Questions and Answers About Lattice-Enabled Nuclear Reactions

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Introduction

Asking questions is basic to many human functions. Without questions, the learning process in schools and universities would be vastly more difficult and less effective. FAQs (Frequently Asked Questions) are a standard part of many websites now. The posing of questions is also an activity fundamental to diverse planning activities, ranging from the formulation of programs to the design of cities. And, questions, commonly driven by "mere" curiosity, are the driving force behind science. So, one can ask: what questions are applicable to the field of low energy, or alternatively, lattice-enabled nuclear reactions (LENR)? That is one of the motivations behind this compilation of some questions, which are asked because they seem significant. The answers are largely the opinions of this author.

There are many ways to organize a set of questions about LENR. One way is to use the sequence shown in Figure 1. It shows the steps in the progression of a knowledge-producing scientific field through the development of technical capabilities to engineering design, fabrication and testing. The results of engineering commonly lead to prototypes, products and profits. If the business phase is large and long enough, there can be significant higher-level economic, social and even political impacts, all based on the original research activities and results. These steps can form a temporal sequence. However, it is not uncommon for other scenarios to unfold, for example, a leap from research directly to prototypes. Many start-up companies follow this path to get to market as fast as possible. Some products can have a societal impact even without producing a major economic effect. Worry over the possible deleterious health effects of nano-materials is a current example, where widespread public concerns have gone beyond the business situation.

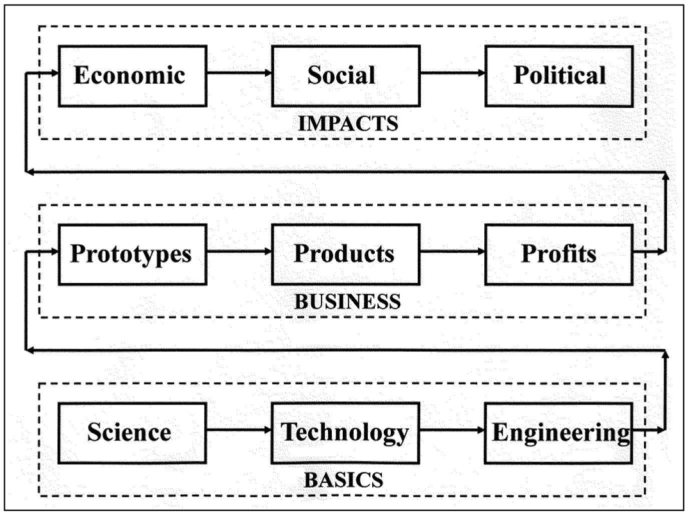

Figure 1. The progression that a concept can take through three levels.

Another way to organize queries about the many aspects of LENR is by the nature of what is being asked, for example, a scientific question or a historical question. Using a chronological order is also sensible. Given that the twentieth anniversary of the Fleischmann-Pons announcement is at hand, it seems worthwhile to ask questions along the lines of where the field has been, where it is now, and how it might develop in the future. That is the approach adopted here, although some of the individual questions will be recognized as scientific and others as business related. We will pose diverse questions, and then offer answers to them. Both what is asked and answered are burdened by the author's limited experience and his perspective from one country, even though the study of LENR is an international activity. It is recognized that questions and answers from others in the field would be different, especially from scientists in other countries. However, it is hoped that this collection of questions and answers will be interesting and even useful. One of the reasons for writing this paper was to attempt to improve knowledge and stimulate actions regarding LENR within the U.S. government. There is some redundancy, so that most questions and their answers can be used separately.

Looking Back

The history of science has cases where the time between experimental demonstration and understanding has varied widely. In some instances, the explanation of a very new phenomenon is given in the first paper with the experimental results on the discovery. The Mossbauer Effect is an example. In the case of superconductivity, over four decades elapsed between the discovery by Kamerlingh Onnes in 1911 and the explanation by Bardeen, Cooper and Schrieffer in 1957. Sometimes, ideas precede evidence. There was another four decade delay between the notion of plate tectonics put forward by Wegener in 1912 and the accumulation of verifying evidence from earthquakes and sea floor spreading in the 1950s. Einstein published the theoretical equations for stimulated emission in 1917, but the maser was not demonstrated experimentally by Townes until 1954. So, the temporal gaps between the experimental demonstration of new effects and their understanding, or the inverse, can span decades, essentially a professional lifetime.

When were LENR discovered?

The year of the initial strong experimental establishment of LENR is contentious. There are claims of the discovery before 1989 of nuclear reactions in lattices at ordinary temperatures. Some people will not accept the initial 1989 and other early reports by Fleischmann and Pons as being adequate evidence. However, others are satisfied with their data. Hence, the production of heat from LENR is sometimes called the Fleischmann-Pons effect (FPE). Whatever one's opinion of the earliest experimental evidence for LENR, there is now a very significant accumulation of evidence that it is possible to initiate nuclear reactions that provide MeV of energy with chemical-scale eV energies. That was held to be possible with only negligible probability, according to the theories available in 1989. Estimations of the probability of LENR being a real phenomenon as a function of time, that is, as a function of accumulating data, have been made. The computed probabilities have steadily increased to almost unity. Now, there are over 100 papers giving experimental evidence of the production of excess heat, that is, heat well beyond what can be explained as chemistry, which must be due to nuclear reactions. In addition, very significant evidence for LENR other than heat has been published.

When were the mechanism(s) of LENR understood?

The question of when LENR was or will come to be understood is even more open than determination of the date at which they became to be known as possible. Many theories, about two dozen distinct concepts, have been advanced during the past two decades to explain the data that must be due to nuclear reactions. At present, none of the theories is widely accepted by those in the field. Some theories have been reduced to equations, which have been the basis for computations. However, there is precious little direct contact between such theoretical and computational results and the many available good measurements. Years, and maybe decades in the future, it might be known if any of the extant theories are correct and possibly useful.

Why were LENR thought to be potentially important?

In 1989, nuclear power was being produced at high levels within fission reactors in many places around the world. For example, at that time about half of the electrical power in France came from nuclear reactors, a fraction that is now near 80%. Fission reactors cost on the order of USD $1B. Large fusion experiments, also costing most of $1B, were in operation in the laboratories of a few countries. After 40 years of research at that time, hot fusion power was (as it still is) nowhere near being useful. LENR were immediately recognized as potentially important nuclear power sources, that is, as much smaller alternatives to large and very expensive central power plants, and the costly distribution of electricity over a power grid. About 10% of electrical power put into the U.S. grid is lost as heat, the equivalent of the output of 40 large power plants. Hence, smaller distributed power sources are attractive. As a measure of the early interest, Figure 2 shows the covers of three major news magazines in the U.S. from the same date, namely May 8, 1989. That was only 46 days after the Fleischmann and Pons announcement at a news conference. Such prompt and widespread attention to a new scientific discovery is rare. It has happened a few times, for example, after the announcement of the discovery of X-rays in 1895. One could buy lead-lined underwear less than a year later! In the case of LENR, the announcement was so astounding that both widespread attention and intense scientific controversy were inevitable. And, mistakes by many people complicated the situation.

What early mistakes were made by those in and outside of the field?

