Questions About Lattice Enabled Nuclear Reactions: Engineering, Commercialization and Applications

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Abstract — A few small companies are now seeking to produce commercial heat generators based on LENR. The steps necessary for development of such products are enumerated and discussed in relation to LENR. Several aspects of the required engineering, especially control and testing, are especially important and are reviewed. Successful commercialization of LENR generators will require particular attention to four aspects, namely competing technologies, insurance of safe operation, regulatory approval and customer acceptance. These topics are discussed in some detail. Two of the primary potential applications of LENR generators are the subject of additional questions. The first is the production of thermal and electrical energy at a wide variety of power levels. These will be among the earliest applications of LENR technologies. The second is the transmutation of elements, either to produce valuable materials or to destroy radioactive waste from fission reactors. Those potential applications seem unlikely in the near-term, but might become feasible in coming decades after much research and development. Finally, a list of the eight areas of the greatest potential impacts of LENR is given and discussed. Success in any of these areas would be momentous. Significant global changes have been foreseen. However, the emergence of LENR as a game-changing commercial source of power will take time, at least years and maybe decades.

1. Introduction

This is the last in a series of three papers dealing with questions and comments about Lattice Enabled (or Low Energy) Nuclear Reactions (LENR). The first paper focused on the two primary scientific issues about LENR, namely the mechanisms that cause them and the influence of materials on producing LENR.[1] The second paper dealt with the trio of interrelated scientific research approaches to understand and exploit LENR.[2] They are experiments, theories and computations. This paper covers questions on the three aspects needed to enable this new source of energy to achieve its potential. They are engineering, commercialization and applications. Product development spans both engineering and commercialization. It is critical to the overall success of LENR generators in the marketplace. So, this paper starts with a section on product development. Then, it has three sections on engineering, commercialization and applications. As in the earlier two papers, some of the reasons for the questions, comments on them and suggestions on how to approach them are provided. And, again, the numbering of the questions is merely for identification, and not an indication of priority. While there are many unknowns about the questions in this paper, much of what is needed to engineer, commercialize and use LENR generators is already clear from experience with other energy sources.

1. Development of LENR Products

Whether or not the mechanisms that lead to LENR are understood, it is possible that prototypes can be engineered and developed into commercially successful products. For such engineering to happen, there are many steps, all of which have to be successful for companies to make money from LENR. The series of 18 steps given below, from concept to disposal, must be considered and executed for most complex products, and especially for LENR generators. These steps are not new to LENR, but are in routine use for the development of diverse products in many markets and regions. They are reviewed next in relation to LENR. Note that they apply equally to LENR generators of heat and to LENR generators that first produce heat and then electricity.

More detailed treatments on product development are available in many books.[3] They are worth reviewing for their applicability to the commercialization of current LENR prototype thermal generators. However, the steps discussed below suffice to illustrate the diversity, complexity and challenges of bringing LENR to market.

Q25. ***What steps must be accomplished to fully develop commercial LENR generators of heat and electricity?***

Many of the activities needed for development of marketable LENR power sources have been discussed in the literature. A short list about technology evolution and LENR is on the web.[4] But, there does not appear to be a synoptic list of such steps, with a focus on LENR. Hence, we document 18 key actions, make a few comments on their general characteristics and, finally, mention how they apply to the development of LENR products.

Concept Development. All products begin with ideas about the purposes they will serve, their approximate design and the market they will serve. There have been some conceptual designs for kilowatt-level LENR thermal generators. However, very few even rough quantitative designs of LENR electrical generators have been presented.

Definition of Performance Goals for Product. Early in the overall process, product designers must develop general ideas of the performance of prospective products. In the case of LENR, a key early goal is whether the generator will produce only heat, only electricity or both. Units for use in homes would ideally supply both heating and electricity to entirely power a house or apartment. In any case, the output power level goal has to be decided, since that one feature will determine a great deal of the design and other actions, plus the range of applications. The overall goals for a potential product are enough to make rough estimates of its manufacturing cost, which enables competitive market estimates.

Market Research. The success of a new product depends on what is already on the market to provide the contemplated function. The best situation for a new product is when there is no competition and it opens a new market. However, that is not usually the situation. It is widely accepted that a new product has to exceed the capabilities of existing products by a factor of a few or be cheaper by a significant factor or offer both of these advantages. Incremental changes on the scale of a few percent are usually not enough to make up for product development costs and to displace already-accepted products. LENR generators might be very much better than current generators powered by fossil fuels, if they cost significantly less to purchase and operate, are reliable, and meet safety and regulatory demands.

Development of Performance Requirements. The next level of detail, beyond the overall performance goals, involves a list of requirements that state qualitatively what a product must do. Also, in some instances, there are nonfunctional requirements that constrain product characteristics. The weight of the product is a common example of such a requirement. It is not uncommon to have a few dozen performance requirements for a product. In the case of a LENR electrical generator, performance requirements could include the ability to provide uninterrupted single-phase alternating current after a brief start-up time at a power level sufficient to maintain the temperature in a freezer.

Determination of Quantitative Specifications. The specifications are numerical expressions for each of the requirements. Often one requirement has a few associated specifications, which are necessary for the product to meet the requirement in the desired fashion. Again, using an electrical generator powered by LENR as an example, the specifications might state that the unit must be brought up to full performance from a cold start in less than 10 minutes, produce an AC output at voltages of 110 +/- 2 V and currents of up to 10 A.

Design, including Choices of Materials and Geometries. Two types of design choices must be made for the subsystems that will make up a new product. The first involves materials, devices and components that do not already exist. These have to be designed from scratch. Many choices of what materials to use and how they should be shaped must be made. There are some modern software packages in common use for making such designs, including ANSYS, COMSOL, MapleSim and SIMULINK. Such software includes integrated "multi-physics" capabilities for electrical, mechanical, thermal, fluidic, optical and other factors. Other design programs are also available for electronics, notably CADENCE, and for mechanical objects, where AUTOCAD is popular. The second type of design choice involves selection of available materials, devices and components for incorporation into the new product. When options exist, there are generally tradeoffs in performance and price, with availability also being a consideration. There have been sophisticated designs of LENR experiments. However, the designs of LENR prototypes of products have yet to attain industrial standard levels.

Simulation of the Performance of the Design. Once the prototype of a product is designed, it is possible to simulate its performance computationally. This is a faster, cheaper and more flexible way to estimate performance than building and testing multiple prototypes. Some of the multi-physics design software can also be used for simulations, especially ANSYS, COMSOL, MapleSim and SIMULINK. There is no published evidence of such system simulations for any of the LENR prototypes announced to date.

Competitive Cost Analysis. By this point in the product development cycle, enough is known to make a reasonably accurate estimate of the cost of manufacturing the product. Expenses for testing and other items, such as packaging, can also be computed. Having a good estimate of what the product will cost permits the developers to compare potential selling prices with what is already on the market. Some computations of the cost impacts of relatively inexpensive LENR heat generators have been made, but the estimates of what LENR units will actually cost have been very rough so far. This should change in the coming few years.

Acquisition of Parts for the Product. After the new product has been simulated and found likely to perform properly, and after a more realistic estimate of costs has been made, it is time to start making prototypes of the product. There are two primary ways to acquire the materials, devices and components that will be assembled to make the product. As noted, one method is to buy them. There are numerous ways to search for parts on the internet nowadays. For one example, a company called GlobalSpec provides means to search for over 180 million parts in 2.3 million product families: http://en.wikipedia.org/wiki/GlobalSpec. That organization became IHS Engineering360 two years ago, but retained the website: http://www.globalspec.com/. The other method for acquisition of parts for a new product is to make them. This is unavoidable for parts unique to the product. The design, manufacture and testing of parts has many steps similar to the overall process of product development.

Product Assembly. The assembly of devices, components and other parts into sub-systems and, then, a complete product can be relatively slow and expensive. There is a discipline called Design for Manufacturing that considers assembly during the design phase of a product. The prototypes of LENR generators have yet to reach this phase. That is, the assembly of laboratory systems and the few early prototypes has been labor-intensive and little like what would be done in more automated production of LENR consumer products.

Performance (Alpha) Testing. Once a pre-product system is in hand, the next step is in-house testing by the manufacturer. There are a few goals at this stage. One is to see if the prototype meets the requirements and specifications spelled out earlier in the development process. Another is to acquire some initial data on reliability. Experimental determination of reliability is especially challenging. Ideally, it would be best to have reliability data for durations of product use similar to what customers will employ. But, testing over months and even years can delay product rollout. Early in-house testing of LENR prototype generators has probably been happening for the past few years. However, the data are proprietary and not publically released. Hence, little is known outside of companies about the alpha testing of potential LENR products.

Beta Testing. Testing by the developers involves people who are already very familiar with the design of the prototype. But, if a product is mass produced and sold widely to people with diverse intelligence and capabilities, the units will be in the hands of people who do not know the inside details of the systems. Hence, it is critical to put the prototypes in the hands of people not involved in their development, so-called early adopters, who do the beta testing. They are also called "third parties," that is, they are neither the developers nor the ultimate users. Their experiences and feedback might do anything from validate the design, making it ready for manufacturing, to forcing a major redesign of the system. There have been a few tests of LENR prototypes that have come close to satisfying the rigor of beta testing. However, in the published cases, someone also involved in the development was involved in the test. And, all of the documented third-party tests have had significant technical shortcomings. So, testing of LENR pre-production systems has been and remains controversial. It is discussed in detail in response to Question 28 below.

Product Optimization. Before locking in the production details, it is sometimes possible to make minor changes in the design and manufacturing processes. But, in other cases, tuning of the design or means of production will only be done later, when another version of the product is to be released. The situation with automobiles is familiar and relevant. Often the differences between car model years are small, but most auto manufacturers will make major design changes every few years. Optimization has yet to be needed for potential LENR products.

Regulatory Approval. Governments at all levels, local, regional and national, have interests in the safety of products used by their citizens. It seems certain that LENR will attract the attention of regulators for two reasons. There have been some explosions in LENR experiments and tests. These are known, albeit not in detail in most cases. Further, the use of the word "nuclear" almost always attracts attention. Plans for adequate testing to satisfy potential regulators should be built into the product development sequence for both thermal and electrical generators based on LENR.

Sales to Distributors or Customers. The companies that make LENR products have two choices for getting them into the hands of customers. They can do that through distributors, other companies that buy from the manufacturer, advertise the products and then sell to "end users." This approach avoids the need for the manufacturer to hire, train and employ people for sales and customer service. The other option is for the manufacturer to develop an in-house capability to do everything needed for sales, advertising included. Possible LENR products have yet to reach this juncture.

Customer Service. Whether it is the manufacturer or a distributor, it is necessary to respond to customer concerns and needs. Once LENR generators are on the market, this function will probably be similar to how other heat sources and electrical generators are now handled.

Product Maintenance. Here also there are two kinds of issues. The first is the repair of systems that have failed to operate normally in some manner. The second is refueling and routine inspection of generators that are functioning properly. The situation is like that for heating units in a house. They need periodic routine examination and maintenance, occasional repair and eventual replacement. LENR generators will face similar requirements.

End-of-Life Considerations. Many products are now designed with attention to the fact that they will ultimately either be recycled or end up in a landfill. That will also be necessary for later LENR generators. Initial LENR products might not attain that level of design attention. But, in any case, the disposal of such units should be no more difficult than the current disposal of major electronic products and kitchen appliances. This expectation is based on the possibility that LENR generators will not contain significant amounts of radioactive or other dangerous materials when they are scrapped.

