactory now, but there has been progress on both. There are many reported cases, when some change has been made in an operating LENR experiment, such as increasing the input current, and an associated change in excess power has been observed. However, this is far from the control that is needed for practical applications of LENR. It is not possible now to say when the full control of LENR experiments, which is necessary for applications, might be achieved. It is conceivable that some significant changes in generally unexplored experimental parameters might be needed, such as the addition or removal of compounds in an operating LENR cell. If that turns out to be the case, the situation would be reminiscent of the neutron-absorbing rods used to control the output of fission reactors.

It might turn out that there are multiple ways to initiate and otherwise control the output of LENR generators. In that case, the question will be which of them are most useful scientifically and practically. In a car, control can be achieved by varying the petrol input to the cylinders, rather than variation of the air intake, although both are commonly synchronized. In order to determine the most effective means of control of LENR, it is desirable to have and use measures of controllability. Speed and precision of the response to control parameters are two common measures.

There is one more characteristic of potential LENR generators, beyond reproducibility and controllability, which is necessary for their commercial success. Such power sources must be reliable.

Q17. *What are the prospects for long-term reliable energy generators based on LENR?*

Reproducibility has been a concern since the earliest days of LENR (then "cold fusion"). Controllability has come forward as a major goal in the past few years as companies seek to develop products. However, the reliability that is needed for successful products has gotten relatively little attention. Imagine a generator that would work well and be fully controllable when purchased, but would begin to be inoperable, or even merely unreliable, within a few weeks. Such a product would rapidly get a bad reputation and fail in the marketplace. Generators must be reliable.

Companies that offer LENR thermal or electricity generators for sale must be able to prove that they are reliable, mainly by offering test data taken by competent and reputable organizations. Such stringent requirements might be relaxed for the initial products, which will be of interest to early adopters who want experience with such generators, even if they are not reliable enough for general consumer use. But, LENR generators that will go into homes, offices, factories and field installations must have reliability sufficient to make them better than current generators. Small, kilowatt electrical generators, which are powered by gasoline, are widely available. They cost a few thousand USD and have one to five year warranties. LENR generators must have similar performance at lower capital or operational costs to be competitive. The new LENR generators could cost about the same, but still capture market share because of other features, such as light-weight fuels, long times between refueling or the absence of noise and exhaust fumes.

What has to be done to establish the reliability of LENR heat and electricity generators seems clear. First, fuel of a proper composition and structure has to be provided to a LENR generator. This might be done by insertion of one charge of fuel prior to operation, as in the most recent E-CAT test. Or, if maintenance of the necessary conditions of the fuel cannot be maintained for the duration of operation, then the fuel must either be reconstituted or new fuel inserted. Renewal of the fuel in place might be possible, but it could require two elements within a LENR generator, one to continue operation while the fuel in the other is renewed. Or, if the application permitted, a single unit generator might be acceptable, if it were shut down during normal operation for long enough to reconstitute the fuel. Provision of fresh fuel to a LENR generator during operation seems possible. Consider the operation of coal-fired electric power stations, in which tons of solid coal are supplied during steady operation. In short, the LENR generators have to be

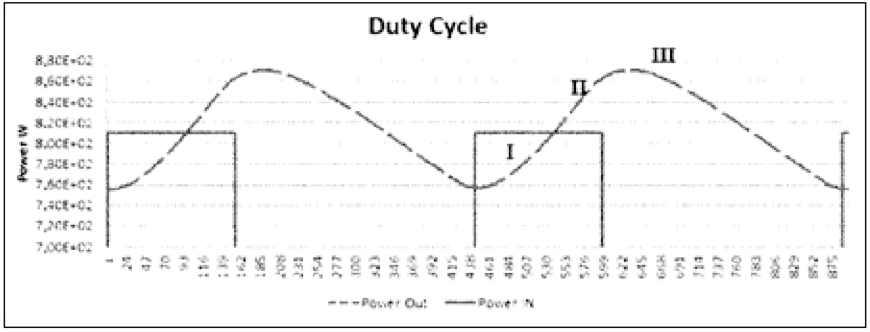


Figure 3. Temporal variations of E-CAT input power (square waves) and output power (dashed curve) for two heating cycles.The horizontal axis is from 1 to 875 sec, and the vertical axis is from 700 to 880 W.

designed so that there is always active fuel within them when their operation is needed.

Given proper engineering design for reliability, serious testing of LENR generators is also needed to establish their reliability and to reveal any problems that limit their proper operations. Long-term tests under various conditions of temperature, moisture and loads are needed. The same is also true of tests to establish the safety of LENR generators, which will be discussed in the third paper in this series. Measures of the reliability of LENR generators are needed, similar to ways to measure the reproducibility and the controllability of LENR power sources.

Among all the "ilities,"[41] reliability is both necessary and essentially impossible to estimate at this time. The duration over which any energy source works properly depends fundamentally on two factors, fuel and the maintenance of required conditions for use of the fuel to produce power. Loss of either of these required conditions usually terminates energy production. We tend to think of running out of fuel as the more likely problem. However, if it is necessary to maintain exquisite control over the conditions, especially lack of contamination, for large surface areas in LENR sources, then fuel might not be the most worrisome and demanding limit to their reliability. This is an enticing engineering problem. Its solution will become clear only as more is known of the basic mechanisms for LENR, and some early engineered units are made, operated and diagnosed. Tradeoffs between the level of operations and the lifetimes of LENR generators can only be determined by tests. Running a system hard often shortens its lifetime.

The topics of LENR reproducibility, controllability and reliability are all complex. There are numerous ways to go wrong in the design of an experiment or commercial LENR generator. The factors considered—namely the equipment, protocols, materials, scientists and their organizations—all offer options for failure. However, there might be several ways to achieve good performance for LENR generation of power. The situation for the practical use of LENR might eventually prove to be like that for internal combustion engines. There are many options, rotary turbines or reciprocating motors. They vary widely in size and power, and burn a variety of fuels. Of course, current engines are the result of a century of innovations and refinements, in contrast to LENR, which remains to be proven to be practical.

We next turn to two related subjects, types of LENR experiments and tools used in them. There are many reasons to perform additional experiments on LENR and to use additional experimental tools in the experiments. Such work can both advance scientific understanding and also provide information useful to development of reproducible, controllable and reliable products. Additional experiments are considered next, followed by consideration of the use of new tools for the laboratory study of LENR.

Q18. *What parametric variation and other experiments might be done to advance LENR empirically?*

Parametric experiments, in which one variable is changed either continuously or continually, are valuable scientifically. They can help determine the location and width of regions in the multi-parameter space where LENR will occur. Such experiments have the potential to show the relative importance of different parameters and how rapidly results, such as excess power production, will vary with the value of a parameter, such as the concentration of some material.

Early in the field, parametric combinatorial LENR electrochemical experiments were performed by Fleischmann and Pons at the University of Utah.[42] They had at least 15 cells running simultaneously. Their goal was to locate the best operating points for the production of excess power. A variety of effects was measured, especially strong evidence for tritium production.[43]

Currently, Passell is conducting as-yet unpublished plasma loading experiments using deuterium and materials known to absorb it.[44] Over the past seven years, he has used about 150 sealed tubes for experiments, one of which ran for four years. The gas pressure, temperatures, voltages and pulse repetition frequency have been varied. About 20 electrode materials were used. Passell is using detectors to search for energetic radiation from activated cathodes.