Study of the research performed by Fleischmann and Pons, and attempts to replicate it, got off to a terrible start. It was almost as if the field had birth defects. Reporting their results at a press conference was the first mistake. The radiation data reported by Fleischmann and Pons was not defensible. Some technical errors were made in other premature announcements, only to be retracted. Tensions developed between parts of the physics and chemistry communities. Some scientists sought to protect their funding by criticizing LENR reports. Clamorous media attention in the early months of the field did not help. Many scientists dismissed the reported results on cold fusion because they were dramatically at odds with hot fusion theory. In fact, the use of the term "cold fusion" did not help the field. The new experiments were deemed to be simple, which is true if one compared them to large plasma fusion devices, notably Tokamaks. However, they are inescapably interdisciplinary, and often require a team of specialists. The 1989 review of the field by the Energy Research Advisory Board was done quite quickly, before it was adequately recognized that the experiments in the field are actually very challenging. It was also concluded at a time when many researchers were not disclosing their results in order to protect their intellectual property. The rush to judgment by some researchers and major laboratories discredited the field and those who worked in it before the end of 1989. The scientific community, and the public with them, hastily moved down the wrong branch of the diagram of possibilities shown in Figure 3. This was a major mistake that has haunted the field and hampered its development. Governments and investors ordinarily provide money to scientists, who return information and get more funding. For LENR, that cycle has been and remains dysfunctional.

Figure 2. Some prominent news coverage of the field in 1989.

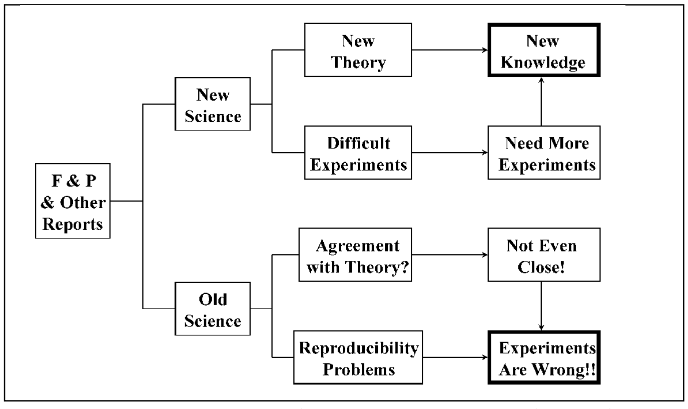

Figure 3. Possible outcomes for the announcement of "cold fusion."

What has been done since the field started?

Many activities have broadened the field from its original electrochemical and heat measurement experiments. This is true for both the way in which hydrogen isotopes (protium and deuterium) were loaded into solid lattices and the types of measurements that have been used to detect anomalous effects due to such loading. The four classes of loading and the four types of measurements are shown in Figure 4. There were new approaches to both loading and measurements within each class shown in that figure. Many variants of electrochemical loading from liquids were demonstrated. Light water, as well as heavy water, electrolytes have been used. A wide variety of materials has been employed in electrochemical and other experiments, for example, nickel and a variety of alloys. Molten salt electrolytes, and co-deposited palladium and deuterium, were other variations on electrochemical techniques. Gas, plasma and beam loading were employed. Diverse types of calorimeters have been used for excess heat measurements. And, a variety of detectors for energetic particles have been used, notably passive track detectors made of the plastic CR-39. In general terms, the variety and precision of measurement tools has improved greatly in the past two decades. In addition, major efforts have been devoted to theories for the FPE. Many essentially independent theoretical ideas to explain various observations in the field have been advanced. Equations have been written out for most of these theories. The number of theories for which the equations have been used to produce numerical data for comparison with past experiments, or prediction of the outcomes of future experiments, is very small. Much of the experimental and theoretical work on LENR since 1989 has respected its intrinsically interdisciplinary character.

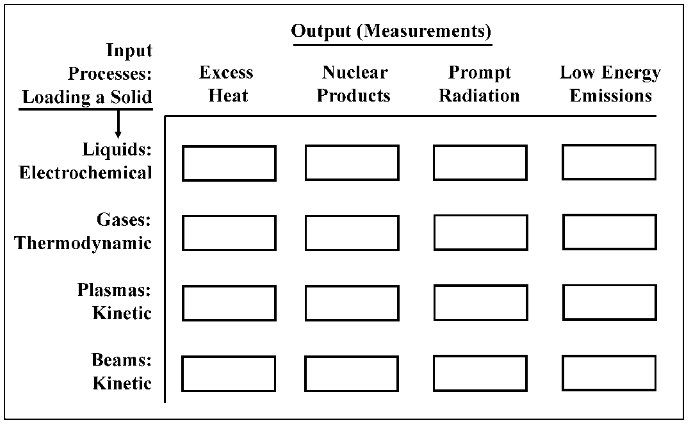

Figure 4. On the left are the four classes for loading protons or deuterons into a solid lattice. They involve (1) use of a liquid containing normal or heavy water in electrochemical experiments, (2) use of hydrogen or deuterium gas in the presence of the material to be loaded, usually at elevated pressures and temperatures, (3) immersing the materials to be loaded into a plasma of hydrogen or deuterium ions, and (4) kinetic loading using energetic beams of protons or deuterons. The four types of measurements are arrayed on the top. They include (1) excess power and energy measurements, (2) assays for the results of nuclear reactions by comparison of the composition of materials before and after experiments, (3) measurements of the relatively few prompt energetic photons, neurons or ions, and (4) measurements of low energy processes, notably sound or infrared emissions.

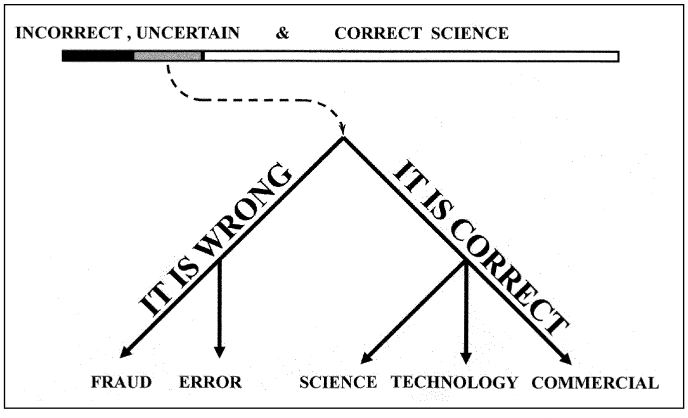

Figure 5. Initially possible outcomes of the discovery of the FPE. It is now known that the reported effect is not due to lies or mistakes. Hence, it is no longer uncertain whether or not the LENR is a legitimate field of scientific inquiry.

What has been found since the field started?

It is now clear from experimental data that it is possible to trigger nuclear reactions, which yield MeV-scale energies, with low energies, on the scale of eV, essentially chemical energies. The "low" in LENR refers to the input or initiation energies, and not to the output energies. Of course, the ratio of one million is not the energy gain, since many eV events can be needed to lead to one MeV event. Observed power gains until now are generally less (usually much less) than a factor of ten. The early accusations that all reports of excess heat were wrong, the result of either lies or errors, have been refuted successfully by data from many experiments. Figure 5 shows the initially possible outcomes. The branch "It is Wrong" was cut off several years ago. There are now over 100 published reports of the production of excess energy. There are many papers that report the appearance of new elements in experiments, but the data on such "transmutations" is not as robust as that for heat production. Data on the appearance of small numbers of energetic particles is also enticing. There are a few reports on low energy phenomena from FPE experiments.