There is one increasingly necessary activity that spans all of the steps, namely cyber security. Theft of information from the computer and other information systems is increasingly common. In any high-stakes field like LENR, it is possible, even likely, that companies or groups developing products will be the targets of theft over the internet. Storage and communication of information from all of the above steps must be done in a secure manner.

These steps offer many modes for failure during the development of a product. Omission of key steps is one way to fail. Insuring that all of the actions are executed properly and in synchrony with each other is a daunting management task. Even if the organization and scheduling of work are proper, it is possible to fail technically. Most product developments do not work out properly. It remains to be proven that LENR power generators will perform adequately regarding controllability, safety and reliability. Even if a product development is a success technically, and the product is ready to market, there are often regulatory hurdles. They can be show stoppers if there is inadequate data on the safety of a potential product. This is a particular challenge for LENR generators, given their nuclear nature and the history of some explosions during developments. And, it is possible for products that operate as desired, and have either regulatory approval or do not need it, to fail in the marketplace. Customer acceptance of nuclear technologies is more difficult than for most products. If early LENR power sources got a bad name, even for reasons having nothing to do with nuclear effects, their eventual success could be delayed, diminished or even forestalled. Technical, regulatory and consumer acceptance of LENR products will be discussed below. But, first, key aspects of the engineering of LENR generators are discussed. They involve materials, control and testing, and will be discussed in the next section.

Successful accomplishment of each of the steps listed above inevitably involves the close cooperation of people with diverse skills, who operate on various levels within an organization. The management of the development of LENR generators is somewhat more challenging than that of products for which the basic principles of operation are already understood. It also requires detailed knowledge of results from LENR experiments, which have been discovered in laboratories around the world during the last quarter of a century. As always, there are the usual management questions of what will be done, when, by whom, where, for how much.

Before turning to the engineering and, then, commercialization of LENR generators it is useful to pause to consider available systems that produce heat and electricity. These are the products with which new LENR generators must necessarily compete on the basis of performance, price and other characteristics, such as usability and reliability. The initial LENR generators probably will be for heating, not electrical production. However, electricity is so broadly useful that LENR products to generate electrical power will have to be developed soon after the thermal units are on the market. Hence, we consider some current commercial electrical generators, which are powered by consumption of fossil fuels, commonly petrol or diesel oil.

LENR products now under development fall in the kilowatt to megawatt range, so we can focus on existing products in that range. Two examples are shown in Figure 1. The first is a kilowatt-class model 5943 unit from Generac.[5] This system is rated at 7.5 kW electrical. It weighs 92 kG and is about a cube 70 cm on a side. The system costs close to $1000. The other commercial electrical generator shown in Figure 1 is a megawatt-class 3512 system from Caterpillar.[6] It is rated for the range from 0.89 to 1.25 MW electrical. The unit is about 22 feet long, 8 feet wide and 9 feet high. It weighs 36,000 pounds and costs $450K. Clearly, many years of sophisticated engineering have gone into units such as these. Also, these systems and many others like them have been used by customers for a long time. Much of the engineering and even some of the experience will apply to new generators based on LENR. But, that does not diminish the multiple large challenges to developing and marketing successful LENR products.

3. Engineering of LENR Generators

Two types of engineering are fundamental to the advancement of the understanding and applications of LENR. The first is the design, production and testing of experimental equipment. There is already a long history of this type of engineering. Many sophisticated experimental setups have been engineered during the past two decades of LENR research. The engineering of experiments has a lot in common with the engineering of products. That is, the steps for engineering of experiments are a subset of those for product development. The second is the complete engineering of prototypes of products and, subsequently, actual products. The steps for such engineering were discussed above.

This section deals with three questions that are particularly central to the engineering of LENR generators of heat and electricity. The first is about maintenance of the necessary properties of fuels and other materials in systems that must perform for adequately long times. The second question focuses on the control of LENR generators, and whether or not they can or should be made self-sustaining. The final engineering question is on the testing of LENR generator prototypes and products. That topic has been a particularly contentious part of the field to date.

Q26: Can materials with the required characteristics be maintained during long-term operation of LENR generators?
Materials are central to the development of products based on LENR and were already discussed at length in the first article in this trilogy in Questions 8 through 12. They also play a key role in questions posed and discussed in the second article on reproducibility (Question 15), controllability (Question 16) and reliability (Question 17). Both the compositions (chemical makeup) and the structure (atomic arrangements) of materials have to be and remain correct for the occurrence of LENR during the operation of a generator. That is, it is necessary for operational and economical reasons to ensure that the active materials in commercial LENR power generators remain effective. If their useful lifetimes are too short, it is unlikely that LENR generators will be commercially successful.

There are two threats to the maintenance of the proper material conditions during operations that span weeks, months and years. The surface conditions needed for production of energy by LENR are not known yet. However, they are highly likely to involve both specific compositions and particular structures on the surfaces. Hence, the first problem is preservation of proper surface compositions, whatever is the shape of the useful materials. The second challenge is insuring that the proper materials structures are maintained, if structure is fundamental to the production of LENR, regardless of the composition. The needed structures might range from the atomic (nanometer) scale to mesoscopic (sub-millimeter) dimensions.

It is particularly challenging to achieve the appropriate chemical composition on a surface. This is a familiar problem for electrochemical experiments. The role of oxides on the surfaces of cathodes in LENR experiments was discussed in a recent review by Biberian and his co-authors.[7] They noted that experiments at the Naval Research Laboratory failed to give excess heat in plastic cells unless oxides were added.[8] McKubre and his colleagues used Hg introduced into an operating electrochemical cell to seal H and D ions within cathodes prior to their removal from the cell and employment in other experiments.[9] Storms did an experiment with a Pd anode and Pt cathode, which produced excess heat after the Pd ions migrated to and deposited on the inert Pt cathode.[10] There have been many electrochemical LENR experiments after which the cathode was X-ray analyzed in a scanning electron microscope. Multiple investigators have found particular elements at specific, often anomalous points on post-run cathode surfaces.[11] There are three potential

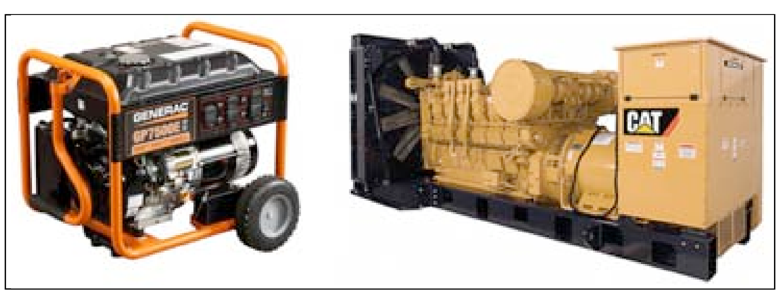

Figure 1. Commercial kilowatt and megawatt electrical power generators, which provide competition for contemplated generators based on LENR.

sources of these unexpected deposits. Two are LENR-induced transmutation products and chemical deposition from the electrolyte in the cells. In some cases, elements that could not be deposited with the voltages used were observed, but they might have been put down in compounds with lower electrochemical potentials. The X-ray analysis detects only elemental composition, and not the type of compounds. Even in the absence of transmutations or deposition from the electrolyte, it is possible that elements within a cathode will move to the surface, possibly poisoning the production of LENR.

It is likely that gas loading will be used for the initial, and probably later, commercial LENR generators. The same problems of impurity deposition and diffusion within active materials apply for this approach, as for electrochemical loading. But, there is a major difference. Electrochemical experiments are rarely done above the boiling point of water, a relatively low temperature for many applications. The generation of electricity using heat from LENR experiments is more efficient at temperatures of several hundred degrees C. This is true whether the working fluid is water (steam) or some other liquid with a higher boiling point than water. The movement of impurities within gas loaded LENR cells at high temperature is likely to be a problem. The high temperatures will remove materials adsorbed on the surface of the container of the experiment or commercial system. And, solid-state diffusion will proceed at exponentially higher rates in hot devices. These processes might both result in reduced lifetimes for the active materials in LENR systems, be they experimental or commercial.

The maintenance of proper structures on the surfaces of materials in electrochemical and, especially, gas loading experiments, is also a daunting challenge. Many of the comments above about insuring that the correct surface compositions are sustained apply to the surface structures. But, diffusion at high temperatures in gas systems might be especially pernicious. That is, even without composition changes, diffusion within nano- or micro-structures on surfaces will change their shapes to reduce surface areas and energies. Also, diffusion from fuel particle to fuel particle at contact points will lead to sintering and possibly reduced LENR rates.

It should also be noted that one of the challenges in maintaining the proper compositions and structures for the active LENR materials could be due to the products produced by the reactions. They are chemically different than the reactants that enter LENR. Whether or not their presence will serve to reduce, or even stop the LENR reaction rate remains to be determined. Recently, Wang and Arata addressed the problem of He, a LENR product, piling up in nano-particles.[12] The presence of the He reduces the rates for H and D diffusion within the materials, and hence cuts down on the availability of one of the fuels for the LENR. The nano-scale particles are expensive, so it would be economically beneficial to have a way to resuscitate them for further use.

The discussion to this point has focused on maintenance of active materials. There is an alternative approach to insuring the presence of effective materials in LENR experiments that deserves attention. It is the *in situ* renewal of those materials. While not discussed in these terms, some of the electrochemical LENR experiments effectively did such renewal within previously or currently active cells, for example, by reversing the applied voltage. Such work is important scientifically. However, as already noted, initial commercial LENR generators are not likely to employ electrochemical processes, so simple voltage-controlled surface renewal might not be possible.

The production or resuscitation of active materials in gas loading scenarios is likely to be practically important. Yoshino and his colleagues have reported on means to produce LENR active materials *in situ*, that is, in the chambers that will be employed for energy production.[13] However, there does not seem to be any published information on renewal of previously active materials within gas loading devices. It is not hard to imagine ways in which such renewal might be accomplished. One way would be to shut down the LENR generator for a period of time to introduce alternative atmospheres and conditions to cause physical or chemical vapor deposition. This would require ancillary equipment and, probably also, additional power supplies.

Automatic introduction of new materials is also a possibility. The old materials could then be renewed in an attached chamber before reintroduction into the power unit. Another approach would be to have a chamber attached to the energy producing LENR device, which could be used to slowly purge (renew) the atmosphere within the generator, maybe even during operation. The new atmosphere could bring with it suspended particles of materials that would then be used for LENR. The overall point is that the degradation of active materials might be unavoidable, but may not be a show stopper for commercialization of LENR. Obviously, means to grow in place or renew the active materials would add significantly to the cost of LENR generators. Only experimental trials will show what is most effective operationally and enable estimation of the costs of the additional equipments.

Another concern regarding materials for LENR generators involves the avoidance of hydrogen embrittlement.[14] This does not involve the materials used for fuels, but rather structural or other metals or alloys that will be exposed to hydrogen. A great deal is known on how to avoid or ameliorate hydrogen embrittlement and subsequent materials fracture.[15]

It must be noted that provision and maintenance of the necessary materials within a LENR generator, while necessary, is not sufficient for proper operation. It is also mandatory to maintain the appropriate ambient conditions within an active generator. It is not known yet which of these two basic requirements will be the greater engineering challenge.

Q27: Control of LENR generator: is self-sustaining operation possible or desirable?

The ability to willfully vary the power output, whether by direct human control or use of programmed computers, is necessary for almost all energy sources. That is likely to be the case for most applications of LENR generators. Hence, it is timely to consider means to control the output of LENR generators. We first consider the possibility of self-sustaining LENR generators. They will still require some means of control to start and stop them, and possibly to set the levels of hopefully-constant power output. But, it is likely that active control of LENR generators of heat and electricity will be required. So, the engineering of such systems is the major focus in most of this section after consideration of the "burning" mode of operation.