There is considerable literature on combinatorial materials experiments[45] and their design.[46] Such sets of simultaneous experiments are widely used in material science to find the values of parameters that optimize specific properties. In those experiments one or two parameters are varied at different positions on a substrate. They have major challenges. The main one is to insure that everything in an experiment is the same except for the parameter being willfully varied. In some combinatorial experiments, one or two parameters are varied at different positions on a substrate. That approach to materials for LENR experiments has been exercised.[47] It is also possible to have chip-scale electrochemical experiments, which could be run simultaneously in one experiment. There have been some attempts at making small LENR experiments using the Ni-H system on a substrate.[48] They indicated high loading and an energy amplification factor of 3. Given those results, combinatorial experiments might be conducted to obtain a great deal of data on excess heat production in a relatively short time.

Returning to the five aspects of any given LENR experiment, each can be examined for its capability and potential to be varied. In general, experimental equipment is relatively fixed. It can be altered, but usually is not a candidate for parametric variations. Changes in scientists and organizations doing experiments are not really parametric variations, but they are important aspects of reproducibility. The procedure for reproducing experiments done elsewhere, which was established by McKubre and his colleagues at Stanford Research International, is worth attention.[49] Materials and protocols are prime candidates for variation, and we will discuss them in the following paragraphs.

Materials within LENR experiments are commonly subject to parametric variations. In many cases, experiments are varied in a binary fashion. That is, one or another chemical is put into the experiments. Examples include either light or heavy water in electrochemical experiments, and either hydrogen or deuterium gases in gas loading experiments. But, it is also possible to vary the composition of the water or the gas smoothly from one extreme to the other. The motivation for such experiments is related to Question 14 above. It might turn out that some experiments will work only with compositions at the extremes, that is, relatively pure H or D compounds. In that case, it would be valuable to determine the amount of the second compound which can be tolerated, and how the production of excess power falls off with the introduction of the second compound. Significantly, the fraction of H_2O in D_2O influences the cost of the heavy water.

The types and concentrations of the ionic compounds in an electrolyte are also available for smooth variations. LiOD at a concentration of 0.1 molar is often used as the electrolyte in experiments with Pd cathodes. Measurements with some variations in concentration have been performed.[50] It seems that more detailed parametric variations of the concentration of the electrolyte should be made. As with the relative amounts of H and D in both electrolytic and gas loading experiments, the amounts of LiOD and LiOH at any given total molarity might be varied systematically.

For both major types of LENR experiments, it is also possible to parametrically vary the composition of the solid materials, either cathodes in electrolysis experiments or various materials in the forms of rods, plates, powders, etc. in gas loading approaches. Alloy cathodes have been used in some LENR experiments, but here also, there have not been tests with a significant number of electrodes with compositions varying stepwise over some range. It is recognized that variations in the composition of materials generally also result in changes in structures. Hence, such parametric studies are complicated, requiring the separation of effects due to composition from those due to structure. If such distinctions could be achieved, they might be instructive.

It was found early in the history of the field that high values of loading, the ratio of deuterons to palladium atoms in electrochemical experiments, are critical to the ability to produce excess power.[51] This is a case where both the composition and structure of the cathode materials change together and significantly during an experiment. The composition is measured from the resistivity ratio. A few attempts have been made to determine the structure of cathode materials during electrochemical experiments by using diffraction of hard X-rays. In one of them, structural data was obtained in real time, but the production of excess heat was not achieved.[52]

Turning to protocols, which determine what is done to an experiment from its beginning to the end of a run, there are again many candidates for parametric variations. The time variations of the magnitude of applied voltages and currents are major parameters for electrochemical experiments. These parameters have been exercised in many experiments, for example, by step-wise increases in the applied current. That is how it was learned that there is a threshold in current density for production of excess power.[53]

Swartz found that there are values of the input power to LENR experiments where the production of excess power and other effects are increased.[54] He calls the ranges of values "manifolds," within which are located maxima termed "Optimal Operating Points" (OOP). That is, the dominant parameter for control of LENR is the input power. On one side of the OOP, the degree of loading of the cathode with deuterons is not optimum. One the other side of an OOP, energy is wasted in production of more electrolysis than is needed. The positions of OOPs for various measured parameters challenge theoreticians to explain them.

There are many options for parametric variations in LENR experiments that have not been exercised, or have been given inadequate attention. Rapid temperature changes were seen in a few experiments to increase excess power production. Their magnitude and time scales have not been thoroughly studied. The role of changes in fluxes within electrochemical experiments is recognized, but there are many more experiments that could be done on the magnitude, rates and limits of such changes.

Opportunities for parametric variations of applied fields abound. We have already noted the scanning of incident THz radiation frequency and its dramatic effect on production of excess heat.[14] The intensities of incident electromagnetic radiation of any frequency are candidates for variation. So also are the strengths and orientations of electric and magnetic fields. It would be desirable to do more experiments where the frequency of electromagnetic illuminations was scanned over the very high natural frequencies of the materials in LENR experiments. The use of "chirped" pulses of electromagnetic, sonic or mechanical excitations does not seem to have been done in LENR experiments.

The discussion above, about matching oscillation frequencies within LENR experiments, can be addressed experimentally. Using different applied electrical frequencies is relatively easy. The same can be said of ultrasonic frequencies. Varying the mechanical resonances of cathodes can be done, but not conveniently.

The number and ranges of parametric variations for materials and protocols are daunting. Thousands of experiments would be needed to systematically vary each of the potentially relevant parameters, while holding the rest as constant as possible. It seems unlikely that theory will be able to provide the answers to questions on what parameters are most sensitive, that is, most worthwhile varying, and what specific ranges of values would prove to be optimum or near optimum. Hence, large and long experimental campaigns will be necessary to determine the best parameter values for production of excess power or transmutations. On the positive side, additional measurements make possible more correlations between parameters, and they might help elucidate the basic mechanism(s) that cause LENR.

Q19. *What experimental tools should be employed for LENR experiments?*

It is generally true that the closer an experiment is examined, the more can be learned. The "closer" can involve higher spatial resolution for images, faster measurements of voltages or other parameters, and higher frequency resolution in spectra. This observation is true of most experiments, and certainly applies to LENR. Hence, we are led to examine what has been, and might be done, in assessing the course and results of LENR experiments.

It seems certain that important new information on the mechanisms of LENR will be learned by the application of new tools to the field. A remarkable variety of experimental techniques has already been applied to LENR experiments. However, there is much room for further use of tools that have been used only a little or not at all. Many are expensive, but there are also simple and inexpensive tools that will be new to LENR experiments.

There are three classes of opportunities for improving LENR experiments. The first is to use more and better "input" equipment for the conduct of experiments. Good equipment generally has been used to both set up and power LENR experiments. But, there is always the possibility of using better designed and controlled equipment to make an experiment operate. An improvement would to use either new equipment, or already-employed equipment in new ways. Examination of the blanks on the input side of Figure 1 gives possibilities for totally new excitations. The employment of stronger magnetic fields is an example of something that can build on past experiments which did use such fields.

The second class of improvements is the use of more and better diagnostics for measuring the "output" of experiments. This is a compelling opportunity. There are many types of measurements that could and should be brought to bear on LENR experiments. The more (especially time dependent) measurements that are made during an experimental run, the more data there will be available to correlate with the performance of the experiment, especially its net (output minus input) power and excess energy. Again, Figure 1 suggests possibilities. Recording of the sounds emitted by LENR experiments in both the audible and ultrasound regions should be useful. Measurements with electric and magnetic field probes are also possible, and should be tried to see if they give useful information. There are only a few measurements of radio-frequencies present in or emitted by LENR experiments. More should be done because such high frequencies might be indicative of the time scales of processes that are fundamental to the production of LENR.