Reproducibility of experiments, even within one laboratory and especially between laboratories, has been a chronic problem in the field. It has improved significantly in the two decades for research, but is still inadequate. There has also been major progress on the control of FPE experiments, but much improvement is needed here also. Some systematic trends for successful experiments have been discovered. There is a significant body of empirical evidence that the production of excess heat requires heavy loading of hydrogen isotopes into solids, and a flux of hydrogen isotopes through the surface of the lattice involved in the experiment. There are correlations between the production of heat and the generation of helium. Significant evidence points to LENR occurring on the surface of solid materials. Similarly, some evidence indicates that the nuclear reactions occur in very small regions, maybe with dimensions on the nano-meter scale. Some researchers think that the lack of understanding from experiments might be due to the fact that modern nano-science research tools, such as the Atomic Force Microscope, are only now being brought to bear for the study of LENR.

Current Status

Why is the field even more potentially important now?

Both the short term and long perspectives on the need for clean energy are problematic. The 1973 OPEC-caused crisis led to long lines at the filling stations that had gasoline in the U.S. In 2008, the dramatic run up in oil prices was another reminder of the vulnerability of the global economy to the costs of energy. In the U.S., recent government support of bio-fuels has had unintended negative effects on the price of some cereal grains, which has also affected other countries. With the relentlessly growing world population, the need for new and improved energy sources will not abate. If LENR can be reproduced, controlled, optimized and commercialized into distributed and clean sources of heat without greenhouse gas emissions, and possibly electricity, the effect might be in the same class with the impact of cell phones on global communications.

Why is the field still controversial?

There are clear reasons why many people are unable or unwilling to accept LENR as a legitimate field of science with significant promise for applications. The most fundamental is simple ignorance. Most people still view the field as it was portrayed in the media in late 1989 and the early 1990s, an example of science run amok. They have not looked at the voluminous data, which are now available and show that it is possible to initiate nuclear reactions with chemical energies. In general, they have not even read up-to-date reports on the field, for example, the summaries that are always written after one of the International Conferences on Cold Fusion. There have been 14 of these meetings on a three-continent rotation, North America, Europe and Asia. The last one in Washington, D.C. during 2008 was attended by 180 people from 15 countries. Some few scientists are keeping up with experimental progress on LENR, but cannot accept what is being reported by workers in the field. Such disagreements in science are not unusual, especially a new field, where they are actually normal. Disagreements certainly do not translate into the field being entirely wrong, a large collection of lies and mistakes.

What can be done to fix the problem of LENR being ignored or disdained?

The key to the field of LENR being accepted, advanced and exploited is education. This must be done by many means, ranging from mass media to courses in schools. The type and targets of such education and the level of detail must vary widely. For example, government officials in the U.S. Congress, including some Senators, Congressmen and, especially, their staffers, should know the status of the field, its prospects and what should be done to attempt to resolve the issues and realize the promise of the field. Senior people in an agency responsible for science, energy or the environment must know these factors, more scientific details and more about prospective applications. In the U.S., such officials work in the National Science Foundation, the Department of Energy, the Defense Advanced Research Projects Agency, the Office of Naval Research, the Army Research Office, the Air Force Office of Scientific Research and the Environmental Protection Agency, among other organizations. The broader scientific community should have available reviews of the field and the detailed technical information about what has been done and found in the past two decades. Scientists in disciplines relevant to LENR should have the most detailed technical information available to them as journal publications, both to satisfy any curiosity and to permit them to apply their expertise to advancement of the field. Mainstream journal editors must learn that LENR are empirically proven. Then, they might consider results from the field for normal publication, as they do in other areas, many of which have far less practical potential. Good popular articles and books on the field should be available to the general public. Teaching materials will become necessary when the field is more widely studied, probably first on the university level. If a new industry based on LENR does develop, then an even wider variety of written, video and other information must be available, for example, for the training of technicians who will work in the industry. For all of these education needs, the web will be invaluable.

What does it mean to reproduce an experiment?

Achievement of very good reproducibility will speed acceptance of the reality of LENR. Reproducibility is commonly and sensibly taken to mean that, if a particular experiment is redone, the results will be repeatable, that is, close to what was originally measured. Reproducing an experiment means that the apparatus, materials and protocols (procedures) are either the same, or sufficiently similar in the key features that determine the outcome of the 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. 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 input factors listed above. 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. In the case of LENR, it is possible that low levels of impurities within the solid materials in an experiment are basic to the outcome. 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. In short, both the input and output sides of an experiment are challenging to reproduce in many cases, including LENR. But, reproducibility remains a critically important goal.

What is the current experimental situation regarding equipment, calibrations and other key factors?

By now, several hundred credentialed investigators have performed thousands of experiments on LENR. Most of the experiments have involved adequate equipment, despite the shortage of financial support for the field. Reasonable protocols, including calibrations and controls, were commonly employed. Results have been obtained with very good signal-to-noise ratios. What was done and what was found have been given in open meetings, at which the investigators presented what they thought to be important and then responded to questions. Their papers have appeared in numerous conference proceedings, journals and other reports. Many of the papers in the field are available on the web at www.lenr-canr.org. This does not mean that all reports in the field are sound, of course. An increasing number of people, who have examined available experimental reports, now feel that the FPE is confidently established by many experiments, and that it must be due to nuclear reactions. However, details on the types and rates of such reactions remain to be determined specifically and quantitatively.

What is now the experimental data base for heat production, both in general and regarding reproducibility and controllability?
There is a large body of evidence from LENR experiments that it is possible to convert the binding energy in nuclei into free energy (heat). Despite the many variations in experiments, it is no longer possible to attribute all the reports of excess heat to fraud or mistakes. Nevertheless, consistent reproducibility of the output (as well as the input) of LENR experiments is still elusive. There are instances, within and between laboratories, in which a high degree of reproducibility has been achieved, where excess heat is seen in over half of the experiments. But, this is inadequate for two reasons. First, it properly bothers people who examine the field. Reproducibility is widely and properly viewed as the hallmark of experimental science. Second, lacking reproducibility, the controllability that is needed for applications of LENR is woefully insufficient. There are very few experiments in which the degree of control permits the production of excess heat to be turned on, increased or decreased and stopped at will. Practical devices will only follow the achievement of such control. If automobiles were as uncontrolled as are LENR experiments now, they would be useless for transportation.

How many papers are there reporting anomalous heat production?
Cravens and Letts reviewed 167 papers, which sought to or did measure excess heat, and presented their analyses at the 14th International Conference on Cold Fusion in 2008. There are over 100 papers that have reported heat in excess of the input energy from LENR experiments. For most, the excess power has exceeded the input power by less than 50% of the input. In several cases, however, the difference between output and input energy, the "excess heat," has been far beyond what can be attributed to chemistry, sometimes over 100 and even more than 1000 times chemical energies. In some of these experiments, the amount of excess power (energy per unit time) was 100 times or more larger than the smallest excess power that could be measured with instrumentation employed. The volumetric power densities in a few LENR experiments greatly exceed those of the fuel rods in fission reactors. Much experimental work and many results for heat production are very high in quality now, not for all papers, but for diverse reports from different investigators in about ten countries. Strong and relentless criticism of the field has forced its experimenters to be very thorough in the design, testing, calibration and use of their calorimetric and other equipment, and in the conduct of experiments.