There are attractive features to energy sources that, once started by use of some external source, can continue to produce heat without further outside inputs. Burning wood is one example. A very small amount of initial energy is needed to release a relatively large amount of chemical energy. That is, the energy gain is very high. The achievement of "burning" is one of the goals of hot fusion research. It is hoped that kinetic energy released by fusion of deuterons and tritons will provide enough energy to sustain the 150 million degree plasma within a Tokomak.[16] Even if that condition is achieved sometime in the next decade or two, it will still be necessary to have some means to initiate burning, control the output power level, and eventually, to stop hot fusion power production.

The big question about self-sustaining sources of energy of all types is control of their output. They can be limited by control of the supply of fuel, as in not putting wood on a dying fire. However, it has already been demonstrated that at least one LENR prototype can run for a substantial time (about one month) on a single small (1 gram) charge of fuel.[17] If that situation continues to apply for longer run times, then it is unlikely that it will be possible to determine the power output of a LENR generator by controlling the amount of fuel present. And, it seems probable that it will not be practical to run LENR generators in a self-sustaining manner at particular desired power levels. So, now it appears that active control of the power output of LENR generators will be required.

Significant consideration of the control of LENR was already given in response to Question 16 in the second paper in this series. Various means of control were considered there, including pressurization, electrical input of heat (generally using resistors) and the use of plasmas. The production of plasmas also requires electrical inputs. Hence, the dominant manner in which LENR generators are likely to be controlled is by use of variable electrical energy fed into the system. Power levels for control of individual LENR generators will mostly fall in the range from something less than 1 W to possibly a few kW.

The use of selectable electrical wave forms and power levels for control of the output of LENR generators is relatively straightforward. There are many, probably thousands, of electrical power sources that supply voltages and currents with wave forms varying from constant (DC) to sinusoidal (AC) to arbitrary time variations. Whether or not any of them can be used without modification for powering and controlling LENR generators is an open question at this time.

An appreciation for the wide variety of electrical power supplies already designed can be gained by searching Google Images with the term "power supply circuits." Many designs are already commercialized. Again, searching for images using "power supplies" yields numerous examples.

Whether an existing power supply, or one that is designed specifically for powering a LENR generator, is used, it will be necessary to have a control loop for proper operation of the system. Some sensor or group of sensors will have to monitor the performance of the system to provide the input to the control loop. It is highly likely that temperature sensors will be used for that function. They could be thermocouples, thermistors, RTDs, integrated circuits or optical pyrometers. Each has advantages and drawbacks. But, whatever sensor is used, it will have either an analog or digital output. If analog, the sensor signal will be digitized and sent to the system controller. That computer will take the amplitude of the sensor signals, compare them with the desired values and send output signals to control the power supply.

If electrical energy must be fed constantly to a LENR generator for it to produce power, shutting off that power provides a means for safe control of the system. That is, if there is an input power failure, the generator will stop. This is good from a safety viewpoint, as will be discussed below in response to Question 30. However, it might be undesirable if one of the reasons for using a LENR generator is to operate independent of the grid. If such isolated operation is needed, it might be possible to quickly start a LENR generator with electricity from batteries or some other uninterruptable power supply, and then keep it operating by use of some of the power that the LENR unit generates. In the case of a unit with a power gain high enough to supply its own input power, once it is started, the control system has to be more sophisticated than for a system that always relies on available external power for operation. It is noted that the engineering of units that stop producing power when de-energized is one challenge. The addition of the ability to rapidly cool overheated units is another engineering problem.

Consideration of and concern about high energy gains is needed. However, it should be noted that even low energy gains might be significant. Energy gains, even as small as two, could be useful for producing hot water for many applications. They might save about half of the heating costs for home and other applications.

Q28: How should prototypes and commercial LENR generators be tested?

As already noted, the testing of prototype thermal generators in the past few years has been contentious, regarding both the equipments and procedures used. This is likely to continue to be the case until LENR sources of heat or electricity are sold in large numbers. Then, their testing will still be critical, but it will attract no more attention than the current testing of complex products, such as refrigerators or lawn mowers.

The testing of engineered systems has a long history, of course. Major organizations specialize in testing, with the Underwriters Laboratory in the U.S. being a good example. Note the name of that company. Insurance underwriters have a major stake in the proper operation of engineered systems. Regulations are often imposed on systems to make their failure, and associated damage, less likely during use. Potential regulatory restrictions on LENR technologies are discussed below.

There are two major motivations for thorough testing of current prototypes of LENR generators of heat. The first is the possibility that robust data from properly conducted tests might help convince remaining skeptics of the reality of LENR. Many people still do not believe that it is possible to initiate nuclear reactions using chemical energies. In most cases, such doubters have not looked at the voluminous empirical data from thousands of LENR experiments. But, really strong test data might impress them. Second, data from well designed and conducted performance tests is of use to two parties who have gotten past doubts about the reality of LENR. The first group is populated by those who design and build the system. They are naturally interested in whether or not a prototype performs up to the specifications they set during its design. The second group of people, who

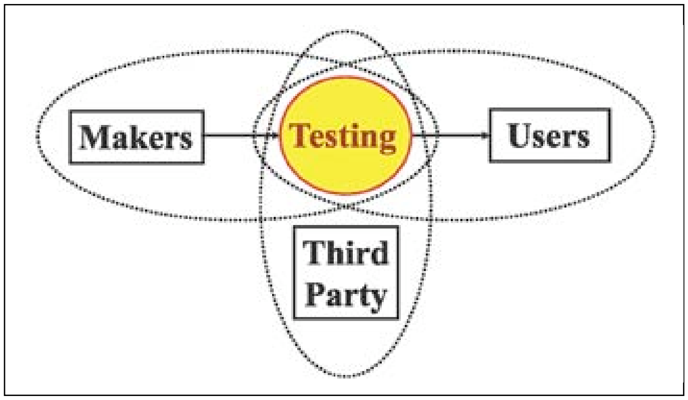

Figure 2. Relationships between makers and users of systems, and third party groups that also test them. This applies to LENR generators as well as to functional products, in general.

already believe in the existence and potential of LENR, includes investors and those who want to buy generators. They are no less interested in actual performance than are those who designed and built the system.

There is another group of people, generally scientists and engineers skilled in measurement science and technology, who get involved in testing of LENR prototypes. Such "third parties" can be hired by either of the first two parties, the developers or the potential purchasers, to conduct thorough tests. Parties contemplating investment in LENR technologies also have a strong interest in third-party testing. The relationships between the groups are indicated in Figure 2. The point is that well-engineered tests are central to the commercialization of LENR.

Third-party tests of different versions of Rossi's E-Cat devices have been conducted since 2009. A summary of those tests is in a recent review of the Ni-H system for production of LENR.[18] There have been four types of major and emphatic complaints about the conduct of E-Cat tests. The first involved the question of the relationship of those conducting the tests to Rossi and his companies. The second deals with the involvement of Rossi in some of the tests. Then, there are serious concerns about the design of the tests, that is, what was done before, during and after the tests. Finally, critics have worried about the data, which was or was not reported, and its analyses.

How to perform rigorous tests of LENR systems was presented at ICCF16 in 2011.[19] Now, it is possible to state how very thorough tests of LENR prototypes could be designed and conducted. One statement of severe demands for such tests follows:

Measure all of the matter and all of the energy that goes into or comes out of the test system from a cold start to a cold stop, for a time long enough to rule out all internally stored chemical energy sources, using redundant sensors for all quantities, which are calibrated immediately before and immediately after the test, and record all of the time-stamped calibration and test data, making it available after the test to interested parties for examination and further analyses along with all details on the planning, conduct and analysis of the test.

Without a doubt, this is an expensive and difficult approach to testing of LENR heat or electricity generators. However, if it is overdone, it is "wrong in the right direction." Testing with an adequate approximation to this degree of thoroughness could go far toward satisfying critics. The issue, of course, is what constitutes a satisfactory approximation to such rigor. It varies with the LENR power levels. Large excess powers are easier to measure with confidence than small LENR powers.

We have noted that the energy gain is the ratio of the total thermal energy that comes out of a LENR generator to the input electrical energy. It is a critical measure of the performance of a system based on LENR, just as the mileage (miles per gallon or kilometers per liter) indicates much about the design and performance of an automobile. There are other parameters of interest for LENR generators, of course, including the absolute magnitudes of the input energy and the generated LENR energy, as well as the operational temperature. Here we will concentrate on testing of the input and output powers, the integrals of which give the corresponding energy quantities.

Measurement of the electrical power going into a LENR generator (or its power supply) requires frequent (rapid) determinations of both the voltage and current. Their product at any time gives the instantaneous input power. There are many ways to make such measurements with commercial instruments. In recent tests of the performance of various embodiments of the E-Cat devices, relatively simple commercial devices were employed. Input electrical power and energy measurements were performed with the PCE-830 Power and Harmonics system from PCE Instruments.[20] In a 2010 E-Cat test, this author used a Voltech PM3000[21] unit to determine the power input to Rossi's system. That instrument was capable of measuring power at frequencies exceeding 50 kHz. Measurement of powers over wide ranges is very important commercially in numerous instances. There should no longer be serious questions about the ability to make input power measurements for LENR experiments and generators.

The major point is that, whatever commercial instrumentation is used for input electrical power determinations, it would be good to follow a particular protocol. It is possible, and not prohibitively expensive or time consuming, to measure a dummy load, say a set of precision resistors, with three of any instruments, or with a mix of instrumentation. The ability to obtain the same power levels with different instruments, which usually have varying calibrations, would be very significant. The use of multiple power measuring instruments during an entire test is also not complex, and would provide strong evidence of the correctness of and variations in the electrical measurements. Differences between instruments provide information on the uncertainty of the input power measurements during the actual tests of a LENR unit. Again, this procedure might be overkill for many LENR tests. However, it can be done for tests that are likely to attract many of the usual criticisms.

It is also possible to sternly test the method to measure the thermal power from a LENR system and to employ multiple means for that determination. Doing so is more complex than measuring the input electrical power because commercial instrumentation designed specifically for the need is not available. There are many means of doing calorimetry during LENR experiments. Most of them were reviewed in a section on calorimetry in the proceedings of ICCF14.[22] It is possible to use some, but not all of those methods, for measurements of powers in the kilowatt range. Mass flow calorimetry with water or another fluid can be used at such powers. Melich came up with a good method during the 2010 tests of E-Cat systems.[23] He and his colleagues employed an on-demand water heater, such as are used to quickly get hot water in hotel rooms, in parallel with the system being tested. The electrical power into either the resistive water heater or the E-Cat could be measured, as explained above. The single-pass water flow for the calorimeter was first directed through the water heater. It was shown that the mass flow calorimetry gave similar thermal values in comparison to the input electrical power. As usual, the flow rate and the temperature increase of the water were used to compute thermal power. Then, manual valves were used to redirect the water around the E-Cat to obtain its thermal output.

The thoroughness of testing depends on the needed or desired accuracy. If signals are small, high accuracy is required. This is well known in the physical sciences. For example, the *Measurement, Instrumentation and Sensors Handbook* has entire chapters on measurement accuracy and measurement standards.[24] A simple example, relevant to some LENR measurements, involves the statistics of the counting of photons or energetic particles. The standard deviation, which quantifies the scatter in the data, goes as the square root of the number N of recorded counts. Hence, the relative standard deviation is root N over N, or 1/(root N). Increasing the number of recorded counts improves the relative standard deviation, a measure of precision. It should be noted that high accuracy testing might also be desired even with large signals. That could be the case if manufacturers of LENR generators are trying to optimize performance, or distinguish subtle differences in performance that might provide useful information.

