The Intersection of Low Energy Nuclear Reactions with Nanometer-Scale Science, Technology and Engineering

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Abstract — Some backgrounds on nanotechnology and on low energy nuclear reactions (LENR) are given as a prelude to citing evidence that LENR are often surface phenomena occurring on the nanometer scale. A simple relationship to compute the powers produced by LENRs and a graphical means to relate the power to four surface and nuclear parameters are provided. Future experimental work on LENR should exploit the tools used for nanometer-scale measurements. The engineering of reactors based on LENRs will also require attention to nano-scale structures. A new reactor engineering discipline will be needed to turn the current science of LENR into practical sources of energy.

1. Introduction to Nanotechnology

The ability to make things out of molecules and atoms is something of a last frontier. They are the smallest neutral building blocks that can be joined to make materials and structures. Nuclei and sub-nuclear quanta are smaller, but they cannot be made into stable materials and structures. Just as things on the micrometer scale are a thousand times smaller than the visible millimeter scale, nanometer-scale items are another thousand times smaller than the micrometer scale. These relationships are illustrated in Figure 1.

There are two key facts about materials and structures with one or more dimensions on the nanometer scale. First, they can usually be grown, that is, made from the "bottom up." This contrasts with manufacturing processes that proceed from the "top down," including ordinary machining and the production of electronic and mechanical chips. The second distinguishing aspect of the very fine-scale structures is their properties, which can differ radically from the properties of the same materials on a larger scale. The new properties permit making electrical, optical, and other materials and devices that have better or, even, entirely new performance and applications.

The promises of nano-science and -technology became widely recognized about a decade ago. The ensuing excitement caused dramatic increases in funding for research and development. The history of public funding of nano-technology in recent years, given in Figure 2, shows the trend. The illustrated growth is among the few fastest increases in the support of specific research and development topics since World War II. That growth made nanotechnology one of the hallmarks of this age, along with information technology and biotechnology.

2. Introduction to Low Energy Nuclear Reactions

In 1989, two chemists announced that they could produce nuclear reactions and thermal energy under ordinary conditions of temperature and pressure using electrochemistry. They were Martin Fleischmann and Stanley Pons. The reactions were termed "cold fusion," even though no one really knew then with confidence that nuclear reactions were occurring. Their novel experimental work was at odds with known theory and became extremely controversial. Many scientists concluded that there were no nuclear reactions, and the reported experiments were in error. In fact, cold fusion became a widely-known and still-cited example of science gone wrong.

As time passed during the 1990s, processes other than fusion of two deuterons were reported. They included transmutation reactions, which involved and produced isotopes of nuclei with moderate and high atomic weights. That is, they are nuclear reactions not involving only two light nuclei, such as fusion. Because of this, and to emphasize their viewpoints, some researchers in the field sought other names for the effect announced by Fleischmann and Pons. These names include Low Energy Nuclear Reactions (LENR), Chemically Assisted Nuclear Reactions (CANR), Lattice Assisted Nuclear Reactions (LANR), Cold Nuclear Transmutations, Cold Fusion Nuclear Reactions, and New Hydrogen Energy. At present, given all the problems with the name of the field, many people are simply referring to the mechanism(s) active in the experiments that followed from the 1989 announcement as the "Fleischmann-Pons Effect" (FPE). We will use the term Low Energy Nuclear Reactions in this paper to emphasize the possibility of producing a variety of nuclear reactions with low input temperatures and energies.

LENR have been studied by hundreds of scientists globally since the field began in 1989. At this time, the experimental evidence for the ability to induce nuclear reactions under very anomalous conditions is very strong. Further, many of the characteristics of the reactions and their products are already known. Measurement techniques, and results obtained using them, have been published in over 1,000 scientific papers, many of them in refereed journals. The mechanisms for the nuclear reactions are not yet understood theoretically or computationally. Nevertheless, the empirical information shows that the reactions commonly produce "excess" energy with harmless helium as the primary by-product. In most experiments, there is neither sig-