Have the products of fusion reactions been measured in LENR experiments?
In ordinary hot fusion, two reacting deuterons (D) produce either a proton and tritium atom with kinetic energies of about 4 MeV, or a neutron and a helium-3 atom with about 3 MeV. These two sets of reaction products occur with equal probability. About once in 10 million reactions, a helium-4 atom and a gamma ray with 24 MeV of energy result from D-D fusion. In cold fusion experiments, the outcome of experiments is very different compared to hot fusion experiments. Tritium has been produced in easily measured quantities in many experiments, but still at levels more than one million times below those for hot fusion. Very few neutrons are produced. Helium-3 appeared in some LENR experiments, but at low levels and with a very different ratio to helium-4 than normal. Helium-4 has been detected in many LENR experiments, both below atmospheric levels and, notably, even above the atmospheric level of 5.22 ppm in some experiments. Heat was measured in many of the experiments that showed an increase in helium. Excess heat correlated with the level of helium production in several experiments. However, energetic gamma rays are not detected when helium is generated, as with ordinary D-D fusion. Much more data is needed in this part of the field. However, it is already clear that the outcome of light atom nuclear reactions in LENR experiments is very different from that of the hot fusion of two deuterons, especially regarding production of helium-4. Hence, other nuclear reactions, which would be consistent with data from LENR experiments, are of great interest.

What about reports of transmutations involving heavier elements? What do they mean? Are they reliable?
If nuclear reactions occur, the nuclei before the reaction are different from those after the reaction. This is analogous to chemical reactions, where the reactants (say, wood and oxygen) are very different than the products (water, carbon dioxide and ash). In the case of nuclei, the change from input nuclei to output nuclei is termed transmutation. If transmutations in LENR experiments are proved, one has direct evidence of nuclear reactions, and does not have to infer it from the level of excess heat production. Hence, it is entirely reasonable to look for the appearance of new nuclei after a LENR experiment, especially if excess heat was measured in the experiment. To do so, the experimenter has to measure accurately the levels of a variety of elements of interest both before and after the experiment. This is challenging even if only solid materials are involved in an experiment. However, in LENR experiments, liquids are involved in electrochemical experiments, gases in gas phase experiments, plasmas in glow discharge and other experiments, and beams in kinetic experiments. The composition of the phases other than the solid lattice, and the exchange of elements between those other phases and the solids, are both fundamental to confident determination of whether or not transmutations occurred during an experiment. There have been reports of transmutations from about two dozen laboratories. As already noted, tritium and helium have appeared in numerous LENR experiments in significant amounts. Only some of the reports of transmutations contain information on isotopic abundances, which is very important. Very few of the experiments have involved the detailed and defensible measurements of the total amounts of elements of interest in all phases in the experiment. One of the primary concerns about reports of transmutations is that the elements reported as products of postulated reactions were initially present, but at concentrations too low to detect with the instrumentation employed. Then, during

the experiments, those elements were concentrated in some regions where they were above the minimum detection limits of the instrumentation. This problem is not applicable to all LENR experiments that have been reported to cause transmutations. However, data on transmutations, in general, is not as robust as the data from excess heat experiments. This certainly does not mean that all the reports of transmutations are in error. A very great deal of relatively expensive experimental work is needed in this part of the field.

What about reports of energetic photon or particle emissions? Are the levels dangerous?

Particles with nuclear energies do not arise from chemical experiments. Hence, the confident detection of such particles would also be a "smoking gun" for the occurrence of nuclear reactions in LENR experiments. Much effort has gone into experimental searches for energetic particles from LENR experiments. There have been many reports of energetic photons or particles being emitted during, and in some cases, after such experiments. There are few reports of weak X-ray and gamma ray emissions. Many papers have reported neutrons, energetic protons and fast alpha particles. The levels of all these radiations are so low that they are neither easy to measure nor dangerous. It is challenging to measure even MeV level energetic ions in LENR experiments because of their short ranges. Neutrons have relatively long ranges compared to charged particles. There have been several attempts to measure neutrons, some with very good equipment and protocols, even in underground laboratories almost free of cosmic radiation. The body of data shows that neutrons have been detected in several experiments, often in bursts. There were attempts to correlate such observations with other events, but generally without success. In many experiments, small eruptive craters have been observed on solid surfaces after LENR experiments. They indicate very local and sudden release of significant energy, maybe as heat or fast particles.

What about reports of low energy phenomena, such as infrared or sound emission?

There have been a few reports of the emission of infrared radiation (IR) from LENR experiments. IR images can exhibit hot spots, and images of operating electrochemical cells show such hot spots. A simple calculation based on temperatures inferred from the IR images indicated that MeV-level, that is, nuclear energy releases are required to explain the data. One experiment measured the emission of sound from an operating LENR electrochemical cell. Here again, fast events consistent with nuclear-level energy releases were observed. Additional measurements of low energy emissions from LENR experiments are needed.

What is the state of understanding LENR, that is, theory?

Theory has only two tasks, to explain the results of past experiments and to predict the outcome of future experiments, especially those that might be designed to critically test a theory. Theoreticians offering explanations of the mechanisms active in LENR can first be asked what they are trying to explain, for example, heat production or transmutations or both. Then, there are the questions of their concepts, and whether or not they have been reduced to equations. If so, it is natural to ask if computations based on the equations have been made. Then, one can ask if the results of the calculations have been compared with available data. Or, can the results be used to design a critical experiment to see if the theory provides numbers in adequate agreement with the experiment. In general, LENR theories fall far short of these goals. There have been about two dozen different mechanisms offered to explain the existence of LENR or some aspect of results in the field. Understanding of many of the theories requires advanced (PhD level) training in physics. Some of the published theories are patently wrong. Almost all of them are incomplete in the sense that they have not been used to compute and explain the results of past experiments. There are a very few detailed comparisons of calculations with the results of data. But, most LENR theories give only qualitative trends and not quantitative rates of nuclear reactions. After twenty years of theoretical work, this lack of quantitative comparisons of theory and experiment is almost an embarrassment to many 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 now. 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. That is, like doing LENR experiments, developing a theory for LENR requires a broad set of skills.

Since there is so much available experimental data on the results of LENR (heat, nuclear ash, energetic particles and other effects) and many theoretical ideas, why is the field still not deemed to be worthy of support?

In the U.S., positional and institutional responsibilities for funding general, energy and environmental sciences have proven to be insufficient to generate the attention that LENR needs. Leaders and managers in the many relevant agencies are busy with other topics. And, many of them seem to be afraid of the poor reputation that still haunts LENR because of the early incorrect, but damning assertions that reports of LENR were all wrong. Few, if any, responsible individuals seem to realize that some of the erroneous reports that damaged the field in its first two years have actually been shown to be wrong themselves. Interest in LENR is not widely viewed as career enhancing. Clearly, incentives are not in place to cause some agencies, leaders and managers to learn the status of the field and to keep abreast of its progress. It has been said that there must be some among the hundreds of managers in relevant fields who pay attention to LENR. Such is the case, but it has not led to a general acceptance of the field as a challenging science with significant promise for important applications, especially the generation of "green" energy.