The safety of LENR generators is discussed in some detail below in response to Question 30. But, safety testing is addressed here. There is a fundamental challenge to testing the safety of LENR generators. Those that will become available from different vendors will have various designs. Hence, what is learned from safety testing of a set of reactors of one design might not carry over to another company's products. Testing the safety of LENR generators will continue for many years after they are on the market in large numbers. As with other questions about LENR, the issue of safety will be resolved only by extensive testing and long experience in operation of experimental and commercial systems.

Another reason for caution regarding the safety of LENR generators is the possible lack of full reproducibility and controllability. These shortfalls make it difficult to produce several generators that are essentially identical in design, construction and performance. Having such a set of generators would make it possible to drive them at different output power levels to experimentally determine when they become unsafe. It might be possible to drive a single operational LENR generator at increasingly higher power levels to determine when it fails, either safely or unsafely. Doing that would be akin to running an internal combustion engine at increasingly higher RPM until it breaks down. For such failure data from a single LENR system to be broadly useful, the tested generator would have to be adequately representative of many such systems. It is also desirable to have another set of reactors that are similar in design, but vary in size and the amount of active materials they contain. The second set would also enable key tests of safety. This variation of the amount of fuel might be done in one LENR system during sequential test runs. Doing that would require the system to change little from run to run. And, again, there would be the issue of how broadly applicable would be the test data from just one LENR system.

4. Commercialization of LENR Generators

The steps outlined in the last section, especially testing, are necessary for commercialization of LENR power generators. However, there are other considerations for commercialization that deserve more detailed discussion. One of them is the competitive environment for such generators. Another is the question of safe operation, which is central to the market acceptance of LENR sources. Regulatory approval of LENR products for sale, and consumer acceptance, are also critical aspects for commercialization of LENR generators. Each of these is discussed in response to four questions in this section.

Q29: What is the competition for LENR generators of heat and electricity?

The production of heat is certainly a very old process with many technologies already in use. They still include the most ancient approach of burning wood. The production of electricity does not have so long a history, but again, there are numerous approaches to generation of both direct and alternating currents. So, when LENR generators, first for heat and later for electricity, appear on the market, they will necessarily seek to displace existing technologies.

It is recognized that, if LENR products are very cheap and good, they will also open new markets. People who did not previously enjoy systems to produce heat or electricity might be able to afford and operate them. But, that pleasant prospect probably must wait for LENR generators to succeed in existing markets. The situation might be similar to that for cell phones. They were first bought in large numbers by people in technological societies. Only then did the prices and reputations reach the point where cell phones were adopted in regions that did not have any phone service previously.

There are thermal sources over a wide range of power levels. They vary from a few watts for cell phones to near megawatt HVAC systems for large buildings to fossil-fueled industrial heaters for smelting metals, which require MW of power. The largest nuclear reactor complex produces over 10 GW of thermal power.[25] Electrical generators also have a very wide range of powers. The lowest produce less than one mW for charging the batteries of nodes in wireless sensor networks. The largest is the Three Gorges Dam in China, which produces 22.5 GW of electricity.[25]

It is natural to ask about the ranges of power output from LENR generators of both heat and electricity. Where in the wide ranges of powers just cited for thermal and electrical sources will LENR technologies fall, and have to compete? It is known that LENR sources can put out very small thermal powers, well under 1 mW. However, will there be any utility for such heat sources? That does not seem likely in the near future. If a LENR thermal source produces sufficiently high temperatures, say 200°C or more, so thermoelectric heat-to-electricity converters were efficient, then sub-watt thermal powers might find use for production of electricity to power small devices. Again, the nodes in wireless sensor systems provide an example. Until the costs of such LENR sources become adequately low, and their reliability is sufficiently high, only high-value applications, such as emergency systems, might be viable. Anti-lock braking systems first appeared on expensive cars. Then, after they proved effective and came down in price, they appeared on lower priced cars.

The high power limits for LENR generators have yet to be defined. An average thermal power of 17 kW was reported in one test of an E-Cat.[26] As will be discussed in response to Question 30 about safety of LENR generators, it is likely that individual units will be restricted to 10 kW or less in the near future. When highly reliable control of LENR systems has been established, it should be possible to make higher-power units. It is noted that current E-Cat prototypes are in the few to 10 kW range. The megawatt system made by Rossi consisted of about 100 individual kilowatt-class units.

The conversion of heat to electricity can be accomplished by various means. The use of thermoelectric devices for such conversion was already noted. They have the advantage of direct conversion of heat into electricity without an intermediate mechanical step. However, thermoelectric modules are relatively costly, and have efficiencies of about one-third (heat power to electrical power). It is possible that small LENR thermal generators, such as NANORs®,[27] could be used with a commercial thermoelectric module to produce enough DC power to keep a cell phone charged.[28]

The production of electricity from LENR units with powers of a significant fraction of a kW or higher is likely to be done by conventional means. The two electrical generators shown in Figure 1 are examples. Reports from testing of E-Cat device prototypes cite temperatures more than adequate to produce high quality steam to drive small turbines for electrical generation.[17,29] Such turbines are based on well-developed technologies and put out alternating currents. That is, they do not need inverters to turn DC current into AC current for applications that require such power.

It is virtually certain that LENR generators of any type and power level will not succeed in the market unless they are highly safe to use. So, we now turn to that aspect of their commercialization, which is a primary commercial challenge for LENR products.

Q30: What are the requirements for safe operation of LENR generators?

The safety of LENR generators is both complex and critical. It was discussed in response to Question 17 in the second paper, and is closely related to control of LENR generators (Question 27) and their testing (Question 29). Here we will review various aspects of the safe use of LENR thermal and electrical generators, and recount reports of major failures of experiments and tests of prototypes.

There are two ways in which the failures of LENR generators might cause problems. The first could happen if a unit stopped producing power. If it were a thermal generator, it is unlikely that it would cause an immediate problem. However, the failure of a LENR heater might lead to significant difficulties, for example, if a home unit faltered in the middle of winter. The failure of a LENR electrical generator could cause more immediate problems. For example, if some key function were dependent on an electrical source powered by LENR, the failure might induce property or personnel damage. Consider the sudden failure of an automobile engine in traffic, which happens seldom, but can cause major problems when it does occur. If failure of a LENR electrical generator could lead to problems, the units will have to be backed up with battery or other standby systems. Uninterruptable Power Supplies (UPS) are now commonly used for computer, communications and other key systems.

The other type of failure of a LENR generator, either thermal or electrical, would be to continue operating, but produce too much power. That could lead to overheating and, potentially, a meltdown. That has already happened in one well-known instance, a very high power event from a LENR experiment that is described in a paper by Fleischmann and Pons in 1989.[30] They were conducting an electrolytic LENR experiment in which the cathode was a cube of Pd 1 cm on a side. During the night, the experiment suffered a thermal runaway, which led to the following statement in their paper: "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." After burning through the table, the thermal event left a hole in the concrete floor about 3 inches deep and 8 inches wide.[31] The level of power actually released in the meltdown in the Fleischmann and Pons laboratory is not known. It might be estimated by a three-dimensional thermal simulation in which temperature-dependent material properties are used. That would be a relatively complex simulation because of the many possible sites within the Pd cube, and the uncertain times, for the release of energy due to LENR.

Explosions are a problem worse than a meltdown, of course. They can cause significant damage to property and people. Several explosions have happened during LENR experiments and tests of prototypes. Mizuno and Toriyabe were operating a relatively large electrochemical cell, which exploded about one minute after the power was turned on.[32] Temperature measurements permitted estimation of the minimum amount of generated energy. It was a factor of 441 greater than the electrical power put into the experiment at the time of the last temperature measurement. The authors also considered energy generated between the last temperature measurement and the explosion, and the energy due to the measured hydrogen production. They concluded: "Taking into account these factors, we estimate the reaction produced ~800 times more energy than was input into the cell prior to the explosion." Many unexpected elements were found on the W cathode after the explosion. If those were actually the products of nuclear transmutations, then the cause of the explosion was certainly due to LENR, rather to a chemical event.

In 1992, Zhang and his colleagues described three explosions in electrolytic Pd-D experiments.[33] The cathode was a hollow Pd tube. They analyzed one of them and wrote "it is not a chemical explosion but a cold fusion explosion." Biberian had an experiment, also using a hollow Pd cathode, end in an explosion.[34] Thrice, he purposely triggered explosions using a mixture of hydrogen and oxygen, but the test cell was not damaged. Biberian concluded, "It is therefore possible that in this case the explosion was of nuclear origin: some kind of a chain reaction." He wrote, "It is very likely that...chain reactions occur in highly loaded palladium samples giving rise to an explosion." Chain reactions for LENR have also been discussed by Arata and Zhang[35] and by Srinivasan.[36]

Rossi was quoted as having observed numerous explosive events during the development and testing of E-Cat devices. On July 21, 2011, a report in Pure Energy Systems News noted: "Andrea Rossi has stated many times in the past a self-sustaining system is dangerous, and there is a chance of explosions. He actually indicated that during stress testing of systems he has witnessed dozens of explosions."[37] A video report about LENR on the web said that there were three LENR experiment explosions at the University of Bologna.[38] The video contains the following statement by Christos Stremmenos, a professor of physical chemistry retired from the University of Bologna: "Sometimes we had explosions, luckily at night. Three explosions. We noted changes in temperature from 400 to 1000 C." Explosive events in LENR experiments were also reported and discussed by others.[39,40] Recently, there was an explosion in the laboratory of the Martin Fleischmann Memorial Project.[41] The cause of that incident has not yet been determined. Explosions due to other causes, notably high pressures, have also occurred in LENR experiments.[42,43]

Smaller high power events have also been observed after LENR experiments. Craters less than 100 micrometers in diameter have often been found in cathodes after electrolytic LENR experiments. Examination of craters shows evidence of melting. Production of craters requires only small energies, 1 mJ or less,[44] but they form on time scales of less than 1 microsecond.[45] That combination indicates a power release of about 1 kW, but only in a very small region for a very short time. The power densities during the production of craters are very high because of the high powers and the small volumes. Craters are evidence of micro-explosions in LENR experiments. If the magnitudes of crater-producing events could be scaled to greater total powers and sizes, it is possible that such events could be dangerous.

One of the reasons for concern about runaway LENR systems is the high energy gains already reported in some experiments. As noted above, the energy gain G in a LENR experiment or generator is the ratio of the output thermal energy to the input electrical energy. In most LENR experiments and tests to date, the input energy has been electrical and the output energy thermal.

There is a remarkable fact about LENR, based on the ability to produce reactions, which release MeV energies, by using chemical energies on the scale of eV. The ratio of those energies indicates that the maximum LENR energy gain might approach one million, even without "burning." However, it is highly likely that many of the eV-level energies have to be spent in order to induce one reaction with an MeV output. Hence, if one thousand eV-scale investments are needed to produce one reaction, the gain would be only (!!) one thousand.

The largest energy gain in a Pd-D electrochemical LENR experiment in 2006 was 26.[46] There were many attempts in two laboratories to reproduce the performance. Several runs showed substantial energy gains. The highest energy gain seen in those replication experiments was 70.[47] Gains in the range of 80 to 415 from Ni-H experiments were reported on the web in 2010.[48] The highest energy gain is the value of about 800 reported by Mizuno and Toriyabe, already discussed above. The various high gains from LENR experiments have not been verified. To put these LENR gain values in context, it is useful to consider the International Thermonuclear Experimental Reactor (ITER) now being built in the south of France. That hot fusion facility is aiming for an energy gain of 10. The project will take much more than 20 years to build and operate at a cost far exceeding $20B. ITER will never produce power commercially. It will be interesting to see how the energy gains within commercial LENR generators evolve with time as experience with their safety record accumulates, and how those gains compare with data from contemporary hot fusion experiments.