The third class of potential experimental improvements involves the materials, chemicals or gases that go into an experiment. If impurities do play some significant role in determining the outcome of a LENR experiment, low level (parts per million and lower) analyses for impurities before and after an experimental run might be invaluable for improving the reproducibility of LENR experiments. Mass spectrometry of the composition of plasmas within either plasma loading or plasma-controlled experiments also seems worthwhile. *In situ* Raman spectroscopy is but one example of capabilities offered by commercial instrumentation, which could give new perspectives on operating LENR experiments. Synchrotron x-radiation can penetrate an operating electrochemical or gas loading cells or plasma chambers. X-ray diffraction and fluorescence data can provide detailed information on the varying atomic structure and composition of the solids in a LENR experiment. The tools of nanoscience should be brought to bear on LENR. Atomic Force Microscopes can provide atomic-level surface structural information before and after, and maybe even during experiments. The use of AFMs is particularly compelling because phenomena in nano-scale regions of a solid material might determine the ability to trigger LENR. Optical interferometers could be used for measurement of cathode displacements and motions during experimental runs.

Approaches to the application of new tools to LENR seem relatively straightforward. Techniques that might be especially productive should be identified, and then incorporated into experiments. This usually involves significant modifications of the experiments. For example, if it is desired to measure X-rays produced in a cathode in an electrolysis experiment, the cell has to have a thin window of low atomic number material, with little electrolyte between the cathode and the window. Similarly, if one wants to perform mass spectrometry during operation of a gas loading experiment, a system must be provided to support the different pressures within the experimental chamber and the mass spectrometer.

In short, a program leading to replication of important LENR experiments with improved instrumentation is needed. Significant funding for LENR experiments will open many opportunities, both technically and in terms of bringing new people with important experimental skills into the field.

3. Theoretical and Computational Considerations

Ultimately, the science of LENR will be put on a solid foundation by both experiments and theories, and, especially, their intersections. That is, it is very unlikely that LENR will be adequately understood solely on the basis of empirical data. Hence, it is worth considering questions about what theoretical work and computations based on theory can contribute to that understanding.

There is a well-known and practiced sequence of steps in the conduct of most experiments, LENR or otherwise. The first is to decide what to do, regardless of the motivation. Then, equipment has to be designed or bought or both, and integrated into a working experimental system. That equipment for LENR experiments includes the container for the experimental materials, the equipment to power the system, and the various measurement instruments. Many tests can be done to insure proper operation and calibration of the entire collection of equipment. Then, in most cases, the experimental materials are prepared and put into the equipment. However, in some cases, they are prepared *in situ*. Whether under human or computer control, the experiment is run using chosen conditions and inputs for desired times.

The employment of new experimental tools in LENR experiments, as noted above, is likely to be beneficial. However, it is difficult to predict the possible payoffs with confidence. Application of new theoretical and computational tools to understanding of LENR might have stronger benefits. There are some basic mechanistic questions that have been approached theoretically and are now being tackled computationally. However, the various current nuclear, solid-state and combination theories, and computational methods applied to them, may not suffice to crack the core riddle of LENR. Other approaches might be useful.

Whatever theoretical tools are used to understand LENR, the overall role of theory, and the several operations for theoretical development, are clear. There are sequential steps for theory, as there are for experiments. First, a concept of what might happen during LENR is required. Then, the concept has to be embodied in a set of equations that describe the outcomes of creating the contemplated conditions, including the energetics and kinetics of the theoretical process. The equations, by themselves, might be interesting, but they are not useful until they are solved numerically. The quantitative probabilities for the LENR process occurring, and the associated energies and rates, can only be acquired from numerical evaluation of the equations. Doing that requires making choices from among diverse algorithms, software languages and computers. Given the capabilities of modern computers, it is increasingly possible to simulate the time variation of the flows of matter and energy in an experiment. That is, numerical experimentation is now an option, but not yet on a par with laboratory experimentation.[55] But, it is increasingly capable.

The overlapping relationships between experiments, theories and simulations are shown conceptually in Figure 4. The arrows indicate the usual sequence of steps. Theories can be developed without reference to experiments, but that is usually not the case. Generally, experiments raise questions that stimulate the development and evaluation of concepts. That is certainly the case for LENR. But, concepts and theories based on them usually cannot be compared quantitatively with the results of experiments. It is necessary to write out the equations based on a theory, and then use them for numerical computations. In the best cases, those numbers can be compared with the results of quantitative measurements. Such comparisons can have different outcomes. If they are poor, concerns are raised about everything from the experiments to the theories to the simulations. If they are good, increased credence is given to the quality of the experiments and the concepts behind the theory. Of course, intermediate cases often exist, where the comparisons are encouraging, but still flawed. Then, more refined measurements and computations are often indicated.

Numbers derived from theoretical concepts have two uses. One is to explain the past and the other is to predict the future. Comparison of theoretical values with the results of earlier experiments is a time-honored process in science, as just noted. But, it is not always possible, since necessary details of past experiments might not be known. And, in the case of LENR, causes of the variations in rates with time are not known. If comparison of quantitative theoretical results with numbers available from experiments can be made, the

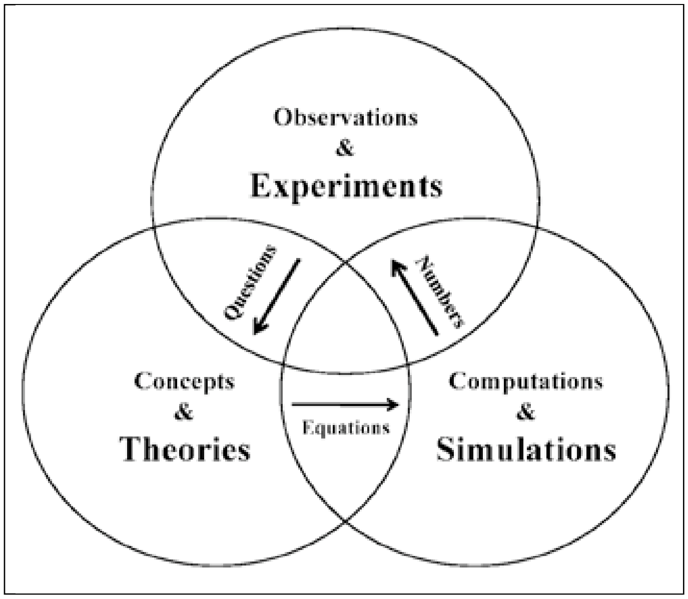


Figure 4. Schematic relationships of experiments, theories and simulations. The arrows indicate the common flow of work from experiment to theory to simulations.

procedure might provide useful insight. The second role of theory and associated computations is in the design of new experiments, which can be done to falsify the theory or add to the likelihood that it contains some useful concept.

After 25 years of theoretical work on LENR, the paucity of quantitative comparisons of theory and experiment is almost an embarrassment to some workers in the field. There have been some attempts to design critical experiments based on particular theories, but these have not proved useful yet. That is, they have neither ruled out any theory, nor provided evidence to support its correctness. In short, developing a theory for LENR is a tough problem, and the mechanisms behind LENR remain contentious and poorly understood. This is frustrating to workers in the field, and to outsiders who look at the experimental data in the field. However, it is not unprecedented in science. About four decades elapsed between the discovery and explanation of superconductivity, for example. Understanding LENR theoretically and quantitatively is one of the best problems now available in physics. It requires major capabilities in solid-state, nuclear and elementary particle physics. Like doing LENR experiments, fully developing a theory for LENR requires a broad set of skills.