What is the U.S. government doing about the field?

The only sustained, but also uneven government interest, has been in various offices within the Department of Defense. In the early 1990s, the Office of Naval Research funded LENR experiments at three U.S. Navy laboratories. More recently, the Defense Advanced Research Project Agency supported the replication of experiments originally done in Israel and Japan. The Department of Energy (DOE) has had a few individuals in its headquarters who have paid occasional interest to the field, besides the two formal reviews of the field in 1989 and 2004. There has been significant work at a few of the DOE national laboratories. But, there have been no actions from the limited and sporadic interest in the Office of the President or Vice President of the U.S. in the past. Visits to the offices of six Senators a few years ago yielded no action. Such meetings with staffers have been more a result of personal contacts than institutional responsibility. In general, the offices responsible for science, energy and the environment in the U.S. government have not given either deep or sustained consideration to the results of research on LENR, or to the potential of distributed nuclear power sources that such reactions offer. The total funding of LENR by the U.S. government since 1989 is probably in the range of a few tens of $M. That amount, on the order of $1-2M per year for the past two decades, was far below what was needed, and is still needed, to advance the understanding and possible utility of LENR.

What are companies in the U.S. and elsewhere doing in this field now?
There was early attention to LENR by a few large companies. Now, there remains some such interest, but it is not public information. A few start-up companies have been formed in the arena. In the U.S., six of them still exist, and three have already failed. Some of the companies are very limited. Most have only a few researchers. These companies are generally doing experimental research, but some of them are primarily pursuing theoretical programs. There was one start-up for work on LENR in Canada. The only other existing LENR company known to this author is in Israel. It is the largest such company, and is producing some of the most important results in the field. It is not likely that any of the current start-up companies will have the basis for an Initial Public Offering of stock in the next decade. The development and sale of energy sources based on LENR are now uncertain and distant in time, probably about ten years before the first potential products reach the market.

What is the situation regarding investments in the field?
Investments in LENR by venture capitalists are virtually non-existent. The policy of the U.S. Patent and Trademark Office (PTO) that prohibits even considering patent applications in the field makes it difficult to protect intellectual property in the U.S. This discourages funding by venture capitalists. The start-up companies noted above are generally funded by "angel" investors, very rich individuals who believe in the promise of LENR and want to make a contribution to the development of a clean source of energy, besides making money. The total private investment in LENR globally for the two decades of the field is probably in the neighborhood of a few tens of $M.

How much money has been spent on LENR research?
This is not, and will not be known in detail. It is probably in the range of $50-100M. While that amount sounds like a lot, it was spread over twenty years and many laboratories in several countries. And, it is only one of the two true costs of research on LENR. The other cost is the uncompensated time of hundreds of scientists and engineers. If there were on average 100 unpaid person years spent on the field each year for 20 years, roughly 4 million person hours would have been spent, since there are about 2000 work hours per year. This amount of time by scientists with graduate degrees and experienced engineers is conservatively estimated to be a figure in the neighborhood of the out-of-pocket expenses just cited above.

Looking Ahead

What is needed experimentally, especially regarding materials?
There are three classes of opportunities for improving LENR experiments. The first is to use better "input" equipment for the conduct of experiments. Of the three classes, this is the least urgent. Good equipment has generally 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 run. The second class of improvements is the use of better diagnostics for measuring the "output" of experiments. This is a compelling requirement. 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. *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 cell or a gas loading cell or a plasma chamber. 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 third class of needed 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. The tools of nano-science 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. In short, a program leading to replication of important LENR experiments is needed. Significant funding for LENR experiments will open many opportunities, both technically and in terms of bringing new people with important skills into the field.

What has to be done to achieve adequate reproducibility?
As already noted, the replication of experiments involves employment of equipment, materials and protocols that are adequately similar to the initial experiments to produce similar results. Hence, achievement of better reproducibility requires careful attention to everything that goes into and is done during an experiment. At the moment, not all of the key factors are known, let alone adequately controlled. Hence, it is difficult to replicate experiments, even within one laboratory and, especially, between laboratories, regardless if they seem to be similar in their construction and

operation. Despite this fundamental challenge, the problem of imperfect reproducibility 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. It is also important to run many experiments in order to obtain statistics on the time-dependent results of the experiments. Remember the many materials tried and numerous tests made by Edison before a reliable filament for light bulbs was discovered. 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 the experimental outcomes that follow from systematic variations. 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 for complex experiments that require expensive equipment. Parametric variation experiments with such equipment must be done sequentially. 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. When such understanding is available and employed, it will significantly improve experimental reproducibility.

What about controllability of LENR? When might it be achieved?

Controllability means that excess power or other outputs from a LENR experiment can be turned on, up, down and off at will. This is fundamentally necessary for practical systems, whether it be an automobile or a home heating unit. 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. The experiments with the greatest control now involve the irradiation with laser light of the surface of an operating cathode in an electrochemical cell. That often increases the level of excess power. However, even this control parameter is currently inadequate. Now, it is not possible to say when the full control of LENR experiments, which is necessary for applications, might be achieved. It is possible 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.

What is needed theoretically and computationally?

The first thing would be to do a hard-headed assessment of the currently available theories. The outputs of such an assessment would 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 two 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 their bases. There are several more-or-less well-established experimental factors that challenge any LENR theories. 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 appear to be beneficial to the production of excess power. The question of where LENR occur, either on the surface or in the bulk of materials, is critical and there is data for both possibilities. Theories should address the location(s) where LENR occur, as well as their rates. 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. Beyond theories aimed directly at understanding the mechanisms behind the remarkable results from LENR experiments, modern computational tools for the design of materials and simulation of their kinetics at the atomic level should prove useful. Molecular dynamics codes provide an example of computational tools that might be useful for understanding LENR, especially if these were expanded to include nuclear effects as well as the normal atomic and molecular kinetics.

What should be done by scientific journals and magazines?

There are thousands of scientific journals. Probably a few dozen of them publish papers that are directly or peripherally relevant to LENR. Most of those journals are quite specialized in what they consider for publication, for example, papers on specific types of materials. But, many of them have broad interests. Some of those are among the most respected journals for scientific publication, for example, *Nature* and *Science*. At present, many of the lesser-known journals will publish papers on LENR experiments. However, the more widely-read and prestigious journals still refuse to publish papers from the field. The same remains true for some important scientific magazines, with *Scientific American* being a prime example. Hence, both the broad scientific community and the general public are denied the opportunity to keep up with the scientific progress of LENR, as well as its possible opportunities. It is now very desirable for important scientific journals and magazines to rethink their policy on publication of articles on LENR.

What should be done by scientific societies?

Intellectual societies, for example, the American Physical Society (APS) and the American Chemical Society (ACS), play multiple roles. One is to represent the interests of their field to their governments. Another is to provide and enhance scientific communication by both their publications and conferences. Currently, the only scientific society to actively assert the value of research on LENR is the one founded within the field, the International Society for Condensed Matter Nuclear Science (www.iscmns.org). That relatively new and small Society has had a useful but limited impact to date. Both the APS and the ACS are now willing to have sessions on LENR during some of their annual meetings. Their utility varies significantly. However, this is decent progress relative to the situation even five years ago. It is important that intellectual societies, in both science and engineering, recognize the existence, challenges and promises of LENR in their announcements, publications and conferences. Their doing so will widen the number of people aware of the field and possibly attracted by either its mysteries or its possibilities.