It is noteworthy that Andrea Rossi and his company are now seeking to develop and market LENR thermal generators with modest gains of six to ten. Given the very high energy gains noted above, it is natural to ask why the commercial LENR generators now under development generally have gains of ten or less. That is apparently being done for safety reasons. High energy gains can lead to fast release of LENR energy. It is clearly necessary to strike a balance between use of possibly dangerous high energy gains and the achievement of adequate safety.

There are a few approaches to making LENR generators safe from runaway thermal or explosive events. It is best if they are fail-safe, that is, they cannot lead to problems that cause damage. Rossi has stated that, if temperatures get too high in one of his devices, they will ruin the ability of the key internal materials to produce energy and automatically shut down energy production. Such intrinsic safety is attractive, even though it would lead to loss of power production until the generator could be refurbished and refueled. Extrinsic means of safe operation are also possible, for example the use of pressure-release valves to prevent the accumulation of pressures sufficient to cause explosions.

Active systems for control of the output powers were discussed above under Question 27. They can be designed to forestall production of too much power by LENR generators. It might be possible to use temperature monitors to shutdown the input electrical power for systems that depend on continuous excitation to operate properly. Another safety measure might be the provision of a capability to suddenly cool a generator by the use of water or oil to prevent overheating.

It is clear that LENR systems can be unsafe due to conventional (chemical or pressure) or LENR-related phenomena. However, potentially unsafe operation is common in widely used engineered systems. Boilers and automobiles are among many examples. It seems likely that, given the several attractive characteristics of LENR generators, they will be engineered for safe operation under usual circumstances. Hence, LENR generators have the possibility of being safe, even in the hands of diverse consumers.

One of the hallmarks of the past two decades of research on LENR is the quantification of excess heat generally without the measurement of dangerous levels of either neutrons or gamma rays, despite numerous and vigorous attempts to make such radiation measurements. The hydrogen in LENR energy generators might prove to be much safer than gasoline now used in vehicles in large numbers (hundreds of millions). The input fuels for current experimental and possible near-term commercial LENR power and energy generators are apparently benign. They are available on the market now. Remarkably, the generation of energy using LENR results in essentially no radioactive waste. Sensitive measurements of some materials from LENR experiments have shown evidence of only weak emissions of unknown species with unmeasured energies.

In summary, some combination of the basic properties of LENR generators, such as fail-safe destruction of the efficacy of fuels in the event of overheating, and active control to shut off input power or provide immediate cooling, should lead to safe commercial LENR generators.

Q31: What are the challenges for regulatory approval of LENR generators?

As noted earlier, even if the development of a LENR thermal or electrical generator is entirely successful technically, there are other barriers to its market success. Regulatory approval is one of them. It is normal for governments to regulate commonly used services and devices that pose safety concerns. Either or both the sale and the use of some products are subject to regulations. There are two main types of problems with regulations. One is the fact that they can be imposed by various levels of government, including municipal, state and national organizations in the case of the U.S. The other is the complexity of many regulatory processes. A serious concern at this stage in the development of LENR products involves the possibility of early negative perceptions of their safety. One worry is that early accidents involving LENR generators would cause problems, even if they are due to incidents with steam or electricity.

The difficulty of getting approval of drugs and other technologies varies widely in different jurisdictions. It can be very expensive and time-consuming in some countries. The variations might be relevant to LENR. Some country, say the U.S., might be slow or reluctant to approve sales of LENR generators. Another country with great need for such technology and fewer regulations, maybe India, might put LENR generators into use more quickly. Then, if their use by consumers proves to be both beneficial and adequately safe, there will be pressure on U.S. regulators. Even if a country like the U.S. or one of the European countries refuses to approve LENR generators, global sales of large numbers of units might still be possible. This is especially true for LENR technologies because they might offer distributed (off grid) electrical power at low prices.

The Nuclear Regulatory Commission (NRC) is a national-level organization in the U.S. which seeks to "protect the people and the environment." Once LENR generators are close to being ready for market in the U.S., it is possible that the NRC will consider that their examination and approval is part of its responsibility. If that turns out to be the case, then adoption of LENR technologies will be considerably slower and more costly than in countries without the equivalent of the NRC.

There is no doubt than many LENR experiments have involved nuclear reactions. The data for reaction products, notably tritium and helium, and for prompt energetic radiations, is robust. However, some theories assert that part or all of the energy from LENR comes from the formation of compact objects.[49] Those hypothetical entities have binding energies and sizes intermediate between nuclei and atoms. The point here is that, even if some of the energy from what are termed LENR is not nuclear, the fact that nuclear reactions have occurred in many experiments might attract the interest of the NRC in the U.S.

There are reasons for regulatory agencies to want to approve the marketing of new products. Good products contribute to the well being and happiness of citizens. Also, most governments want to be friendly to companies in order to attract industries to their regions, since their sales will contribute to employment and the local economy, and generate taxes in the process. So, it is possible that LENR generators, with all of their potential advantages, will make it through approval processes in reasonable times and for appropriate costs.

Q32. What are possible problems with consumer acceptance of LENR generators?

Assuming that prototype LENR generators prove to be technically sound, that is, controllable, reliable and safe, and that regulatory approval is either not needed or secured, it is still possible for them to fail in the marketplace. That is not highly likely due to the many performance and cost advantages they might offer compared to existing thermal and electrical generators. However, the fear of things "nuclear" in some societies has to be considered. Without doubt, that N-word comes with negative public perceptions and challenges. Deft handling of public relations for early LENR products will be mandatory. It might happen that effective advertisement will play a significant role during the early years of LENR products, and maybe even later. In the U.S. now, there is relentless advertising of new drugs, and automobile sales are still the subject of numerous ads.

Terminology will also be important. Nuclear Magnetic Resonance (NMR) is the physical effect that makes it possible to obtain high resolution images of both soft tissues and bones from within a live body. When it became possible to commercialize that technology for medical diagnostic imaging, the companies decided to use the term Magnetic Resonance Imaging (MRI). That term is technically correct, of course, and has the marketing advantage of not including the word "nuclear" in the name. MRI has proven to be a routine procedure, a great boon to thousands of patients. Now, it does much more than only imaging. Functional MRI (fMRI) gives information on processes within the body. And, the recent development of Diffusion Tensor Imaging, based on MRI (dMRI), is now providing much information on connectivity in the brain. One can wonder if, given all the advantages, the public would have come to accept the term NMR, or if the terminology change to MRI was an enabling step in the acceptance and development of imaging technologies based on NMR.

It is well known to scientists and engineers working on LENR that there are many names for the field. A listing has been published in this magazine.[50] The situation is now complicated by the fact that there are some theories of energy generation in LENR experiments that do not involve nuclear reactions, as already noted. Of course, the appearance of nuclear transmutation products, especially tritium, and of energetic particles, especially neutrons, shows that nuclear reactions must occur in the experiments, whether initially or later. It may be that a widely accepted name for the effects behind LENR and for the field will not be achieved until after the mechanism or mechanisms causing LENR are understood. The current uncertainty, both in mechanism and nomenclature, was the reason for the naming of the company NUCAT Energy LLC. That was not motivated by Rossi's E-Cat. Rather, it is a meld of the words, NUClear and ATomic, the two levels of matter that are certainly involved in whatever is happening in LENR experiments and prototypes.

The widespread public ignorance and fear of things nuclear stands as an indictment against the educational systems in many countries. It is clearly borne of concerns about the effects of radiation from the atomic bombs used in World War II, and fears about radiation from reactor accidents. However, it must be realized that we are all (a) made of nuclei and (b) radioactive. The human body contains 0.4% of its mass as potassium.[51] Potassium has 25 isotopes, one of which is radioactive, namely ^{40}K. In a human body with a mass of 70 kg (154 pounds), there are about 4400 disintegrations of ^{40}K per second.[52] This is a very small fraction of all the atoms in the body, but it evidences the fact that we are radioactive.

Even if terminology is not a problem for nascent LENR technologies, there is the matter of consumer inertia. It has been said that, in order to succeed commercially by displacing existing products, a new product has to be faster, better or cheaper by significant amounts than what people are already buying. That view has its roots in an approach to space systems development espoused by a former head of NASA.[53] If LENR generators have the needed features of reliability and operability that they might, then their cost advantages should insure consumer adoption. The rate at which that evolution will happen is entirely uncertain now. It is very significant for people who are currently investing in the development of LENR products.

Companies developing LENR generators are hoping, actually betting, that all possible problems will be solved, even expeditiously. They expect to produce technically sound units that will receive regulatory approval and be accepted by consumers. Each of those factors is an issue. The times and costs it takes to achieve good performance and government approvals are also very uncertain now. However, despite such major concerns, it is still reasonable to look past current challenges to the availability and commercial success of LENR thermal and electrical generators. What will be their uses and impacts? Some of them are considered in the following section.

4. Applications of LENR Generators

There are two major ways in which technologies and applications interact. In one of them, the "pull" mode, the unmet needs of one or more applications drives the later development of technologies to satisfy the needs. In the other, called the "push" mode, the prior existence of devices leads to subsequent applications. This is a matter of opportunity, given a technology. The development of commercial LENR generators is an example of the second of these modes. That is, LENR generators are not being developed for any one use or set of applications. They are expected to have broad applicability to many current, and possibly some new, uses of heat and electricity. The specific uses will depend largely on the thermal and electrical powers available from LENR generators, as well as their reliability and economics. So, power levels are considered next. The potential use of LENR for production or destruction of specific elements or isotopes also leads to questions, which are addressed below. Finally, we address the question about the several larger possible impacts of LENR technologies.

Q33: What are the lowest and highest powers possible from individual LENR units?

The utility of reliable commercial LENR generators will depend on the magnitudes and characteristics of their output thermal and electrical powers. Such generators will fit into a spectrum of power generation technologies now in use. So, we begin with a brief review of the wide range of current energy generators. Commercial devices and systems generate thermal or electrical powers over a range exceeding a factor of over 10^{12}, from below milliwatts to over gigawatts.

On the low power end, there are some practical systems that use very little energy, for example, some nodes in wireless sensor networks.[54] These networks periodically turn on to relay data from places of interest to a central repository. When they are in the sleep mode, the nodes in wireless sensor networks consume very little power (microwatts). Those nodes are powered by batteries. That is, they do not require cables to obtain power, which is one of their trump advantages, enabling both remote and mobile operations.

There is a great deal of thermal, kinetic and photonic energy in most environments. However, the densities of environmental energies are low. Despite that fact, and inefficiencies in capturing, converting and storing such energies, it is practical to harvest (or "scavenge") the energies to power nodes in wireless sensor networks and other very low energy systems. The basic idea is to obtain and store energy at very low powers, even microwatts, to trickle charge batteries, which then deliver the energy at higher powers for very short times at long time intervals between transmissions. In the recent decade, the field of energy harvesting has grown greatly and become commercial.[55,56]

At the high power end, hydroelectric facilities produce powers as great as 22.5 GW.[25] Nuclear fission plants have power outputs as high as 8.2 GW.[25] Power stations that burn fossil fuels give outputs exceeding 5 GW.[25] Such centralized electric power facilities dwarf the units that are available for local power generation. The generators within some plants have power ratings of 125 MW.[57] Large but still portable electrical generators can put out powers exceeding 1 MW.[58]

The useful powers from LENR generators might also vary over many orders of magnitude. There has been research on the development of chip-scale LENR devices, which would have low but useful powers.[59] In another study, wires of Pd were micro-patterned on an inert substrate in a serpentine pattern. The wires were 2 μm thick, 100 μm wide, with a total length of 100 cm.[60] The experiments produced evidence for production of He. Power inferred from the He quantification was about 250 mW. The powers measured with thermometry were 10% of those values, presumably due to conductive and radiative heat losses. Importantly, there occurred regions about 2-3 mm long in which the wires were significantly altered, either melted or vaporized. Electrical heating could not account for the observed melting. Work with microstructured LENR devices has yet to result in devices that produce useful excess power. It remains to be determined if such devices are practical and reliable. Their utility will turn on the ancillary materials and devices that are needed to make them operate controllably. The reliability of such devices will depend on degradation by diffusion and chemical reactions within the key materials.