Theoretical and computational factors are considered together in this section because of their close relationships. Without ideas and equations based on them, there is no basis for computational simulations. And, without making calculations based on them, concepts and the equations that embody them are usually difficult to compare with data from experiments. In short, theoretical ideas and computational simulations are the yin and yang of quantitative science, LENR included. Together, they interact with the results of experiments to validate concepts and produce information, which might be of use for engineering and other purposes.

The first question in this section confronts the assessment of existing theories about LENR. Then, we consider theoretical rates and energies for LENR. It is not always easy to obtain such numbers from theory. However, they can be obtained from a fully developed theory. Because both reaction rates and energies per reaction combine to give the excess power, it is not usually possible to obtain separate rates and event energies from calorimetry experiments. This section ends with three questions, all of which have a computational character. The first deals with tools that can be used for calculation of rates and energies specific to LENR. Second, there is a question on the computation of materials characteristics and properties, since materials considerations are central to producing LENR. Finally, data analysis and mining are closely related and are considered together.

Q20. *What might be done theoretically to speed the understanding of LENR?*

There are dozens of theories about the mechanisms that produce LENR. Thorough understanding of many of the theories requires advanced (Ph.D. level) training in physics. A review of "cold fusion" theories in 1994 critiqued the many ideas already in circulation.[56] Over three dozen theoreticians had already offered ideas about the mechanism causing "cold fusion," which the authors organized into 20 categories, some of them related. Many of those early concepts have become dormant or modified over the years, and other ideas have been added. Recently, Storms published a qualitative review of 23 LENR theories in seven categories.[57] He is one of the few scientists in the field who has sought to understand most of the theoretical concepts and to evaluate them against both known scientific principles and the results of LENR experiments. Scrutiny of remaining theories is needed. And, since some of Storms' views are controversial, examinations and evaluations of LENR theories by other scientists are needed. This has been done on a piecemeal basis in the CMNS GoogleGroup for some theories.[58] A comprehensive approach to assessing LENR theories seems desirable. It might produce more progress in a shorter time than the continual but uncoordinated development of theories by individual scientists.

There are practical motivations for the examination and evaluation of available theories about LENR. Such an exercise could quickly show the state of development (or lack of development) of various concepts for LENR mechanisms. If the scientists, who have published partly developed ideas, are still active, comparisons of the states of different LENR theories might motivate them to further develop their ideas. Or, maybe other theoreticians would be willing to pick up the development of ideas from earlier researchers, who are no longer alive or active. The main point is that most of the current disconnected approaches to the theory of LENR are running "open loop." That is, there is little evidence of convergence toward the few ideas that are most worthy of attention and funding. Of course, it is the nature of science that an individual researcher can work on whatever they want to pursue within funding constraints. However, having a limited number of LENR theories as a focus might speed the achievement of the desired ultimate understanding. If the mechanisms active in LENR were understood, the scientific development of the field could accelerate. And, importantly, the development of commercial products would proceed much faster and with greater assurance of success.

There are problems associated with the evaluation, prioritization and down-selection of theories about LENR. One of them is the natural tendency of scientists, theoreticians included, to want others to pay favorable attention to their work. Another is the fact that some of the concepts are not clearly documented. And, even if the ideas are clear, the equations embodying them have not been developed. That is true for the energetics and the kinetics (rates) of many LENR theories. Very few theories have been carried all the way to numerical evaluation. This prevents quantitative comparisons of theories with each other and with the results of experiments. Another challenge is due to the fact that many of the ideas are still evolving because of recent activities of their originators. Hagelstein has stated that he has developed and discarded many ideas of the course of a quarter of a century of theoretical work on LENR.

If this author were to manage a program, which included theoretical and computational LENR research, he would want to start with a tough evaluation of available theories on LENR. Imagine a two-dimensional matrix with all active LENR theoreticians listed on both axes. The top-to-bottom listing on the left would treat the scientists as the promoters of their own ideas and results based on them. The left-to-right listing across the top would cast the same people in the role of critics of other theoretician's ideas and results. Each proponent would be asked to list the state of development and the strengths of their approach. Each critic would be requested to summarize their concerns about the theories from all other theoreticians. The advantage of using theoreticians, who are already active in LENR research, is two-fold. They already know a lot about the topic and they are motivated to advance the science of the field of LENR.

This radical approach to evaluating LENR theories could be impractical. The involved people might be hesitant to tout their own results in cases where they are not very complete. And, most people would not like the role of critic, if others were to see their comments. Because of human nature and the readiness of critics from outside of the field to point out problems, the quality of criticism within the field of LENR has not been high, in general. That is as true for experiments as it is for the scrubbing of theoretical developments.

Another operational approach would be to task (and pay!) a group of qualified individuals to thoroughly assimilate the various theoretical approaches and to provide summaries of their status, strong points and problems. Finding adequately qualified scientists to perform such evaluations would be challenging. Many of the prospective reviewers would be reluctant to perform the needed service because of the large and evolving literature that would have to be digested. And, their careers might suffer if they concluded that the study of LENR is a legitimate scientific pursuit.

However the perceived need to examine and evaluate LENR theories might be approached, it seems clear that the first step is to characterize all theories using a common template, and to do so as specifically and even quantitatively as possible. A significant step in that direction was taken by Johnson, S. Chubb and Melich in the *Proceedings of ICCF14*.[59] See Table 1. The theories that were characterized were limited to those presented at ICCF14. But, the table shows the criteria on the top of the matrix that were used to characterize different LENR theories. The list of criteria is certainly not complete, and could be extended to embrace other factors. They include the need for high loading of deuterons (D) into palladium (Pd) or its alloys, that is, the ratio of D to Pd atoms must be near unity. Strong fluxes of D through the surfaces of solids in electrochemical experiments are beneficial to the production of excess power. Theories should address the location(s) where LENR occur, as well as their rates. The question of where LENR occur, either on the surface or in the bulk of materials, is critical and there are data for both possibilities. The fact that the power and some other outputs of LENR experiments vary widely with time is also important, and has not been adequately addressed theoretically. One of the important factors for describing the applicability of any LENR theory is whether or not it can deal with both protons and deuterons. Another question asks if a given theory is consistent with the very small amounts of radioactive materials that result from LENR. The table also shows the wide variety of combinations of approaches exhibited by the various theories. Making a comprehensive and up-to-date compilation similar to this old table could be a significant step toward a broad comparison and evaluation of LENR theories.

The outputs of such an assessment could be two-fold. First, it would be useful to document the case for setting aside some of the theories that continue to be touted by their originators. This would serve to reduce the "noise" in the field. Second, it would also be most helpful to identify quite precisely what has to be done to advance the theories that are not trashed. If such theories and their associated equations could be developed further, then the "signal" in the field would improve. The goals should be (a) to employ the surviving theories to compute numbers for comparison with the results of past experiments and (b) to use the results of calculations to design experiments that will provide critical tests of the basic ideas.

As noted, the thorough evaluation of available LENR theories discussed above is not likely to be palatable to leading theoreticians in the field of LENR. A thoughtful discussion of the role of theory in the field was published by Hagelstein in Issue 108 of this magazine.

Q21. *What are theoretical LENR energies and rates?*

For each reaction, chemical or nuclear, there are a few basic numbers. The first two are the energy of the reaction and the size of the energy barrier that impedes the reaction. The energy change from the initial reactant state to the final product state quantifies the energy that might be realized per reaction. The barrier energy is fundamental to knowing how much energy has to be put in to make a process proceed. That is true of both LENR scientific experiments and expected commercial LENR generators.