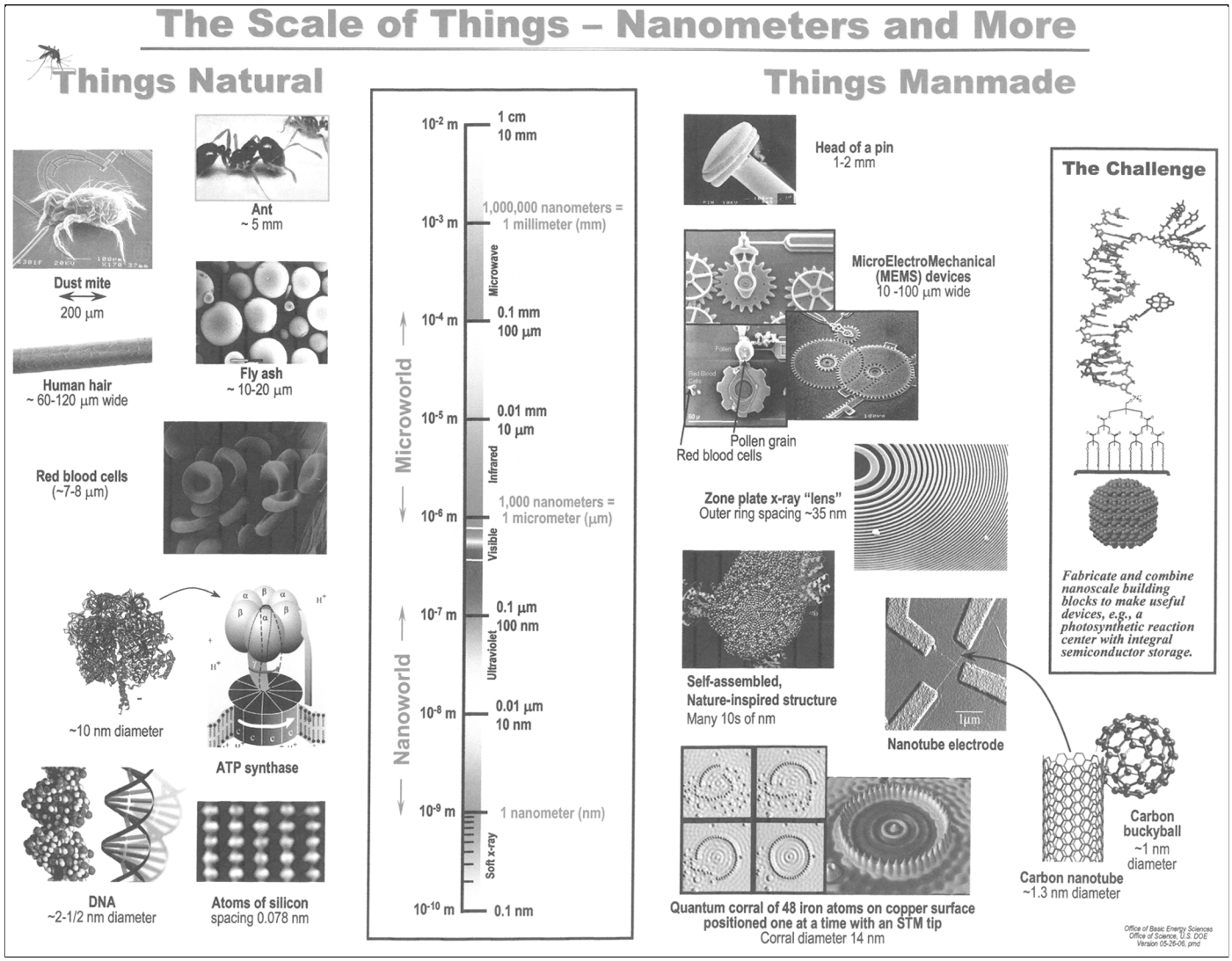

Figure 1. The size scales of natural and manmade objects, ranging from 0.1 nanometer to 10 millimeters. The domain of nanotechnology is 0.1 to 100 nanometers. Similarly, the range of microtechnology is 0.1 to 100 micrometers. Source: U.S. Department of Energy

nificant immediate radiation nor residual radioactivity. Several start-up companies in the U.S., and many other academic, government, and industrial organizations worldwide, are working on the science of nuclear reactions, in which a solid lattice plays a central role.