What is the role of universities and schools in training people for the field?

Both the establishment and pursuit of new fields of science influence curricula in universities and even lower schools. This is due to a combination of reasons, including their excitement for teachers and students, and the need for knowledgeable workers in any fields that follow from the science. For example, many universities have new departments, institutes or centers on energy and global climate change. If LENR are controlled and engineered into products, workers to manufacture, sell and maintain such products will be needed. The desired capabilities will range from the creative and sophisticated design skills of specialized engineers, to knowledgeable sales personnel, to the abilities of technicians, who will keep LENR-based energy sources operating. There will be a growing need for training workers for the entire range of functions needed to fully exploit the possibilities of LENR energy sources. However, now many university professors and other instructors think that teaching a controversial subject, like LENR, is unnecessary and unwise, and might even damage the careers of students.

What should be done by agencies of the U.S. Executive Branch?

The U.S. power industry spends less than 0.25% of its annual turnover on research and development. This is a factor of ten less than the average R&D investment by major industries in the country, and, interestingly, 2.5% is also the fractional investment by the U.S. automobile industry. It is clear that significant government support is needed to provide the level of funding required to advance the field of LENR, both in terms of science and applications. The top organization responsible for science and technology policy in the U.S. is the Office of Science and Technology Policy in the White House. The head of that Office reports directly to the President. The National Science Foundation is an independent government agency with an annual budget of $6B (20% of federal support for basic science in the country). There are several cabinet-level agencies in the U.S. government with responsibilities for the funding of scientific, energy and environmental research. They include, but are not limited to the National Science Foundation, the Department of Energy, the Defense Advanced Research Projects Agency, the Office of Naval Research, the Army Research Office, the Air Force Office of Scientific Research and the Environmental Protection Agency. These agencies have mission-related responsibilities for paying attention to and funding research on LENR. There is no need to set up new offices for LENR within such agencies. However, new programs to meet the challenges of understanding and exploiting LENR would be appropriate. A strategy for such programs has been published in this magazine: "Program Strategy for Low-Energy Nuclear Reactions" [#69, September/October 2006, www.infinite-energy.com/iemagazine/issue69/programstudy.html]. An initial investment of $10M annually in pre-competitive research on LENR by the U.S. government is recommended. That amount would logically be increased in the following years, depending on the results obtained from the supported program in its first years. $10M is less than one part in one thousand of the total annual U.S. government research budget, and much less than that when compared to the funds devoted to development and testing of systems, especially military systems.

What should be done by the U.S. Congress?

Several standing committees in the Senate and the House of Representatives are responsible for oversight of science, energy and the environment. For example, the Senate Committee on Commerce, Science, and Transportation has a subcommittee on Science, Technology and Innovation. The Committee on Science and Technology of the U.S. House of Representatives has subcommittees on Technology and Innovation, Energy and the Environment, and Research and Science Education. Like many agencies in the Executive Branch, these groups in Congress have institutional responsibilities for knowing about significant research areas and possibly-important technologies. The staff personnel, who work for the committees, should be giving the status, progress and promise of LENR the same kind of ongoing attention as program managers in the Executive Branch of the U.S. Government. Given the lack of attention to date, it would be entirely appropriate for some of the Congressional subcommittees to hold multiple hearings in the near future on LENR. One potential focus of an initial hearing could be the state and promise of the field. A subsequent hearing might be on the possibility of the U.S. developing a new nuclear industry, which would sell products globally. If, as many people believe, LENR power sources will be commercially important, the U.S. might turn out to be either a net exporter or importer of the potentially significant products in a new industry. Now, the country imports about $700B worth of energy annually. It would be very useful if even one respected U.S. Senator or Congressman took continual interest in LENR, and demanded at least periodic public attention to progress in the field.

What should the U.S. PTO do in the near future?

Patents and Trademarks are fundamental to commerce. The first U.S. patent was issued in 1790, only two years after the Constitution was ratified. The U.S. PTO is now part of the Department of Commerce. The Office is not a scientific authority, and depends on the views of the scientific community. To date, in contrast to patent granting agencies in some other countries, the U.S. PTO has refused to consider patent applications on "cold fusion." Their policy was and remains to treat such applications as they do applications on perpetual motion machines, that is, by immediate rejection without other consideration. They are said to lack "enablement" and "credible utility." It happens that some U.S. patents are granted on LENR and related materials, apparently because the PTO does not recognize them as such. The policy of automatically rejecting patent applications on LENR severely disadvantages start-ups in the U.S. Venture capitalists are generally unwilling to invest in a company, if it cannot protect its intellectual property (IP). And, the PTO policy even deters interest by established companies, who also have to protect their IP, which cost them money to develop or otherwise acquire. The U.S. PTO should realize the fact that it is significantly restricting U.S. companies, both absolutely and in relation to potential competition abroad. It is recommended that the Department of Commerce or the U.S. PTO conduct a review of LENR, which would show it to be a legitimate field of scientific inquiry with several possibly significant applications. If the Office changes its policy after such a review, the only downside risk is the granting of some weak or worthless patents. However, that risk is common, and it does not deter the granting every year of over 150,000 U.S. patents on very diverse topics, many of which prove to be useless.

What are potential roles for both start-ups and existing companies?

The fundamental function of companies is to make profits. New products and services offered by companies can fall into two classes. They can replace existing products, or garner at least some of their market share, by being better, cheaper, longer lived, more attractive or a few other factors, including fashionable. Or, new products can open up markets that did not previously exist. The ability to generate a new market leads to great profits, with Microsoft and Google being prime examples. Many established and profitable companies have a very good position for commercial development and sales of new energy sources based on LENR. The several start-up companies now working on LENR have the advantage of a dedicated focus and the generation of significant early intellectual property. However, they are usually short of money. It is hoped that more major companies will actively monitor and then participate in the advancement of even the science, and especially the technology and engineering of LENR energy sources. This will position them to grow their business in this arena, either on their own or by acquisition of one or more of the start-up companies. A lot of money might be made from LENR in coming decades.

What has to be done to turn the current LENR science into a technology?

Science produces knowledge, which can be used to build capabilities, which are called technologies. Ideally, a rather complete understanding of the physics of LENR experiments would be available to use in making operating prototypes of energy sources. However, sometimes even imperfect knowledge of fundamental mechanisms is sufficient to enable creative inventors to produce something that works. This might turn out to be the case for early energy sources that exploit LENR. However, the surest path to any operating LENR technology is research to provide a useful knowledge base. This is one strong argument for support of LENR research, in addition to being able to confront a sweet scientific problem.

What are the engineering challenges for making LENR products?