The third very important parameter is the rate at which a reaction occurs for a given set of conditions. For chemical reactions, concentrations, temperature and, often, pressure are most significant. For ordinary nuclear reactions, the center-of-mass energy of the colliding partners is the main parameter for determining the reaction cross section. Knowing the barrier energy, and the rate at which it is desired to produce reactions, can give the power that must be fed to a process. Similarly, the reaction energy and the reaction rate enable calculation of the rate at which energy might be generated from an exothermic reaction. The power P at any time is the product of the energy per nuclear reaction E_N and the number of reactions per second R_N: $P = E_N \times R_N$. The number of new atoms (isotopes) produced per second by a particular LENR is the same as R_N.

The equation for power production just above assumes that the LENR are a one-step process. That is, there is no intermediate entity which is first produced, and is then consumed during the LENR. However, there are a few theories about mechanisms for LENR that do involve two-step processes. Takahashi has developed and elaborated a concept in which combinations of four deuterons assemble at a point within a lattice.[60] Then, that cluster of ions undergoes a "condensation" LENR. There are also about half a dozen theories in which the first step is the production of "compact objects." Such theoretical entities have yet to be observed, but were reviewed recently.[61] Compact objects have computed binding energies and sizes intermediate between those of nuclei and atoms. Their exothermic formation does not involve nuclear reactions. That is, they might account for some or all of the power that is now ascribed solely to LENR.

The fact that the compact objects are small means that the nuclei in them can move relatively close to the nuclei in nearby atoms. This shortens the distance over which tunneling must occur to produce nuclear contact and reactions. If there are subsequent nuclear reactions, that is, actual LENR, they might dominate the energy production.

If formation of compact objects is indeed the initial step in the production of excess heat, the total amount of excess energy E_T depends on the number N_C of reactions that form compact objects, the energy E_C released per formation of a compact object, the fraction f_N of the compact object formation reactions that lead to subsequent nuclear reactions, and the energy E_N released per nuclear reaction: $E_T = N_C\{E_C + \Sigma f_N E_N\}$. The summation is over the number of subsequent distinct exothermic nuclear reactions. The values of f_N can range from zero (no secondary nuclear reactions) to unity (when a particular nuclear reaction follows each compact object formation event). This equation can be put on a power basis by replacing E_T with power P (in watts) and N_C with the rate of compact object formation R_C (in Hz). Both equations can be put on the basis of area or volume, if one wants to deal with powers relative to those geometrical parameters.

It might turn out that none of the several theories about the formation of compact objects, their energies and sizes, and the possibility of them entering into subsequent nuclear reactions, turn out to be consistent with nature. However, they are certainly in play now as candidate explanations of some observations from LENR experiments. If compact object formation occurred without later nuclear reactions, the absence of prompt energetic radiation and residual radioactivity could be explained. If there were some subsequent nuclear reactions, the small levels of products like tritium might be rationalized. The possibility of nuclear reactions involving heavy nuclei is also consistent with ideas about compact object formation. And, if most of the deuterium-containing compact objects that formed led to reactions with nearby deuterons in highly loaded Pd, the appearance of He in amounts consistent with the measured excess heat could be explained. Given this situation, it is desirable to compute nuclear reaction rates between either protons or deuterons, presumed to be in the center of compact objects, and elements across the periodic table. Such tunneling calculations could be done as a function of the distance between the hydrogen isotope and a neighboring atom, that is, the size of the compact objects.

Rates for LENR can be obtained from theory by evaluation of any of the few published rate equations. They are especially important. It is not possible to compute LENR rates from experimental excess powers without knowing the energy per reaction. And, that energy is generally unknown. It is possible to obtain LENR rates from transmutation experiments. However, there are two difficulties in doing so. First, accurately determining the increase in the number of atoms of a particular product element (actually, isotope) in an experiment is challenging. Very sensitive and accurate measurements of the number of atoms have to be made before and after the experiment. And, the spatial distribution of the element is rarely uniform, so that sampling is a problem. Second, even if the total number of atoms at the beginning and end of an experiment are properly determined, the production rate during an experiment might vary. So, only the average production rate can be determined. Such a rate might

Table 1. Characteristics of the papers on theory presented at ICCF14.

	Authors	Which LENR?	Coulomb Barrier	High-Energy Particles	Concept	Equations?	Numerical Results?	Use of Results?	Comments
1	Adamenko, Vysotskii	Transmutation	N/A	N/A	Magnetic monopoles	Yes	Approx. bounds	No	
2	Alexandrov	$e + P \rightarrow N + \nu$	Neutrons	No	Band theory, effective mass	Yes	Yes	Applied to semicond.	
3	Bass, Swartz	D fusion	No	No	Control theory	Computer simul.	Yes	Future work	
4	Breed	$4D \rightarrow \alpha + \ldots$	Yes	Yes	Band theory, effective mass, resonance	Yes	No	N/A	
5	S. Chubb	$D+D \rightarrow {}^4He + heat$	Yes	Yes	Nonlocal quantum effects, resonance	Yes	Yes	No	"Real barrier is conceptual"
6	T. Chubb	Various	Yes	Yes	"Ion band states"	No	No	N/A	
7	Cook	Transmutation	No	N/A	Lattice model of nuclei	Yes	Yes	Compare with exp't	
8	Dufour et al.	Pd+D, D+D	Yes	Indirectly	New force	No	No	N/A	
9	Fou	D+D fusion	Yes	No	Neutron exchange, electrostatic fields	No	No	N/A	
10	Frisone	D plasma oscillations	Yes	N/A	Gamow and Preparata theory	Yes	Yes	No	
11	Godes	$e + P \rightarrow N + \nu$	Neutrons	No	Various	No	No	N/A	
12	Hagelstein, Chaudhary	$D+D \rightarrow {}^4He + 24\ MeV$	Yes	Yes	Coupling 2-level systems to phonons	Yes	Qualitative	N/A	
13	Hagelstein, Melich, Johnson	Various	Yes	Yes	Various	N/A	N/A	N/A	Survey of experiments
14	Hagelstein et al.	Various	No	No	Existing theory	Yes	No	N/A	General framework
15	Kim	$D+D \rightarrow {}^4He + heat$	Yes	Yes	Bose-Einstein condensate	Yes	Yes	Yes	
16	Kozima	Not stated	No	No	Cellular automata, recursion equations	No	No	N/A	Complexity theory
17	Kozima, Date	Transmutation	Neutrons	No	"Neutron drops"	No	No	N/A	
18	Li et al.	$D + P + e \rightarrow {}^3He + e + \nu + \overline{\nu}$	Neutrons	Indirectly	Resonance, tunneling	Yes	Yes	No	
19	Sinha, Meulenberg	D fusion	Yes	No	Screening via local e^- pairs	Yes	Yes	No	
20	Swartz	D fusion	No	No	Relations between operating parameters	Yes	Approx.	Yes	
21	Swartz, Forsley	D fusion	No	No	Relations involving operating parameters	Computer calculations	Qualitative	Yes	
22	Takahashi	$4D \rightarrow {}^8Be^* \rightarrow 2\alpha$	Yes	No	"Tetrahedrally symmetric clusters"	Yes	Yes	No	

be practically useful, but has limited value for comparison with theoretical rates, which depend on specific conditions that vary during an experiment. It is noted that the use of (a) experimental powers and (b) theoretical rates enables computation of the energy per reactions. But, again, the rates depend on conditions within the experiment that produced the powers, and these are often not adequately known. LENR rates obtained from both theories and transmutation experiments have been reviewed recently.[62] Theoretical rates are generally in the range near 10^{14} Hz. They are generally higher than those extracted from experiments.