Many LENR experiments have produced powers ranging from milliwatts to a few tens of watts.[61] In general, such experiments are not even close to prototypes of products. An exception may be the NANOR®, which was developed and demonstrated by Swartz in 2012.[27] That device produces excess powers up to one watt. So far, it is only a laboratory device, albeit a very useful one because of its reliable operation. NANORs have been run for over three months, so they can be used for measurements not possible with less reliable LENR devices. There is no LENR experimental device that exhibits the reproducibility, controllability and reliability to form the basis for a product that would produce even 1 W of power. There have been multiple reports of LENR devices that produce kilowatts of power. They are summarized in a recent paper on energy gains.[62]

It might eventually prove possible to design, fabricate, test and operate safely individual LENR units in the megawatt range. They might be either scaled-up versions of kW units, or some entirely new design. However, the initial approach to that power range with LENR units has been made by scaling the number of units within the overall system. Rossi of Leonardo Corporation demonstrated a nominal 1 MW system. It reportedly produced 470 kW during a test in October of 2011.[63] The overall system contained 52 modules, each with three nominally 6+ kW E-Cat units.[64] However, different numbers of units were published in a recent book. Lewan, the author, counted 116 such modules, but Rossi stated that 107 were used.[65]

Scaling by using a large number of subunits has both advantages and disadvantages. If the basic unit works well, replicating it might be costly, but can result in an overall system that is satisfactory. But, the larger system is complex due simply to the number of components. Consider the number of connections needed in Rossi's 1 MW unit. Each of the individual E-Cat subsystems needs one input electrical power connection and, possibly, an input hydrogen gas line. It also requires one liquid (usually water) inlet and one outlet to carry away the thermal power generated by LENR. The total number of connections and seals totals a few hundred. It is worth noting that the large off-grid fuel cell systems can now produce over 7 MW.[66] MW LENR systems, once perfected and produced in significant numbers, might have complexities comparable to existing fuel cell systems.

It seems virtually certain that the issue of the lowest and highest powers available from LENR generators will not be resolved theoretically. Only when the means to control the rate of power release are known and reliable, will it possible to empirically determine the limits of power production by LENR.

Q34. What are LENR rates, and might they be sufficient for commercial production of valuable elements?

The primary commercial interest in LENR is due to the possibility of producing heat energy, which can also be used to generate electricity. But, that is not the only practical reason for attention to LENR. Considerable experimental evidence shows that LENR make it possible to transmute one element into another.[67] Attempts to cause such transitions, notably turning common metals into gold, are a well-known part of alchemy, as practiced in medieval times.[68] In response to this question, we review available or calculable LENR rates. They are then applied to compute the amounts of valuable elements that might by produced by LENR.

The rates at which LENR occur can be obtained from experimental or theoretical results. There are two ways to obtain rates from published experimental data. The first is based on reported rates of LENR energy production. The power P from LENR is the product from the rate R of reactions times the energy E per reaction, that is, P = R x E. Hence, experimental powers divided by the energy per reactions give the rates. The problem, of course, is that the individual reaction energies are usually not known. However, it is possible to use estimates of those energies to obtain rates.

Published reports of recent tests of E-Cat devices have given LENR powers as 532 W[17] and 1674 W[29]. Hence, for purposes of illustration, we consider LENR powers of 1 kW. Those tests presumably involved reactions between hydrogen and nickel. Dufour published the energies from neutron or proton captures by isotopes of nickel.[69] He included the decay energies of short-lived isotopes to obtain values near 7.85 MeV for the sum of reaction and radiation energies for both capture modes. The combination of this value and 1 kW indicate that the reaction rate in the E-Cat tests was 8×10^{14} Hz. That is, then, the rate at which transmutation products are produced.

The second method for obtaining LENR rates from experimental data does not require any assumption about the reaction energy. There have been several experiments in which the amounts of specific elements before and after the experiment were measured. They are referenced in a review on transmutations.[67] The differences between the ending and starting values, and the time of the experiment, give the average rate of LENR during the experiment. Measured values depend on the specifics of experiments, so they vary widely. One recent compilation, presented but unpublished,[70] gave them in the range from 10^6 to 2×10^{11} Hz. One example of such experiments is given in the following paragraph.

Miley and Patterson used plastic or glass spheres 1 mm in diameter that were coated with 0.65 microns of Ni in a recirculating flow electrolytic cell.[71] They performed analysis for the elemental compositions of the thin films before and after two-week long runs. Elements from Si to Pb were quantified. Using their measured rates of up to 10^{16} atoms/sec-cm^3 of nickel initially present in the system, we can estimate the elemental production rates. The volume of the Ni on a single micro-sphere was about 5×10^{-7} cm^3. If there are 1000 spheres in the system, the total volume of nickel would be near 5×10^{-4} cm^3. This volume, with the above rate, would yield about 5×10^{12} atoms/sec, or about 1.5×10^{20} atoms in one year of continuous operation. This is about 2×10^{-4} of a mole, or a small fraction of a gram for elements across the periodic table. If only the surface of the metal film mattered, rather than the volume, then the experiments might be redesigned using materials with large surface areas compared to their volumes.

LENR rates have been published by several theoreticians. Theoretical values vary widely. An unpublished paper presented at ICCF18[70] in 2013 gave values in the range from 10^{12} to 10^{14}. Here again, we will use the results from only one of the theoretical papers to illustrate available LENR rates.

The Widom-Larsen theoretical rates for LENR[72] can be used to estimate the time and surface areas that might be needed to produce significant amounts of elements by LENR transmutations. Taking their central value of 10^{13} reactions/sec-cm^2, the product of time in seconds and surface area needed to produce one mole of a reaction product is almost 10^{11}. One year is equal to about 3.15 x 10^7 seconds. Hence, for a reaction area of one meter squared (10^4 cm^2), it would take 10^7 seconds or roughly 16 weeks to make a mole of an element. That seems like a long time. However, the use of finely divided materials offers large areas for modest amounts of materials. Commercial catalyst materials have areas higher than 100 m^2 per gram. For them, one gram of materials has a total surface area of 10^6 cm^2. For that mass, the time required to produce one mole of atoms of a given element would be 10^5 seconds, or about 28 hours. For 100 grams of such material, 17 minutes would suffice to make one mole. Such estimates depend on the entire surface area being active.

Whatever the source of LENR rates, they can be used to compute the amounts of materials that might be produced in a given time. Such times are central to the possibility of making money by the generation of valuable elements, for example, platinum, from less costly elements. There is said to be an interest by one company, Continuum Energy Technologies LLC, in the possibility of production of elements for profit.[73] Their technology is based on what they term as "thermally tailored copper."[74]

The equation relating the LENR rates R in Hz to the grams G of an element with molecular weight W that can be produced in time T involves Avogadro's number A: $G = (W/A) \times R \times T$. This equation shows the production of valuable elements will not be fast because Avogadro's number, which is in the denominator, is so large: $A = 6.02 \times 10^{23}$ atoms per mole. For purposes of illustration, we can use the rate of about 10^{15} Hz obtained above from the E-Cat tests and Dufour's estimates of energy per reaction. One mole of an element is equivalent to a number of grams numerically equal to its atomic mass. For platinum, W is 195 grams per mole. In one hour (3600 sec), about 10 micrograms of platinum would be produced. One gram of platinum is worth about $40, so the amount produced by LENR transmutations in an hour would be worth less than one penny. That is certainly not enough to pay for the amortization and operation of the LENR reactor, and the building in which it is housed. This problem cannot be solved by the use of multiple LENR reactors in the same building, because the production rate of a valuable metal is so slow.

The energy that would be produced as a byproduct of transmutations would be valuable, of course. So, what is the value of 1 kW steadily produced for one year (8766 hours)? At $0.1 per kW-hr, it would be $876.60. That greatly exceeds the value of the platinum produced. The energy might be used to operate the LENR generator and its controls, and heat the building, and even be sold to the grid. However, the remarkably small value of the produced metal would not make that approach viable for any reason other than energy production.

Meulenberg suggested the possibility that valuable elements might be generated as byproducts in LENR generators of heat or electricity.[75] If they are operated in large numbers, as many people expect, the recovery of valuable elements after operation is worth considering. Using the same numbers as in the last paragraph, operation for one year would result in about 0.1 gm of platinum worth approximately $4. The ability to make money from that "waste" would depend on two key factors. The first is the requirement of producing a valuable element during production of heat or electricity by LENR. Experiments to date, and theories about LENR, have not shown or suggested that it is possible to transmute any element into any other. If nickel and hydrogen react to produce copper, as reported for the E-Cat, the economics are not favorable. The second requirement is low-cost extraction of any valuable elements from the spent fuel of a LENR generator. The field of chemical separations is well developed,[76] so it should be possible to make good cost estimates for elemental separations, given the materials involved and assumptions about specific processes.

It is possible that much higher LENR rates will be achieved in the future, enabling shorter times for production of valuable elements. But, relatively short transmutation production times would still come with practical challenges. The locations at which transmutations occur are critically important to the possible commercialization of LENR production of desired elements. If transmutations occur partially or completely within the bulk of materials, the situation is much less likely to be commercially viable than if they occur only on the surfaces of the materials that are needed to cause LENR. That would be the case because chemical extraction of elemental products from on or near surfaces requires less reagents and is faster than removing products from within the bulk of materials. However, reaction products on surfaces, or processes to remove them, might destroy the ability to produce more LENR and transmuted elements.

Given the empirical evidence that LENR occur on or near surfaces, we consider practical implications. Suppose that a finely-divided substrate material could be used to produce useful amounts of an element. It would be necessary to get the precursor element into position on the surface and to remove the transmutation products from the surface quickly and in an energy efficient manner. There are two general approaches to such processes. In one, the reaction surface is fixed in place within a reactor. Then, the reactants would be brought to the surface and the products removed from it. This method is commonly used with immobilized catalysts in many bulk organic chemical processes. The other method is to mix the reactants with the particles on which transmutations would occur in a liquid or fluidized medium. After the desired transmutations occur, the combinations of the products and the particles with reactive surfaces could be moved downstream for chemical separation and recycling of the particles. This would require complex process equipment. In either approach, it is necessary to avoid destroying the long-term efficacy of the surfaces on which the transmutations occur. It seems unlikely that it would be cost- or energy-effective to use the particles with active surfaces only once and then discard them.

It is evident that a great deal of materials and chemical engineering is needed before designed transmutation of elements is commercially viable. It seems likely that such engineering will occur only after LENR has been shown to be a commercially valuable source of heat and electricity.

Q35. Is the destruction of radioactive waste materials by LENR possible and practical?