To people unfamiliar with literature of the field, the very wide variety of experiments and results presents a barrier to learning about what has been done and found. It is possible to organize the reported experiments according to what was put into them and what came out of them, as shown in Figure 3. In the field of LENR, solid lattices are common to almost all experiments. However, the phases from which hydrogen isotopes are introduced into lattices span the possibilities indicated in Figure 3. The ways with which lattices can be loaded with protons or deuterons fall into four broad categories. Initially and most commonly, electrochemical methods are used for loading protons from light water or deuterons from heavy water into an immersed lattice. In a few experiments, molten salts were the liquid source of the hydrogen isotopes. Many experiments have also been done with lattices placed within hydrogen or deuterium gases, usually at elevated temperatures and pressures. The next large class of loading methods involves plasmas as sources of energetic protons or deuterons. Glow discharges are commonly used. Finally, many experiments have been done in which beams of protons or deuterons impact a solid. Some of these beam experiments are done at energies high relative to ordinary temperatures. However, their relevance to the field of LENR has been established. In all four cases, a solid is involved, with palladium being used most commonly. Many LENR experiments have been done with nickel as the solid.

No matter how the conditions to achieve LENR are produced, there are four major types of products from those reactions, as indicated in Figure 3. The production of energy, called excess heat, is of greatest interest. The nuclei that result from the reactions, that is, the nuclear products, sometimes called nuclear ash, can also be significant. The production of desirable elemental materials or destruction of unwanted isotopes might be very important. Thirdly, energetic quanta, both photons and particles, which are sometimes observed from LENR, are diagnostically useful and possible concerns for radiation safety. Many other sources of radiation for applications ranging from medicine to security are now in use. However, any unwanted or wanted source of radiation inevitably comes with concerns over its possible degradation of the health of people or the environment. Finally, low energy processes have been observed in some

experiments. These include generation of sound and infrared radiation.

The largest and most robust data base exists for heat production experiments. The amount of information on production of transmutations is large, but still fraught with many uncertainties. Data on production of energetic radiations is also rather voluminous, but serious questions about it remain. Very little data on the generation of low energy

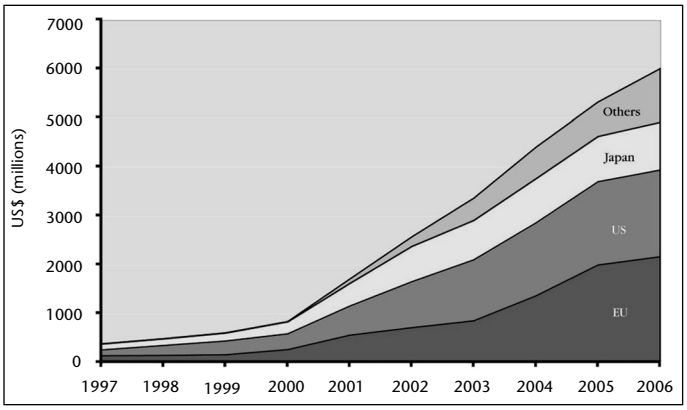

Figure 2. The history of recent government funding of nanotechnology by geographic regions. Source: DG Research. Data: European Commission and Lux Research.

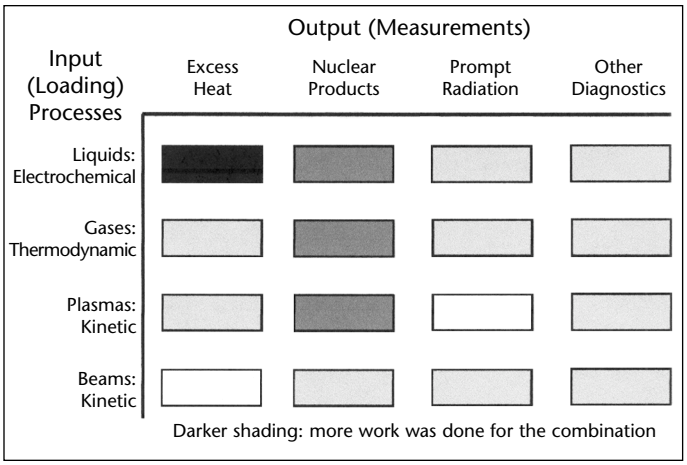

Figure 3. The sixteen combinations of the four major means of producing LENR and the four classes of measured quantities.