Obtaining numbers about energies, rates or other quantitative factors from theories about LENR is important, as discussed above. But, there are other opportunities for numerical research on LENR. They depend on the availability and applicability of computational tools, which are addressed in the next question. It is the computational equivalent of Question 19 above on experimental tools that might be applied to the study of LENR. Another of the computational opportunities is to calculate the characteristics and properties of materials. They are widely acknowledged to be central to fully understanding LENR. Computations of the arrangements of atoms and molecules in solids, and their energies and dynamics, are discussed in response to a separate question. The last question in this paper addresses data analysis and mining. Those activities are designed to pry additional information out of data from LENR experiments.

Q22. *Which computational tools should be employed for LENR theories?*

Experimental and computational approaches to research on LENR and other topics have similar steps. They are illustrated in Figure 5. The processes for both experiments and product developments begin with a Concept, the idea that will be examined. It leads to a set of Requirements that describe what the system must do, regardless of whether it is an experimental apparatus or the prototype of a product. The Specifications are numerical embodiments of the Requirements. They state specifically how the system being designed must perform. The design phase is usually carried out on a computer nowadays using electronics software such as PSpice or MultiSim, or mechanical software like ANSYS or COMSOL.

After producing a Design, there are two options. The historical approach is to Fabricate and Test the system in a laboratory. That is almost always slow and expensive. The availability of modern computers makes possible the second approach, which is usually both much faster and cheaper. While the iteration of the laboratory approach is usually time-consuming, parametric computer calculations can be performed quickly at low cost. Programming of the software for simulations is challenging and expensive. But, the ready availability of good software packages, including those just noted, permits a person to proceed to the simulation phase quite rapidly. For both laboratory and computational approaches to determining how a system performs, the results permit comparison with the original Requirements and Specifications. The approaches to experimentation, physical and numerical, are broadly applicable. They will be increasingly germane to LENR.

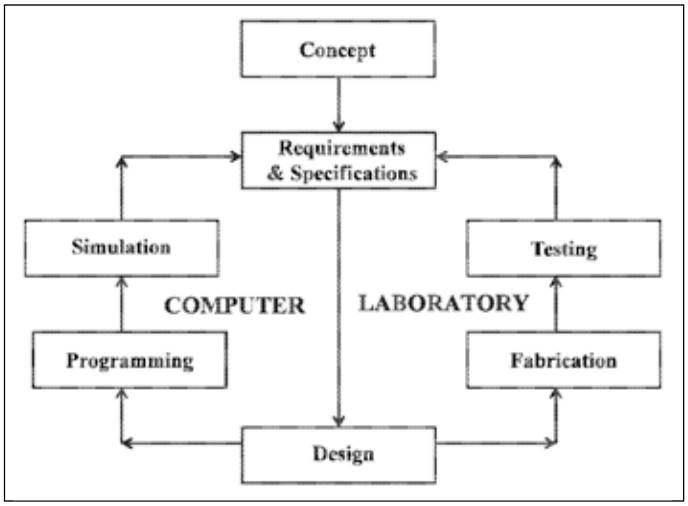


Figure 5. Activities, and their relationships, for both physical experimentation in a laboratory and numerical experimentation in a computer for design and evaluation of systems.

The synoptic computational approach just outlined cannot be fully applied to LENR now due primarily to lack of understanding of the central mechanism(s). Nonetheless, some simulations of parts of LENR experiments have been reported already. They are illustrative of the more complete computations that should be possible in the future. A few of them are noted in the next paragraph. Several computational papers about materials relevant to LENR are reviewed in response to the next question.

Temperature has been found to be relevant to the behavior of LENR experiments. And, the production of energy within an experiment or generator obviously produces higher temperatures within the active system. Hence, the computation of temperature distributions in materials and devices is germane to simulation of the effects of LENR. This is particularly true of calorimeters used to measure the excess power output due to LENR. McKubre and his colleagues found that the production of helium was strongly correlated with temperature in Pd-D gas loading experiments. So, they did finite element modeling of calorimetric behavior for the system.[63] They studied temperature variations due both to production of excess power and to variations in the ambient temperature. The study concluded that their system would detect an excess power as small as 100 mW, and could be made even more precise. In a later study, most of the same scientists and several others computed the effects of bubble flow along the cathode surface on the temperature within the cell.[64] The agreement with measurements was much better than when the fluid dynamics caused by bubble flow was ignored. Using commercial software, it is now possible to thoroughly model the flow of matter and energy in electrochemical cells. Velocity and temperature distributions can result from such simulations.

There is a very long history of the computation of aspects of materials, including perfect (bulk) lattices, surfaces, defects and, more recently, very small particles. Both the statics and the dynamics of the electronic structure (including charge distributions and energies) and atomic motions (due to phonons and diffusion) have been addressed. Many of the techniques, and some of the results, are germane to LENR. So, we now consider materials computations and simulations.

Q23. *What is the value of computing material characteristics and properties?*

All materials have two types of factors. The first is their characteristics. These simply describe the type and arrangement of atoms or molecules within a material. They are equivalent to descriptions of an automobile that is parked and turned off. Characterization of materials, systems and other engineering constructs simply gives their appearance, volume, weight, etc., without saying anything about how they perform. The second class of factors about materials includes their properties. They are quantitative descriptions of how a material responds to application of some stress. The properties of materials are very diverse. They include responses to electrical, magnetic, electromagnetic, mechanical, sonic and several other applied fields and factors, many of which are relevant to LENR.

Conventional nuclear reaction theories and tools commonly do not include solid-state effects. Conversely, solid-state theories, and the associated large collection of computational tools, usually ignore nuclear reactions. It seems clear that any theory, which will successfully explain LENR, has to include both nuclear and solid-state physics, maybe on equal footings. Some, but not all of the current LENR theories, incorporate that balanced approach. Theories that do not include both parts of the LENR puzzle are candidates for improvement. Those that do, notably the theoretical approaches by Hagelstein,[65] can serve as models.

The case for performing computer calculation of materials was nicely made by Rothwell in an email in November of 2013.[66] He wrote: "Researchers no longer need to test thousands of materials. They can use supercomputers to simulate materials and narrow down the list of candidates from thousands to dozens before doing an actual test. There is some risk that present day theory is incomplete or the model does not work, and the supercomputer will not recommend testing a promising material." The situation touted by Rothwell is quite like that shown in Figure 5 and discussed above. So, computations of materials characteristics and properties have two types of applications to LENR research: (a) the interpretation of data from past experiments and (b) the selection of materials for new experiments. In both cases, sophisticated algorithms, diverse codes and powerful computers can give the atomic and electronic structure of most materials, and both the energetic and kinetics of their constituents.

The following few paragraphs will review some of the past computational studies of materials relevant to LENR. In the process and after that, we will consider some computational tools that might be useful for study of LENR materials.

Quantum Espresso is a broadly applicable and facile set of codes for computation of the electron distributions and energies in solids.[67] That capability is, according to its website, "an integrated suite of Open-Source computer codes for electronic-structure calculations and materials modeling at the nanoscale. It is based on density-functional theory, plane waves, and pseudopotentials." The software has the great advantage of being able to specify a complex atomic structure, and then compute its stable configuration and energetics. The suite of Quantum Espresso codes, and other software for calculation of materials characteristics and properties, can determine favored phases, give the distribution of electrons in perfect and defective lattices, and produce the energy band structure.