For a good part of the history of LENR since 1989, hopes have been expressed that LENR could be used to remediate radioactive waste from fission reactors. That waste has three very unsavory characteristics. It remains radioactive for times on the order of thousands of years.[77] It can be used for dirty bombs and other threats by terrorists. And, there are massive amounts of such waste. The roughly 400 fission reactors active in the world produce about 10,000 m^3 of high-level waste every year, which requires both shielding and cooling.[78] It should be noted that hypothetical hot fusion reactors, which might come on line around the middle of this century, will also produce significant radioactive waste. It is projected to be dangerous for "only" a century. But, whatever the source, some people have speculated on the possibility of turning radioactive elements into benign, even valuable elements, and extracting more energy from them in the process by using LENR.

One of the motivations for hoping that LENR can remediate fission waste is the experimental fact that little radioactivity remains after LENR experiments. However, there are two major shortcomings directly relevant to this hope. First, there is little experimental data on the efficacy, and even the possibility, of turning all of the radioactive isotopes in fission waste into benign materials. Second, no one has done even rudimentary estimates of the practicality of LENR processing of radioactive waste. In the following paragraphs, we summarize the experimental work done on attempts to destroy radioactivity by means of LENR. Then, we offer some estimates on radioactive remediation rates, quite in the same spirit as those above for the production of desired elements by transmutations.

In the mid-1990s, the Cincinnati Group provided evidence for remediation of radioactive elements by a process they called LENT for Low Energy Nuclear Transmutations.[79,80] Their process was said not to be the same as LENR (then "cold fusion"), but it involved use of an electrochemical cell. The experiments were done with and without a thorium salt in the electrolyte. They claimed that a large fraction of the initial Th (over 90% in some runs) was transmuted into copper and titanium. The copper, which was found in the cells after the hour-long runs, was reported to have a strongly reversed isotope ratio for ^{63}Cu vs. ^{65}Cu. Several analytical techniques were employed in different laboratories to quantify the contents of the cells before and after the runs. The results of two third-party tests were published. The group offered kits for sale, but it is not known how many were bought. Apparently, the Cincinnati Group no longer exists.

Another study published in 1998, which attempted to destroy radioactivity by LENR, employed a circulating electrolyte in a Patterson cell, which contained ^{235}U depleted uranium and thorium "slightly impregnated" into a proprietary matrix.[81] One part of the overall experiment was performed inside of a lead housing to shield cosmic ray effects. The housing had old lead, with very low radiation background, lining its interior. A gamma ray detector viewed the entire LENR experiment. No decrease in radioactivity was observed during a run of a few days. Results of other analyses are also given in the paper on related experiments.

Work on the possibility of using LENR to remediate nuclear fusion waste has continued. Esko and his colleagues conducted transmutation experiments in vacuum systems in which glow discharges or arcs were produced near materials. They summarized such experiments in an article in this magazine in 2014[82] and in a book.[83] The experiments were reported to consistently produce potassium, germanium and gold. In a recent book, Esko and Jack "present a fresh approach to solving the problem of nuclear waste."[84] Their optimism contrasts with the engineering and financial realities for remediation of nuclear waste by use of LENR.

Simple calculations illustrate the challenges of rendering fission products harmless. If the density of radioactive waste from fission reactors is taken, very conservatively, as the density of water (1 gm/cm^3), then the 10^4 cubic meters of waste produced annually weigh 10^{10} grams. Taking the atomic mass of the waste to be 200, there are about 5×10^7 moles of waste generated per year. Curiously, this is about the number of seconds in one year. Hence, to keep up with the ongoing waste production, one mole of radioactive materials would have to be handled and subjected to effective LENR each second. Note that this would not address the large stockpile of fission waste from previous years. That amounts to about 3×10^5 m^3, which is about 30 years of waste at the production rate of 10^4 m^3 per year.[85]

We have yet to consider the overall engineering and economic situation for LENR remediation of radioactive waste. Assume for the moment that it is possible to induce all of the radioactive isotopes in fission waste to participate in LENR. That is, we imagine a scenario where it had been established scientifically that LENR provides a means to render safe all dangerous isotopes in radioactive waste. It has to be noted that such complete remediation is not a likely scenario, given the wide variety of radioactive isotopes in fission waste.[86] Next, consider the engineering challenges of retrieving that waste from current storage locations and introducing it into large numbers of LENR reactors positioned near the stored waste at many locations globally. The handling would have to be done with automated machinery because of the danger of the radioactive waste to humans. It is likely that the LENR reactors and the materials within them would become activated. That is, even after large expenditures of money and time for LENR reactors and for equipment to handle the high-level waste, there might still remain significant amounts of lower-level radioactive waste.

The LENR reactors for remediation of fission waste would require significant ancillary equipment to carry off the heat produced during the remediation process. If that energy were to be used beneficially, the equipment and facilities that would run on it, or use it for materials processing, might have to be located near the stored fission waste. Almost certainly, moving the waste to where the LENR reactors are located would be prohibitively costly. It would also raise public safety concerns. That means both the LENR reactors and the facilities that employ the heat produced by LENR using radioactive waste isotopes would have to be located near the many reactors that currently store fission waste. There are hundreds of sites globally where fission waste is stored, over 100 in the U.S. alone.[87] The capital investment to build LENR reactors and heat-consuming plants at even half of those would be very high, probably on the order of several $B. The operation, maintenance and eventual disposition of the facilities and their equipment would also be very expensive. If the heat generated by LENR remediation of radioactive fission waste were not used, its dumping into the environment would contribute, albeit insignificantly, to global warming and climate change.

In addition to the engineering and environmental difficulties posed by processing radioactive waste from fission reactors into something more benign, there remain the underlying scientific questions. The makeup of fission reactor waste is well known.[86] Currently, there is very little data on the ability to induce those medium or heavy waste elements to participate in LENR and become less radioactive elements. The reason for this is simple. The handling of radioactive elements in LENR experiments is challenging from both safety and regulatory perspectives. Hence, it is expensive and has not been done.

It is obvious that much scientific work is needed, probably in heavily shielded enclosures, to establish which of the many radioactive isotopes in fission waste might be rendered safe by LENR. It is possible, maybe even likely, that not all long-lived radioactive isotopes can be turned into benign elements. That is, even after overcoming challenging engineering and processing issues, substantial radioactivity might remain. However, advances in the understanding of LENR might eventually change the current perspectives on what is practically achievable regarding transmutations. Current means of storing fission waste, generally at or near reactor sites, are not likely to be impacted by LENR technologies in the foreseeable future.

Q36: What might be the greatest impacts of LENR generators?
Whatever the long-term outcome of the use of LENR to produce valuable elements or destroy radioactive isotopes, the available experimental database indicates that such reactions have many possible advantages. That is most true for energy generation. If those advantages are realized, LENR could have major global impacts. The 2004 book by Rothwell deals with many of the advantages and potential impacts of LENR technology.[88] Chapter 1 of that book is a list of ten Frequently Asked Questions written by Rothwell and Mallove. A summary of the advantages and possible impacts of LENR was published in this magazine in 2012.[89] A similar paper giving the challenges, advantages and impacts of LENR is on the web.[90] Here we simply list the potential advantages before discussing the larger conceivable impacts of LENR.

The contemplated advantages of LENR can be grouped into a few categories. They include:

1. High performance due to large energy gains from fully controllable reactions, which generate heat for diverse uses, or electricity for immediate employment or for charging of batteries in cars and other systems.
2. Low costs for equipment, fuels and operations, including long lifetimes, which should lead to widespread adoption.
3. Attractive operational features, including easy and silent operation, straightforward refueling and long times between changing fuel canisters.
4. Designs for safe and even fail-safe operation, with very low probabilities for explosions or other serious malfunctions.
5. Benign and abundant fuels and products, free of chemical or radiological dangers.
6. Environmentally friendly operation without greenhouse gases, significant prompt radiation and radioactive waste, with normal disposal of generators at the end of their utility.
7. High energy and power densities, leading to generators that are small, lightweight, portable and distributed, with fewer large power stations and lessened grid requirements.

These possible advantages of LENR power generators are very important. They are, in fact, the basis of the optimism about the future large-scale impacts of LENR. However, it should be noted that there is significant over-enthusiasm about the promise of LENR. The subtitle of a recent book *Rossi's eCat* reads "Free Energy, Free Money and Free People." LENR generators of heat and electricity will have to prove to be (a) technically reproducible, controllable, reliable, safe and cost-effective, (b) properly regulated by governments and (c) accepted by consumers, before they will capture even a small share of the energy market. That will not happen soon. However, if all those requirements are well met, it is possible that LENR will capture a significant share of the global energy market in the coming decades. That market in 2013 was equivalent to 9.3×10^{10} barrels of oil.[91] The tally includes commercially-traded fuels, including modern renewables used to generate electricity. At $60/barrel, the equivalent is about 6×10^{12} USD. Hence, even a 1% market penetration by LENR will be enormous.

Whatever the ultimate achievements of LENR technologies, they could be very significant. We will now consider each of eight conceivable major long-term impacts in view of the possible advantages of LENR.

Low Cost Power. Some predictions have already been made. Rossi has asserted two particularly interesting numbers. The first is his expectation that electricity produced with his E-Cat units could cost only about 2 cents per kW-hr. That is less than 20% of the cost of power in most of the U.S. now. By itself, such performance would insure the widespread adoption of LENR sources of electrical power. The numbers for production of thermal energy using E-Cats are even more compelling. Rossi estimated that the amount of nickel in a U.S. five cent coin, that is, 1.25 grams, would produce energy equivalent to five barrels of oil. This author has checked that computation and got 2.5 rather than 5 equivalent barrels. What if the nickel in the coin produced energy equal to "only" one barrel of oil? A barrel of oil now costs roughly $60. Hence, the fuel cost of a LENR thermal source could be 20 x 60 = 1200 times less, compared to oil. If this proved to be the case, then the availability of commercial LENR power will be remarkably "disruptive" to the global economic and political status.

Distributed LENR Generators. One of the greatest projected impacts of small, few kilowatt LENR generators of heat or electricity is the possibility that they will be in individual homes and other small buildings. Homeowners now have considerable control over their *consumption* of electrical energy. If they have their own LENR power generators, they will also have much control over their own *generation* of energy. That control naturally comes with the responsibility to keep the units in good operating condition. It would be much like the current use of automobiles. Drivers are responsible for insuring that they have adequate gasoline on board and for proper maintenance of the car. If, as expected, both heat and electricity are produced locally, then homeowners and other users of electricity would no longer be susceptible to brown- and black-outs due to power station or grid problems. They might be able to produce energy using an as-needed routine.

Proliferation of Electricity. Not long ago, over half of the people on earth had never talked on a telephone. The explosive adoption of cell phones is rapidly increasing the use of telecommunications in poorer as well as richer countries. Similarly, over one-third of the seven billion people in the world still lack electricity. If LENR electrical generators are affordable to the developing parts of the world, then those 2+ billion people could use technologies that require electricity, most notably computing and communications. The pervasive availability of computers and the internet would have dramatic impacts on education and, hence, economic productivity, not to mention greatly improved lifestyles and contentment.

Production of Clean Water. Humans need water on a frequent basis to sustain life. Roughly one billion people on earth do not have good drinking water now. Being able to produce drinkable water from dirty rivers and saline seas using the heat from LENR would be momentous. It could turn out to be one of the main drivers for exporting LENR generators into what are called "third world" countries. Favorable pricing of LENR generators for such countries could conceivably contribute significantly to world peace. The situation might be similar to the current sales of medicines for AIDS to poor countries at reduced prices. Rich countries will not soon give poor countries a significant fraction of their wealth. However, they could provide some of the energy needed for development and local wealth production at discounted prices, while still making much money from manufacturing LENR energy generators.

Global Medical Impacts. The availability of water free of pathogens and parasites to a very large number of people should lead to dramatic reductions of the incidence of many diseases. The savings of lives, human suffering and costs of medical assistance, where it is available, might greatly outweigh the cost of buying and using LENR generators. The better availability of electricity would improve both the diagnostic and therapeutic sides of clinical medicine.