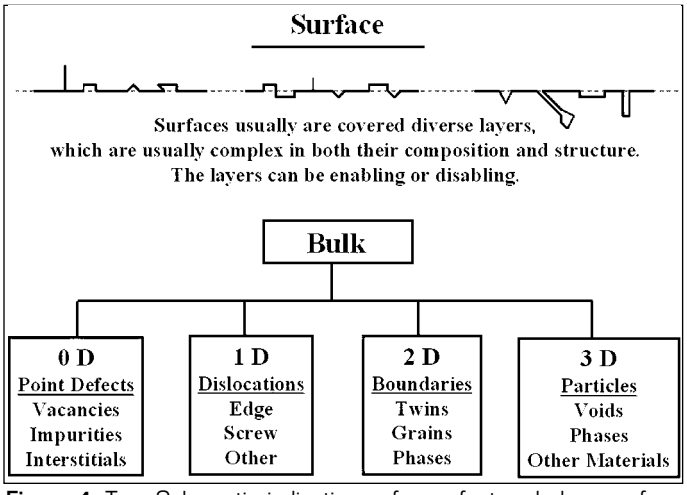

Figure 4. Top: Schematic indications of a perfect and clean surface and of imperfect surfaces that have structures above or below the average surface level. Bottom: Schematic of a perfect bulk material and lists of the various zero, one, two, and three dimensional defects that can occur within a bulk material.

phenomena exists. It appears most likely that LENR will be used for energy production, and most uncertain that LENR will be the basis of practical radiation sources. Having energy (heat) sources without significant energetic radiations is a very attractive possibility, although scaling of power outputs must be achieved to make practical, commercial sources.

In this paper, we are interested in all four of the means to produce LENR. However, because most of the research in the field has been done with electrochemical experiments, such work is most commonly cited. The production of thermal energy, elemental materials, energetic radiation, and low-energy emissions are all of interest scientifically. But, since the production of clean energy is probably the first and most important potential application of LENR, our focus is on the power available from such reactions.

The nuclear reactions that occur at ordinary energies near room temperature can take place on the surface of a lattice, within its bulk, or in both locations. There is substantial experimental evidence for the first possibility, that is, reactions happening on or very near to the surface of a lattice. This evidence is briefly summarized in the next section. Then, we provide a simple equation that relates the rate of production of energy, that is, power to a few basic surface and nuclear factors. A simple, but very useful graphical means of relating surface areas to nuclear power production in LENR experiments is also given in Section 4. Next, the relationships between LENR and nano-science and -technology are examined in Section 5. Measurements that might be made with the tools of nano-science and -technology to elucidate what is happening in LENR experiments are outlined in that section, prior to the concluding section. The Appendix relates surface areas to the volumes of materials.

3. Experimental Case for LENR Occurring on Surfaces

It is appropriate to begin by considering the possible locations on or near a surface or within the bulk at which LENR can occur. This is done with the use of Figure 4. Clean surfaces can be classified as either smooth, if the shapes of the atoms and molecules that constitute the surface are ignored, or else structured with various geometries of different size scales. Surfaces usually are covered with diverse layers, which are generally complex in both their composition and structure. This is especially true of the environments in electrochemical cells. The layers on surfaces can be enabling or disabling for the chemical or nuclear reactions of interest. The bulk of a material can be even more complex than the surface because of the various dimensionalities and types of defects that are possible. Most of these are listed in Figure 4. Our focus here is on the surface as the environment for LENR.