Quantum Espresso has been applied by DeChiaro and his colleagues to compute strained layer ferromagnetism and its relationship to LENR.[68] Results of the spin-polarized Density Functional Theory calculations were applied to layered structures employed in two well-known LENR experiments. The CaO:Pd and MgO:Pd interfaces in the materials of Iwamura, and the ZrO_2:Pd interface in Arata-Zhang experiments, were modeled. Lattice energies and magnetism were obtained as a function of the lattice constant for these systems. Dimitriyeva and her coworkers also used Quantum Espresso to study the absorption of hydrogen and deuterium in transition-metal alloys.[69] Among other results, they found computationally that loading of Pd with H reduces the surface adsorption energy. It was also seen that near-surface doping of Pd with Rh improves surface mobility of H, even if reaching high loading ratios is not possible. There are numerous other opportunities for application of Quantum Espresso to computation of the atomic and electronic structures of materials relevant to LENR. There are also many other methods and codes for computing the band structure of solids.[70] However, such capabilities have been little used in LENR research.

Turning now to other computational tools, there are some opportunities for application of little used tools to LENR. The prime candidate is molecular dynamics (MD).[71] This well-developed technique uses potentials to track the motions of atoms and molecules in very small time and spatial steps. The number of quanta that can be followed for a reasonable period is limited by the power of the computer used.

MD simulations are applicable to small regions in solids, including point, linear, internal planar defects and surfaces. MD was used to understand spectroscopic data on the presence of H on the (111) surfaces of both Ni and Pd.[72] Simulation of nuclear active regions might be done with molecular dynamics. Details of atomic distributions and fields at crack tips have already been simulated with molecular dynamics.[73] More recently, Miura has used MD simulations to study the hydrogen states around the tetrahedral sites in nickel, palladium and copper.[74] Molecular dynamics codes might be expanded to include nuclear effects as well as the normal atomic and molecular kinetics, if they are going to be directly applicable to the mechanisms behind LENR.

The loading of protons and deuterons onto and into nickel and palladium is central to understanding LENR. Hence, there have been a few simulations of loading. Szpak and his colleagues developed and employed an early model for electrochemical charging of palladium.[75] Swartz published a quasi-one-dimensional model for electrochemical loading, which included the deuteron flux and gas evolution at the surface of a cathode.[76] De Ninno and Violante used a transport model to describe the evolution of the deuterium concentration profile inside of a palladium membrane cathode for different operating conditions.[77] Celani and his team did a similar simulation for microsecond-pulsed electrolysis and different surface treatments of cathode materials.[78] An early paper on the times scales of both sorption and desorption of hydrogen in electrodes dealt with surface and bulk effects on rates and distributions.[79] A Ph.D. dissertation treats similar dynamics in nickel and nickel alloy systems.[80]

At ICCF18, Goukas presented his views on modeling LENR environments by computational chemistry.[81] He provided a list of software packages that might be applied to the modeling of LENR environments, but have yet to be used. They include NWchem, a computational chemistry software, and LAMMPS, a molecular dynamics package for surfaces, defects and charged particle motions. Goukas favors ECCE, Avogadro or GaussView for visualization, Python for programming and Scientific LINUX as an operating system. The overall goal of his work is to arrive at standard *ab initio* software for modeling conditions related to LENR.

Q24. *What is the payoff from data analysis and data mining?*

We now turn to the last of the computational methods relevant to the science of LENR. It includes two types of activities to obtain additional information from data gotten during and after LENR experiments. Data analysis, the older of the two, is considered first. Then, a brief overview of data mining is provided. Combinations of data analysis and mining are also considered.

Before considering the analysis of data from LENR experiments, we pause to note another type of closely related analysis. There have been sophisticated mathematical analyses of some instruments used for acquisition of data from LENR setups. This has been most true of the performance of calorimeters. They are central to the quantification of excess power. But, calorimeters are not familiar instruments in the broader scientific community. And, there have been concerns, both within and outside of the group of scientists working on LENR, about the precision and accuracy of calorimeters. Fleischmann published extensively on the analysis of isoperibolic calorimeters. A paper by him and Miles reviews that work.[82]

We now turn to analysis of data measured during LENR experiments. A common sequence in science and some other fields is germane to this question. There is a temporal progression from *data* to *information* to *knowledge* to *wisdom*.[83] This situation involves a compaction of data originally obtained from experiments, be they physical or numerical. It is similar to the compaction of scientific knowledge from letter journals to archival journals to review papers to monographs to textbooks to encyclopedias. In response to this question, we are concerned about the step from data to information. The techniques mentioned in the question enable wringing more information out of a given data set. Methods for data analysis are not routinely applied to the results of LENR experiments. This is a significant shortfall, given the ease of some analyses and the significant information they can yield.

Analyses of data involve using various computational methods, each based on particular mathematical algorithms, to extract additional information from a set of data. A common example is the application of a Fourier Transform to a times series of data from an experiment. The data used as input to the Fourier Transform can be raw data, such as voltages, or reduced data, notably excess powers, both of these as a function of time. Given the large amount of temporal data from LENR experiments, and the availability of many codes to perform Fast Fourier Transforms (FFT), it is remarkable that there are no publications of frequency spectra obtained from time-series in LENR experiments. Commercial software, such as MatLab and LabVIEW contain FFT modules. The ability to use the FFT to obtain spectra is even a part of several modern oscilloscopes.

There are many other algorithms, besides the FFT, that can be applied to data from LENR experiments. Statistical analyses have been carried out for some LENR data. Scholkmann and his colleagues did analyses of two types of LENR data. The first were time series of excess power from two very different electrochemical experiments.[84] In that work, it was found that the data from both experiments did exhibit a diurnal, that is, 24 hour repetition frequency. The second type of data analyzed was from LENR transmutation experiments. Rates of elemental production were found to exhibit peaks as a function of atomic mass. Data from different electrochemical experiments appeared to be similar. Statistical analyses showed that the data were indeed related quantitatively.[85] A concern was expressed that the similarity was due to contaminations. So, another statistical study compared LENR transmutation data with the distribution of elements in the earth's crust.[86] It was found that contamination from the outdoor environment could not explain the peaking in the LENR data. There are many opportunities for application of the computational methods of statistics and digital signal processing to data from LENR experiments.

Opportunities for fitting data from LENR experiments with analytical equations are also common. However, only a few such studies have been done in the field. McKubre and his colleagues published an empirical equation that related the excess power from electrochemical experiments to (a) the first power of the current density (mA/cm^2) above a threshold value, (b) the square of the loading factor (D/Pd), also above a threshold, and (c) the rate of change of the loading ratio.[87] That equation can be used to predict the performance of experiments, given the factors that are expected to be achieved in planned measurements.

Letts developed an equation that gives the excess power as a function of (a) the number of vacancies in a Pd cathode, (b) the strength of an applied magnetic field, (c) the energy released per LENR and (d) the beat frequency in the THz range of two lasers that are applied to the cathode.[88] The number of vacancies depends on the volume of the cathode, the vacancy formation energy and the temperature in the electrochemical cell. Letts used the equation with the same vacancy formation energy of 1 eV and the same LENR energy of 23.8 MeV to the compute the excess power from 40 experiments, which he ran during 2007 and 2008. The empirical excess powers varied from zero to about 1.4 W. The computed excess powers agreed with the measured values remarkably well. Letts has an EXCEL spread sheet programmed with his equation, so he can do numerical experiments as a function of parameters such as the temperature and magnetic field strength.[89] The success of his equation in fitting measured excess powers challenges theoreticians to explain the influence of the terms in the equation on the production of LENR.