Fewer Environmental Impacts. The production of LENR generators should cause no more environmental degradation than the manufacturing of cars or other large-volume consumer products. Their operation should not produce air pollution, greenhouse gasses or other emissions, such as dangerous radiations. The wide adoption of LENR technologies will not, by itself, solve the climate change problem. But, it could slow the increase in global temperatures and, thereby, ameliorate the already clear and possibly devastating effects of global warming. This scenario depends on disciplined use of power from LENR. Cheap water in some places leads to wasting of water. Wasteful use of LENR energy must be avoided, or it could lead to a new (non-solar) contribution to global warming. LENR generators will leave behind no significant radioactive waste, and can be recycled as is increasingly normal for consumer goods. So, their overall effect on the environment might be strongly positive, if they are used conservatively.

Global Economic Shifts. Should the uses of LENR generators approach the possibilities now contemplated by some people, there might be dramatic economic changes in the world as we know it today. There could be new economic paradigms on levels ranging from the personal to organizational to national to global. If individuals were able to spend dramatically less on energy, money would be freed for other expenditures and for investments. Existing industries could redeploy capital from energy to use of newer technologies. More energy intensive industries might become viable. Nations that now get a large fraction of their energy from abroad might be able to afford better education or medical care. Transportation costs might decrease at all levels. The sum of the potential impacts on many levels would change the economic world as it now exists. However, such changes would take decades.

Global Political Changes. If the dominant source of energy in the world did not depend on the vagaries of geology, but on the technology and manufacturing prowess of any (or many) advanced nations, the world could have a new political paradigm. Greater efficiencies of production of goods and delivery of services in the advanced countries would be a "game changer." Peoples and nations that have not enjoyed the benefits of modern technologies could begin to do so, and gain hope in the process. Healthier and more capable people could do more and accelerate globalization of good conditions, the so-called "flattening" of the earth.

One possible impact of the widespread adoption of LENR technologies was the subject of recent comments by Rossi. Ackland asked him, "What are the kinds of jobs you hope to see created as a result of your work with the E-Cat?"[92] Rossi responded: "The mass production of E-Cats will generate a miscellanea of jobs: blue collars, white collars, chemical engineers, physicists, informatics, electronic engineers…industrial E-Cats are very complex machines, demanding many integrated disciplines; I hope this work of us will be a game changer in the employment sector. I really hope that we will be able to create jobs in massive measure, directly and indirectly." Adoption of E-Cats in developed countries would displace currently-employed generators. That is, it might not lead to greatly increased employment in advanced countries, unless it leads to much more widely available energy sources. It is in poor and developing countries that the adoption of LENR generators could have strongest impacts on employment.

5. Conclusion

This set of papers was organized along the lines of Figure 3. It shows the relationships among Science, the focus of the first two papers, and Engineering and Business, covered in this paper. This is a beneficial cycle in which scientists, engineers and business people are all able to pursue their interests in synchrony with each other. The current situation for LENR is indicated within the boxes in Figure 3. The experimental side of the science of LENR is rich with results despite many remaining challenges. In contrast, theoretical understanding of LENR is still in an early phase, the large number of theories notwithstanding. The engineering of many LENR experiments has become quite sophisticated after a quarter of a century of criticism. However, engineering of many of the prototypes of products is still relatively crude due to lack of funding and haste by companies racing to get to market. There are basically two types of companies interested in LENR. The first is a group of small and relatively new companies devoted exclusively to the development of commercial LENR products. The second contains a significant number of existing companies that might be impacted by LENR, which are closely watching developments in the field. It is hoped that the questions in these three papers are of interest to people in all sectors shown in Figure 3.

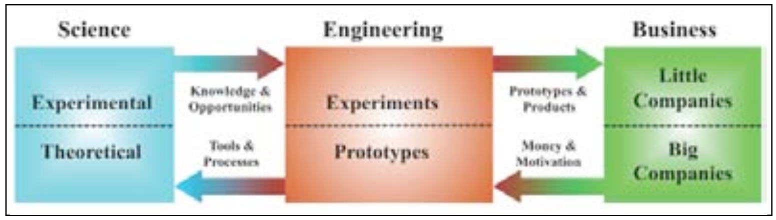

Figure 3. Knowledge and Opportunities flow from Science to Engineering, which provides Prototypes and Products to Business. Money and Motivation are provided by Business to Engineering, which develops Tools and Processes for use in Science. Business success clearly depends on applications of products that make money.

The three dozen questions addressed in this trio of papers is certainly not an exhaustive list of remaining questions about LENR. Each of the conditions already known to promote the production of LENR generates questions, such as the need for high loading in electrochemical experiments. There are serious issues about the role of magnetism in LENR, the absence of prompt gamma ray emission during most LENR experiments, the remarkable lack of radioactivity after such experiments and the role of rapid thermal changes in enhancing excess heat. Also, the causes and characteristics of heat-after-death and radiation-after-death are still not understood. There are also questions about the highest potential energy gains in LENR systems. It is certain that a poll of scientists active in the field would generate more questions and suggestions on how to address them. Nonetheless, it is hoped that the questions in these papers provide an adequate basis for planning of research and development programs on LENR in the feasible future.

Program plans for addressing the science and applications of LENR are not new. Many have been considered by individuals and organizations. However, there are few papers on them. One was offered by this author in this magazine in 2006.[93] Very recently, a research program was posted online by Prosvirnov.[94] It uses CNF for Cold Nuclear Fusion rather than LENR. The recommended activities are:

1. Fundamental studies of the phenomenon of cold fusion.
2. Development of experimental and technological base to work on the problem of CNF.
3. Study of the environmental problems associated with the phenomenon of CNF.
4. Evaluation of the possibility of commercial use of the results of work on CNF.
5. Patent and information support. Creating a database of information.
6. Conducting R&D to create demonstration power plants and prototypes of new equipment technology using CNF reactions.

Here again, many individuals active in studying LENR could provide plans for addressing the science and commercialization of LENR.

There are many other less scientific and practical questions about LENR. One of the most important is what will it require for the subject to be accepted as a legitimate field of science, regardless of its practicality? Many people think that a reproducible and easily replicated experiment, maybe even available in kit form, would cause LENR to be accepted as the scientific field that it is and has been for one-quarter of a century. Another possible breakout could come from a clearly correct theory, one that has been tested adequately and widely accepted in the LENR scientific community. Some people have adopted an extreme position. They will not accept the existence of LENR until there are products on the market that operate because of LENR.

There are numerous published questions about LENR and other areas of science. A key point is that, however interesting and potentially important are the questions about LENR, there are larger and probably more significant questions abroad in science today. We note two sets of LENR-specific questions, and then briefly turn to another two lists of questions that involve much bigger concerns.

A recent paper by McKubre, which addressed questions and criticisms of research on LENR, is available.[95] It dealt with three questions:

1. What do we think we know?
2. Why do we think we know it?
3. Why do doubts still exist in the broader scientific community?

McKubre and other scientists working on LENR can pose many more detailed technical questions than these strategic concerns.

The blog by Gluck provides an interesting and useful mix of commentary and references. He recently posed the following questions about LENR:

1. In order to become accepted does LENR have to demonstrate that it is real, or must it be both real and useful?
2. Is research aimed at intensification of heat release a deviation from the main task, *i.e.* scientific understanding of the LENR phenomenon, or, on the contrary, a very necessary shortcut due to a hostile and dim reality?
3. Must the solution of the LENR problem start from and be based on what we already know, or will we be forced to discover surprisingly new ideas and facts?
4. Are the basic facts discovered for the primordial PdD system valid for the entire range of temperatures at which generation of excess heat was demonstrated, or does increasing the temperature lead to more transformative and disruptive qualitative leaps?
5. Is the NiH LENR system mirroring the PdD LENR system, or is it a different species, scientifically and technologically?
6. Can a single theory describe comprehensively both the Fleischmann-Pons phenomenon and everything that was discovered later or, due to the complexity of LENR (multiple stages, including pre-nuclear, nuclear and post-nuclear), does LENR need a combination of different theories?
7. Does Nature always take the simplest path and use the fewest mechanisms possible, or on the contrary, is Nature narcissistic trying to be as interesting as possible, because Nature has no problems, only solutions?

Gluck does not expect quick answers to these questions. They are not likely to be answered until the mechanism(s) behind LENR are understood.

There are also scientific questions of a nature larger than those about LENR. The human brain is said by some to be the most complex entity in the universe. A great deal is known about our brains at the lowest levels, including molecules, cells and some circuits. And, much is known about the highest level of behavior. But, the intermediate levels that connect chemical and electrical events to perception, cognition, emotions and behavior are still not understood. Major brain research initiatives began recently in the U.S. and Europe for both scientific understanding and clinical applications. They are driven by many questions. One set was given in a book published this year.[96] Paraphrased and simplified, they are:

1. What kind of information processor is the brain?
2. What type of computations do we use in domains where knowledge and instructions are not explicit, as they are in an electronic computer?
3. How does the brain implement the rules that govern language?
4. Is there a single form of computation or a range of basic operations, similar to instructions in a processor?
5. What formats does the brain use to encode information?
6. Why does the brain contain so much diversity, ranging from hundreds of types of neurons to over 100 cortical areas?

These questions have a decided computational bent since the author studies computational aspects of the brain. Answers to these and many other questions about the brain may beneficially impact the treatment of various mental disorders such as autism and alzheimer's disease. It might take decades to obtain answers to these questions.

There are a few scientific questions that are widely recognized as being among the most important and difficult of our times. One list of such questions was published by Achenbach last year.[97] They are:

1. Why does the universe exist?
2. What is matter made of?
3. How did life originate?
4. How does consciousness emerge from the brain?
5. Is there intelligent life on other worlds?

Answers to these questions should not be expected soon. It is impossible to predict now what, if any, practical impacts will come from the answers. By contrast, it can be hoped that answers to questions about LENR can and will be available in the coming years and will have great commercial importance.

The questions asked in this trio of papers should not leave the impression that little is known about LENR. Thousands of experiments, and hundreds of reports based on them, have provided an empirical database on many of the procedures needed to produce LENR and what happens when they occur. The website lenr-canr.org is a particularly rich and well organized source of information on LENR. That site has a few thousand papers, which are downloaded at monthly-averaged rates sometimes exceeding one per minute. The International Society for Condensed Matter Nuclear Science (http://www.iscmns.org/library.htm) has a large compilation of LENR references. Dieter Britz has a major compilation of references and abstracts at: http://www.dieterbritz.dk/fusweb/papers. Cold Fusion Times offers an interesting and useful mix of news and technical material: http://world.std.com/~mica/cft.html. This magazine has almost 400 full articles and other information about LENR and various topics at its website: http://www.infinite-energy.com. The website of the New Energy Institute is also a rich source of information about LENR and related topics: http://news.newenergytimes.net/. Many of the proceedings of the International Conferences of Cold Fusion can be found there. E-Cat World is a good source of news about E-Cat and related technologies: http://www.e-catworld.com/. ColdFusionNow has a website with much useful information on the topic, including many videos listed under Events: http://coldfusionnow.org/. Pure Energy Systems News reports on alternative energies, LENR included: http://pesn.com/

Logically, reviews of what is already known should have preceded this series of questions. However, it is the hope of the author that there will soon be serious consideration of major programs to understand and exploit LENR. What is not known, the foci of these questions, should be immediately useful in planning both research and development programs. That would be true for governments, industrial organizations, companies, foundations and any other organizations or individuals with the significant funding and the foresight to recognize the potential of LENR.

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