The definition of a surface or near-surface region can be complex, especially for contoured surfaces. Electronic structure calculations made for layers of atoms parallel to the clean surface of a crystal provide useful guidance on what constitutes a surface. They show that the band structure and density of states for the single surface layer of atoms is markedly different from those of bulk layers. This is due to the absence of bonds on one side of atoms in the surface layer. However, the second layer has an electronic structure that is very much like that of bulk layers. So, the surface and near-surface regions can be reasonably defined as just the top two layers of atoms on a surface. That is, the width of the surface and near-surface region is on the scale of one nanometer. However, diffusive and other more energetic

processes can affect depths extending one micrometer or more into the bulk of a material.

There is evidence from electrochemical and from gas loading and permeation LENR experiments that the reactions occur near the surface of the usually-ordered solid materials involved in the experiments. Many workers have found that excess power scales with the electrical current density through the surface of the cathode. A summary of such data is given in Figure 5.[1] Letts and Cravens[2] and Swartz[3] showed that shining a laser on a cathode in an electrochemical cell increases the rate of power production. The skin depth for the laser-solid interaction is on the order of nanometers. Arata and Zhang used Pd black in their Double Structure Cathodes, which had a high pressure of deuterium gas inside of the hollow cathodes.[4] In such finely-divided Pd, most of the atoms are near the surfaces of the nano-particles. The gas permeation transmutation experiments by Iwamura and his colleagues show the reaction products occur within about 10 nm of the surface, as indicated in Figure 3.[5] In his recent book, Storms cites other evidence for the surface occurrence of LENR.[6] Included are the appearance of tritium in the gas above an active cell (rather than in the electrolyte) and the surface-sensitive open circuit voltage in power-producing cells.

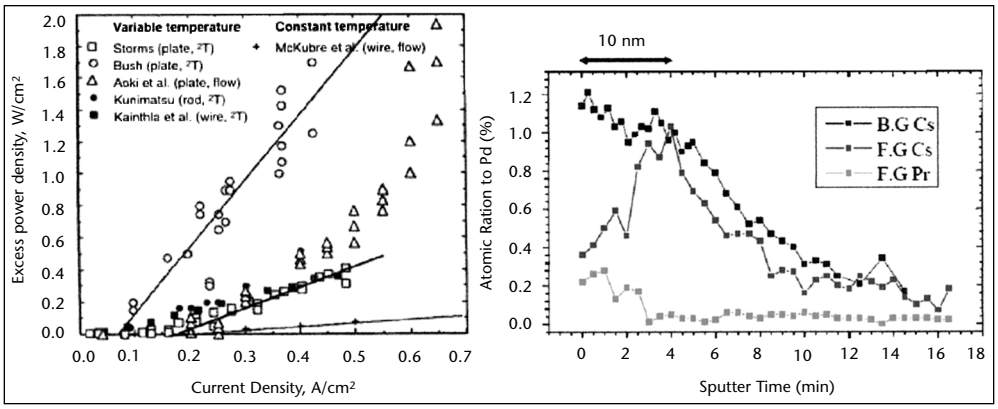

Figure 5. Some of the experimental evidence that LENR occur on or very near surfaces. Left: A compilation by Storms of the dependence of excess power on the current density through the surface of the cathode in electrochemical experiments. Right: Profiles of Cs and Pr into a complex Pd foil that had been permeated with deuterium gas, as measured by Iwamura *et al.* B.G. means Background and F.G. means Foreground.

In summary, there is substantial experimental evidence of varying quality which indicates that LENR occur on or near the surface of solids. However, the case for where LENR occur is certainly not closed. Additional data is needed both from reproductions of experiments already run, and from new experiments, such as Raman scattering. Even if a much stronger case can be made for LENRs on surfaces, the possibility of bulk reactions is not automatically ruled out.

4. Equation and Graphs for Power Production by LENR

A simple equation gives the rate of excess energy (E) production per unit time (T), that is, the power (P) from low energy nuclear reactions. It is shown in Figure 6. The relevant factors are the area (A) of the surface, the fraction (F) that is nuclear active, the areal reactions rate [N/(A x T)], and the energy (*E*) released per reaction. The active fraction links the total surface area to the total active surface area. Then, the number of reactions per second per active area can be used to obtain the total number of nuclear reactions per second. Finally, that rate and the energy per reaction gives the energy per time, that is, the excess power. These four factors are discussed in detail in another paper.[7] The total area is a key experimental variable, which is increased to increase the output power. However, it is desirable for economic and weight reasons to minimize the total mass (volume) of the material on which LENR occur. The Appendix gives relations between surface area and bulk volume of the key materials in a LENR reactor.