Data mining is a relatively new field made possible by increasingly powerful computers. It is defined as "an interdisciplinary subfield of computer science, the computational process of discovering patterns in large data sets involving methods at the intersection of artificial intelligence, machine learning, statistics, and database systems."[90] Voluminous data, in itself, can reveal much about the operation of a particular set of equipment, materials and protocols. And, it permits determination of improvements in experimental outcomes that follow from systematic variations. Despite the emphasis on large data sets, the methods of data mining can be applied to smaller collections of data, such as the published information from LENR experiments. While there are many LENR publications, the totality of LENR data is still small compared to what is nowadays called "Big Data" in Computer Science.

Numerical values for various quantities can be found scattered throughout the literature on LENR. They can be "mined" by gathering them, putting them on a common basis, and comparing them. Histograms of their frequency of occurrence can be made as a function of some parameter relevant to the data. Storms provided histograms of the distribution of excess power measurements prior to 2007.[91] A similar distribution of excess energy and of electrochemical cell volumes was published in 2009.[92] There are many other opportunities for pulling together, plotting and analyzing numerical data from LENR experiments.

As noted above, the rates at which LENR occur are central to the production of power. They can be obtained from theory or experiment. LENR rate constants from theory were noted above. They are generally near 10^{14} Hz. The same study, which produced them, also gathered together LENR rates from the several experiments that either provided them or made possible their calculation.[62] The rates varied from about 10^6 to over 10^{11} Hz for the conditions of various experiments. It must be recognized that the overall rates in an LENR experiment scale with the size of the cathode or other key materials in the experiment. Whether that scaling goes with the surface area or the volume of the active material is still being debated vigorously. There is experimental evidence on both sides of the issue. Resolution of that question has major practical consequences.

Opportunities for combined application of data analysis and data mining to LENR experimental results also exist. Again, there have been few applications to data from LENR experiments. Miles conducted a large number of electrochemical experiments during the past quarter century. Many of them used solid palladium cathodes and produced both heat and helium. In 2003, he reviewed the correlation of heat and helium, which he discovered early in the field.[93] Of the 33 experiments he conducted with both heat and helium measurements, 30 were consistent with the hypothesis that excess heat is correlated with helium production. Miles also performed experiments in which palladium and deuterium are simultaneously co-deposited on a cathode.[94] A statistical analysis of 18 such experiments gave a probability of 0.999989 that the production of excess heat by that means requires both palladium and heavy water.

Another statistical approach to estimation of the reality (occurrence) of LENR was made by Johnson and Melich. Their starting point was a set of 167 LENR papers identified and analyzed by Cravens and Letts.[95] They published four conditions that, if met, will result in production of excess power, and, if not met, will not lead to LENR. Johnson and Melich applied a Bayesian network for a probabilistic analysis of that claim.[96] Only eight papers were sufficient to give a 10-to-1 likelihood that the criteria are valid. As more papers were added to the set used in the Bayesian analyses, the probability increased, although not monotonically.

Another possibility for combining data analysis and mining arises from the production of heat and radiation after LENR experiments are over. Fleischmann and Pons reported that some of their experiments continued to produce excess power even after the cells boiled dry.[97] They called the effect "Heat After Death" (HAD). This phenomenon has also been observed by a few other scientists, who conducted electrochemical LENR experiments. They continued to measure power generation after zeroing the input current to their cells. The production of radiation after cutting power to electrochemical experiments has also been observed.[98] This might be called Radiation After Death or RAD. Curiously, the decay time curves for HAD or RAD have not been analyzed to see if they are exponentials, as they appear, and to obtain numerical values for their decay constants. If such analyses were performed, their comparison would constitute a form of data mining. It might be instructive to see if those decay times were similar, that is, possibly indicative of the basics of LENR. Alternatively, the decay times might be quite different for cathodes of different geometries, and correlate with the times it takes for deuterons (D) to diffuse out of palladium. The latter case could also be valuable from a scientific viewpoint if the decrease in loading (the D/Pd ratio) could be estimated separately and related to the measured decay times of HAD or RAD.

One additional point about data analysis and mining to gain additional information on LENR deserves attention. Many of the papers published in the field have significant omissions. Missing numbers on sample sizes and other characteristics, on the time histories of applied voltages, various output measurements and other factors make it difficult or impossible to compare results. More fastidious reporting is highly desirable.

4. Conclusion

This paper dealt with a dozen questions about LENR that fall into five categories. Some comments on each of the related questions follow.

Questions 13 on stimuli and 14 on resonances are related because both have to do with potential applications of particular types of energy to LENR experiments, and possibly commercial generators. Even though thousands of very diverse LENR experiments have been performed and reported, there are many possibilities for new experiments. It is conceivable that application of stimuli of the right frequency and magnitude will prove critical to both the understanding and commercialization of LENR.

Questions 15, 16 and 17 deal with the key topics of LENR reproducibility, controllability and reliability. The overall situations for all three subjects are still not satisfactory, but they have been improving over the years. Some experiments are reproducible, even between laboratories. However, they have yet to be reduced to a kit that could be sold to amateur scientists and other interested people. Tests of various versions of Rossi's E-CAT devices during the past three years are encouraging, even though the tests have many shortfalls. In 2011, the tests ran for less than a day, but they produced powers in excess of 1 kW and had energy gains of 8 or more. In 2012 and early 2013, two E-CAT tests ran for 4 and 5 days, with powers near 1 kW and energy gains of about 6 and 3. A square waveform was used to control those runs. In 2014, the test of one e-CAT ran for 32 days, with power production around 2 kW and an energy gain as high as almost 4. In this test, a DC electrical input was used for control. So, both the control and the reliability of Rossi's systems are reportedly improving. A recent review of these tests is available.[99]

Questions 18 on parametric experiments and 19 on experimental tools are both concerned with other opportunities for new LENR experiments. Additional experimental data from LENR experiments should be useful, even if it will not produce the desired basic understanding by itself. This has been the situation throughout the history of the field. And, it has long been recognized that more experiments with new tools is limited by funding. If programs to study LENR experimentally become significantly funded, a great deal of progress should be made rather quickly, at least in comparison to the rate of progress during the past 25 years.

Questions 20 and 21 both deal with theories about LENR. The evaluation of theories called for in response to Question 20 runs a risk of being impractical. If none of the many theories already put forward to explain LENR in the past quarter of a century is on the right track, understanding will ultimately come from a theory yet to be published. If that turns out to be the case, examination and evaluation of extant theories would not be useful in the end. Of course, historians might be interested in the results of comparisons of present theories, but that information might not help with either the science or commercialization of LENR. Question 21 is essentially a request (plea!) with LENR theoreticians to produce quantitative energies and rates for LENR. Much has been done in that regard, but most theories have yet to yield useful numbers.

The last three questions in this paper all involve computational aspects and opportunities for LENR research. Question 22 concerns computational tools for the production of quantitative results from LENR theories. That is, it considers means to produce numerical results from any of the many theories about LENR mechanisms. Question 23 has a similar flavor, but deals with the computation of the characteristics and properties of materials in LENR experiments. The last question in this paper considers the payoffs from analysis and mining of data already available from experiments on LENR. For all three of these related topics, there has been some work done. However, their evident value, and the many possibilities for additional work, makes them attractive areas for new research on LENR.

A simple summary of both the experimental and theoretical sides of the science of LENR is possible. It has two facets: (a) there is a great need for more research on LENR, and (b) there are countless opportunities for new measurements and computations. Many chances exist for researchers new to the field to make some fundamental discoveries.

The last paper in this trio will appear in Issue 120 of this magazine. Its focus will be on practical questions about the engineering, commercialization and applications of LENR power generators.

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