Engineering of prototypes and products involves a few familiar phases, namely design, fabrication and testing, which is done first in house by the developers and then elsewhere by early users. These phases will probably apply to any LENR products that are developed. Nowadays, the design phase for almost all new products involves modeling and simulations using complex software based on physical, chemical, electrical, mechanical, thermal and other principles. It is likely that such codes will also be applicable to the design of products based on LENR. Most manufacturing and product testing requires the use of specialized machinery. This, also, will probably apply to both production and assessment of LENR energy sources. It now seems that many of the manufacturing tools that might be needed for the production of products embodying LENR are either available or similar to what is required for making a wide variety of other products. But, a challenge specific to LENR is the engineering scale-up from the current low excess powers, generally on the order of watts, to higher and more broadly useful powers. This requirement comes on top of the needs for reproducibility and controllability already discussed. There are four choices for working fluids, as indicated in Figure 4, namely liquids, gases, plasmas or beams. So, which of these has the best chance to appear in any initial LENR products? The complexity of liquid electrochemical systems tilts against their early commercialization. The energy requirement for vacuum pumping within plasma and beam systems does not favor them. Hence, it now seems likely that, if LENR sources are commercialized, the early versions will be combinations of gases and solids.

Can LENR be optimized to reduce costs and increase outputs?

Virtually all products involve some optimization to reduce manufacturing or maintenance costs or improve some aspect of system performance. If the expected understanding, reproducibility, controllability and the possible commercialization of LENR energy sources are achieved, then it is almost certain that optimization will follow. The century-long history of the automobile provides a good example. Cars first became more reliable, then more comfortable and, finally, more efficient. So, now it is much too early to consider optimization of LENR in detail. However, two general comments can be made. First, bringing very new technologies to market generally takes considerable time, not just a few years, even if the science behind them is known. Hence, sophisticated engineering of many (any?) LENR power sources is not likely to be done in the coming few years. Second, LENR sources might not be very simple systems. That is, they may require significant ancillary control and other equipment, such as pumps and power supplies. Think of a home furnace or a fuel cell, which involve much more than the core unit where combustion or recombination occurs. It is likely that much of the equipment required for long-term operation of any LENR power sources will be adapted and optimized from other complex, but commonly-used energy sources.

What are the prospects for long term (reliable) energy producing units based on LENR?

This is another relatively inscrutable question. Favorable answers to issues, such as reproducibility and controllability, have to be correctly concatenated for LENR based power units to make it to market. Among all the "ilities" (http://en.wikipedia.org/wiki/Ilities), 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 one or the other 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 to occur and some early engineered units are made, operated and diagnosed.

What is the likely time scale for development of the early LENR products?

Given the results from some of the more important experiments, it seems quite possible that prototype products might exist in five to ten years. They will almost certainly be proprietary, and not widely known or available. If such prototypes exist, and they prove to be viable energy sources, with some (several!) significant prospective applications, then the early products might be on the market by 2020. And, if the products find market acceptance for any reason, low cost, performance or any other, then the period from 2020 to 2030 could see significant growth in the annual sales of LENR-based sources. These projections are certainly speculative. But, the early history of the scientific field of LENR, and historic timelines for bringing really new hardware technologies to market, both make it unwise to expect faster product development and market penetration or creation. Of course, sale and widespread acceptance of LENR sources could also turn out to be very important, but on a much slower time scale than envisioned above, taking maybe several, rather than two decades. However, the growing global need for energy, and the attractions of small and widely deployed clean nuclear power sources, especially in developing countries, may tend to move the field along more quickly than several decades. That is an exciting possibility.

What might be the power levels of commercial LENR systems?

Energy sources vary widely in the powers they deliver. The small battery that keeps time in a cell phone yields less than one milliwatt, while a large power plant can generate much more than gigawatts. The utility of an energy source is determined largely by the power it can deliver, either steadily or variably, or for some repetitive duty cycle. Hence, it is natural to wonder about the powers that might be available from LENR sources of energy. There are some soft limits on both the low and high end of the possible range. On the low end, the likely complexity of LENR sources, while not great, will probably keep them from being very small, say, under a milliwatt. On the high end, the facts that current LENR sources do not now produce either high powers or high temperatures tends to weigh against early products giving very high powers. It seems reasonable to expect the largest early LENR sources to have power levels below 1 to 10 kW, that is, possibly adequate for home heating and for powering small vehicles. This perspective on larger LENR sources is not solidly defensible. Consider transistors. The first ones were large single devices. Now, commercial chips with half a billion transistors are moving into production. It is conceivable that, after a few decades of development, even megawatt LENR sources consisting of large numbers of individual modules will be possible. Now, multi-megawatt fuel cell installations containing hundreds of identical sub-units are being planned. There is no obvious reason to bet against this also happening for LENR sources.

Will it be possible to produce electricity from the excess heat due to LENR?

Currently, LENR produce heat, the so-called excess heat. In general, temperatures in operating LENR electrochemical cells are below the one-atmosphere boiling point of water at 100°C. However, in some cases, such cells have achieved higher temperatures and boiled dry. In one infamous case, the Pd electrode melted, indicating that a temperature exceeding 1554°C, the melting point of Pd, was attained. In one gas phase experiment in Japan, a vessel with nanometer scale Pd particles and high pressure deuterium gas was preheated to about 140°C. It then reached a temperature near 200°C, reportedly from energy released by LENR. If high temperatures can be maintained in LENR power sources, then it is possible to use ordinary rotating electrical generators. There is a question of the most appropriate size for such generators, but they would work, in principle. An alternative means of generating electricity from heat is to use solid semiconductor converters. They offer the possibility of working with lower-temperature LENR sources, and do not have moving parts. The older of these is thermoelectric materials, which have long been commercialized. If such materials span two regions at different temperatures, the flow of heat through them produces a voltage (and vice versa, that is, they can also be used as heat pumps). There is an immense motivation for the development of efficient thermoelectric materials, namely refrigeration. The availability of good thermoelectric materials would make possible solid-state home and other refrigerators without compressors for working fluids. The newer solid-state technology for converting heat to electricity is micro-gap thermo photovoltaics (MTPV). This technology is a relatively recent development. It could turn out that both commercial LENR sources, and either thermoelectric or MTPV materials, will be developed and mated for production of electricity from LENR power. Electricity consumption in the U.S. averages about 1 TW, so significant generation of electrical power from LENR sources would require many units, if each could produce 10 kW of electricity.

Are there other potential uses of LENR besides production of energy?

Conceivably, yes. Considerable existing experimental data indicates that it is possible to transmute one element into another, not only with light elements as input, but across the periodic table. If the nuclear ash from LENR can be produced in needed amounts, and it has significant applications, then such reactions might be used to produce a less abundant and valuable element from another available and cheaper element. Some countries, the U.S. included, stockpile key elements, which are needed in the manufacture of important devices and systems. If it were possible to use LENR to make desirable but scarce elements, the need for stockpiling critical materials might be reduced. Then, industrial countries would not be at the mercy of the vagaries of geology, or international markets, politics and tensions, to obtain needed materials for any reason, commercial or military. In order for this possible use of LENR to come to pass, most of the same factors like reproducibility and controllability, which are needed for energy production, would have to be tamed. Even if production of elements in significant amounts by LENR were possible, the costs of the processing would certainly be an important consideration. Of course, the energy market is a larger and more compelling force for the development and commercialization of LENR compared to materials production. It should be noted in passing that some people have hoped that LENR could be used for the remediation of nuclear waste, that is, the rendering harmless of very long lived isotopes produced from fission reactors. That application seems unlikely. Even if it were possible, it would be very expensive, especially compared to the current, apparently safe and cost-effective methods of storing nuclear waste in secure above-ground casks.