The parameters in the equation for power production by LENR, given in Figure 6, can be used algebraically or graphically to estimate the power available from a LENR experiment. It is convenient to use three related graphs to display

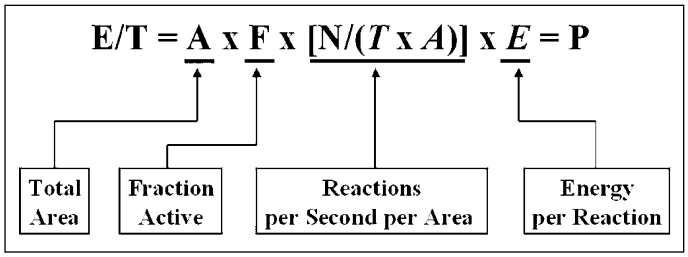

Figure 6. The equation governing power production by LENR, with labels for the four individual factors.

the relevant factors and parameters, and the resultant power. This is illustrated in Figure 7. Importantly, log-log scales are employed in order to span the wide range of parametric variations and because it is easy to plot the diverse values for the key factors and parameters.

In Figure 7, the first graph (lower left) involves the total and active areas, with the active fraction being the key parameter. The second graph (lower right) relates the active area to the number of reactions per second, with the areal reaction rate as the important parameter. Finally, the third graph (upper right) links the reaction rate to the output excess power, with the energy per reaction being the pivotal parameter. The key fact is that the two pairs of graphs (the first and second, and the second and third) have one axis in common. The utility of the linked graphs is due to the possibility of varying any of the parameters, and seeing simply and clearly the effect such variations will have on the LENR excess power.

We note that there are seven quantities in Figure 7, namely the values of the factors on each of the four axes and of the three parameters, one on each graph. But, it is important to realize that four of the seven quantities are enough to fully determine the output power. This is because there are only four vertical and horizontal lines needed to fully define any case, that is, to determine the operating points in each of the three graphs. The situation is illustrated in Figure 8. Note that any of the lines can be moved, which affects the values that depend on the factors intersecting any of the lines, and possibly but not necessarily, the power output.

As one example, if the active fraction F is constant, increasing the total area will first increase the active area, and then both the reactions per second and the output power, if the areal reaction rates and energies per reaction are constant. However, the active area can be constant and the output power constant if an increase in area is just bal-

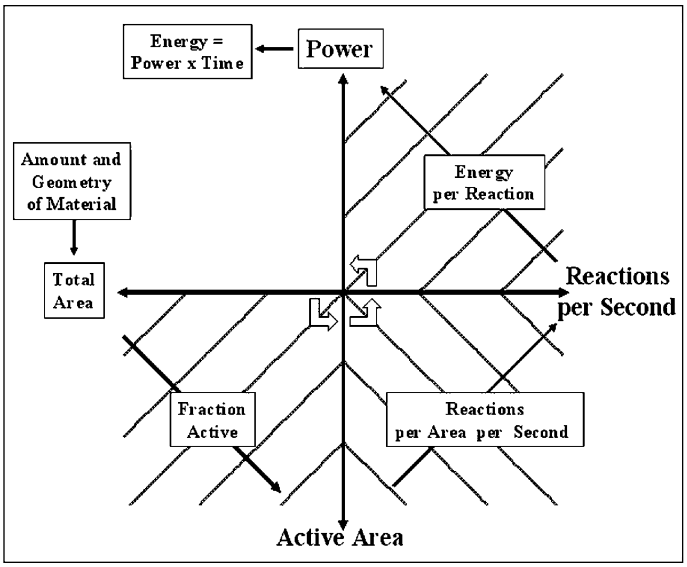

Figure 7. Three linked diagrams that permit graphical determination of the output power in LENR. The diagonal arrows indicate the directions in which the three indicated parameters increase.