What about radiation safety during operation of LENR sources?

Current fission reactors and hoped-for fusion reactors both produce large fluxes of energetic particles that are dangerous to human and environmental health. So, it is natural to wonder about the emissions that might come from LENR energy sources during their operations. The experimental data now available shows that it is very difficult to measure energetic photons, neutrons or ions from LENR experiments. That is, they appear to be entirely safe from the prompt radiation viewpoint. However, it could turn out that LENR sources optimized for energy production will be significant radiation sources, and require some shielding plus stringent operational safety features, such as interlocks. Further, scale-up of LENR sources to higher power levels than current experiments, which are rarely above 10 watts, could conceivably produce radiation safety concerns. However, it is also possible that LENR energy sources will be intrinsically safe, maybe even safer than electrical systems that can short to ground and gas systems that sometimes explode.

What about radioactive waste from operation of LENR sources?

Fission reactors have the tremendous disadvantage of producing a great deal of radioactive waste, which must be stored for thousands of years to reach safe levels by radioactive decay. The fast neutrons within contemplated fusion reactors will also induce troublesome levels and amounts of radioactivity. Hence, the worn out structures of a Tokomak or other hot fusion reactor would be important and problematic radioactive waste. As with prompt radiation, measurements indicate that the small LENR experiments already conducted have not produced significant radioactive waste. Placing solids from LENR experiments on photographic films and other detectors has shown evidence for some residual emissions. The radiations do appear to be low in both intensity and energy. However, they have yet to be adequately characterized. Again, optimization and scale-up of LENR sources might lead to some difficulties in this arena. But, problems with radioactive waste from LENR energy sources are not assured. Past measurements of harmless helium produced in LENR experiments bode well for the possibility of LENR sources not being a source of radioactive waste. Of course, even without radioactive waste, LENR sources will eventually wear out and produce scrap, much as do automobiles. Like any waste, dysfunctional LENR power sources will have to be handled in an environmentally responsible and economically sensible fashion.

Could LENR provide the basis for weapons?

Historically, many new energy sources have been used for warfare. It would be nice if LENR sources were an exception. However, there have been a few LENR experiments that clearly produce high energy density events. The best known is the experiment by Fleischmann and Pons that was reported in the *Journal of Electroanalytical Chemistry* in 1989 (Volume 261, pp. 301-308). They had a cell running with a cathode consisting of a cube of Pd 10 mm on a side. Their article carried a notice "Warning! Ignition?" It went on to say, "We have to report here that under the conditions of the last experiment, even using D_2O alone, a substantial portion of the cathode fused (melting point 1554°C), part of it vaporized, and the cell and contents and a part of the fume cupboard housing the experiment were destroyed." This event raises the concern that LENR could be employed either to augment existing weapons or even develop new kinds of weapons. The possibility of fast energy releases from LENR experiments not only raises the weaponization question. It shows that it is fundamentally necessary to insure that any commercial sources based on LENR are very safe. Fortunately, small modern sensors, plus diagnostic and information systems, make monitoring of the operation of complex systems much easier and cheaper. This translates into the ability to detect potential problems before they become serious, with benefits similar to the early detection of cancers. It may turn out that LENR energy sources will not be explosive.

What are now the most attractive applications of LENR sources?

If LENR sources produce only heat, even if they do not involve high temperatures, they might still be useful for production of clean water. Polluted rivers supply drinking water to many people around the globe, who develop dire health problems. The ability to produce clean water for people in developing countries, and also to desalinate water in them and even developed countries, could have great impacts. If LENR products can also produce electricity, then they might find use for powering millions of homes, either as the primary or backup sources of energy. They could also be employed in offices, factories and other buildings, and for military installations and operations. As is the case for most energy sources, unexpected applications would be found for commercial LENR sources.

Can LENR be the basis for a new nuclear industry?

Here, again, there is a series of issues that have to be favorably resolved for LENR to be the basis of a significant new industry. Not only must LENR be commercialized and the products prove to be reliable, they must also be cost competitive in one or more old or new major markets. It is clear that LENR sources need not capture a large fraction of the market for energy sources for them to be the basis of a significant new industry. Even a few percent of the global energy market is a very large amount of money. Hence, achievement of a niche status by LENR sources could make them economically important. If they are indeed, clean and green, as current research indicates they might be, then their market could be significantly larger and their impact correspondingly greater. Nothing other than adequately funded research and development of prototypes needs to be done by the U.S. or other governments in the next decade or so to speed development of a new nuclear power industry based on LENR. If LENR source commercialization proceeds increasingly over the following one or two decades, then it is likely that an industrial association, industry magazines, many websites and LENR-centric business conferences will emerge and grow with the new industry.

What about the overall economic aspects of LENR?

The economic importance of LENR energy sources will follow from their market success, which is entirely unclear now. But, given the size and increasing importance of the world energy industries, it is possible that LENR-based energy sources will have significant economic impact even within the lifetime of current school children, that is, in roughly half a century. It should be remembered that sales and service of commercial LENR sources will not be their only economic impacts. The favorable effects of small and distributed nuclear power sources on reducing the cost of emplacing, maintaining and managing the power grid in the U.S., plus ameliorating expensive power losses during transmission, will also be important. Brown- and black-outs due to power interruption caused by problems in centralized power plants or the grid are very expensive. This is both because of their interruption of factory production and, increasingly, due to their deleterious effects on digital computer and communications systems across the economy.

Are there any certain or potential societal or political implications?

Consider the current importance of micro-credit in many poor countries. Its impact greatly exceeds the amount of money involved. Hence, it is not unreasonable to contemplate the favorable impacts of small and possibly long-term distributed nuclear power sources on developing countries. Should the U.S., or other developed countries, commercialize LENR power sources, providing them to developing countries at reduced prices could be incredibly beneficial. The situation might be analogous to giving some countries medications at reduced prices, which is done now to the benefit of all involved. If LENR-based energy sources do become really important commercially, even in one country, they will have political implications. Should their importance be global, as it is likely to be the case if they are commercially important anywhere, then there will be global societal and political concerns.

Conclusion

It is now clear from two decades of experimental results that the study of LENR is an exciting new science. The current and potential issues in the field are certainly numerous and challenging. LENR also offers the possible basis for small, clean, distributed sources of nuclear energy. However, it may be a decade or more before practical LENR energy sources are realized.

The field is now in something of a “Catch-22.” Ordinary publication of results in good journals is needed. That might start to happen routinely, if more scientists simply studied already available data. But, there is little motivation for scientists, or editors or program managers, who depend on scientific opinion, to become conversant with available data. The field needs attention to get attention.

The questions posed above are only a sub-set of the questions that can be asked about LENR. In particular, there are many more scientific questions, such as the possible effects due to the use of amorphous alloys as cathodes in electrochemical cells. And, as noted earlier, the questions considered here are only some of those of interest to one person in one country. But, the author has given numerous presentations on the field and been asked many questions. Hence, some of the questions qualify as “frequently asked.”

The entire set of questions posed and considered above is not the result of any survey of colleagues in the field, although they might be of significant interest in the LENR community. It is hoped that other scientists in the field will expand this limited set of questions and provide their opinions as answers. That activity might help focus the very restricted resources that are now available in the field.

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