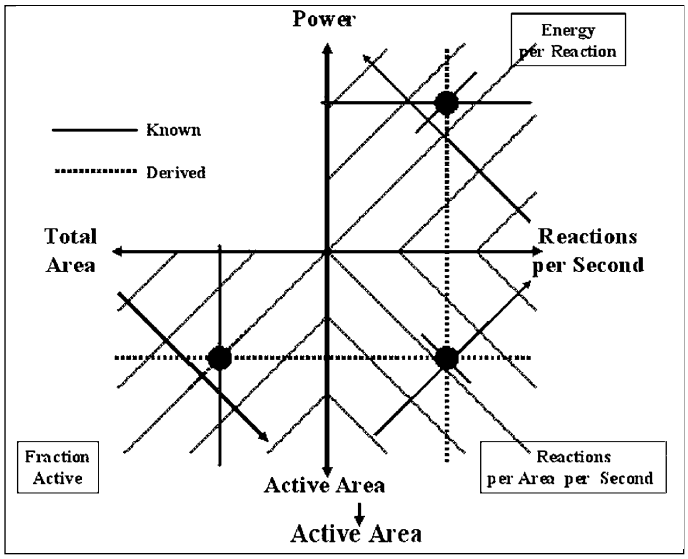

Figure 8. Four of the seven quantities suffice to determine the entire situation for the three graphs. This diagram illustrates how the trio of graphs can be used with four known quantities to derive the three others. Either experimental or theoretical quantities can be used.

anced by a decrease in the active fraction. This would be the case if all the new area were inactive.

There is another use of the linked graphs that makes it possible to estimate values of otherwise poorly known or unknown parameters in LENR experiments. The point is, since four quantities completely determine a particular situation, but there are seven total quantities, three can be derived in some cases. This is illustrated qualitatively in Figure 8 and quantitatively in Figure 9 for one set of circumstances. In the case shown, the power from an experiment and the reaction energy are known. This determines the position of two of the four lines and gives the reaction rate. If the areal reaction rate is known, the position of another line and another factor is determined. That is, the active area is then known. Finally, use of the total area sets the last line and the active fraction can be determined.

A realistic example is given in Figure 9. If an LENR experiment gives an excess power of 10 W and the reaction energy is taken to be 24 MeV, then the reaction rate is close to 10^{12} Hz. Using an areal reaction rate from the theoretical estimate of Widom and Larsen,[8] namely 10^{13} Hz per centimeter squared, indicates that the total active area is a few times 0.1 cm^2. It the total surface area is known to be 10 cm^2, then we have a value for the active fraction on the order of 10^{-2}, that is, a few percent. This is the initial estimate of a parameter that is key to power and energy production with LENR, but has yet to be either measured or calculated from theory. If the total area in the experiment were ten times less, then the active fraction would have to be ten times higher for the same reaction rate and output power.

Two things should be noted about the set of linked graphs. First, the active fraction is unity or less. That is, there is a part of the total and active area graph that is excluded. The second is related to the common observation during a LENR experiment, namely the variation of the excess power with time. It the horizontal line cutting the excess power axis moves up and down, and the reaction energy is fixed, then the reaction rate, and the vertical line intersecting that axis, must vary. If the total area is fixed, then either (or both) of the active fraction and the areal reaction rate must vary. This clearly points to the determination and control of these two quantities as being among the major challenges of the field, both for scientific understanding and for engineering utility.

Finally, we note that the set of linked graphs can be used to plot the range of variations for each of the seven parameters. Observed powers in LENR experiments have usually fallen in the 10 mW to 10 W range. The lower value is set by calorimetric limit of detection in many cases. The upper limit has been exceeded in only a few cases. Reaction energies of 2 to 25 MeV are reasonable, and can be refined as more is known. There are no independent values for total reaction rates, but use of the two variations just cited gives reaction rates that can fall in the range of a few times 10^9 to a few times 10^{13} Hz. Areal reaction rates are not available from experiment, but have been estimated theoretically to be in the range 10^{12} to 10^{14} reactions/second/cm^2.[8] Total surface areas are known for simple electrode geometries, usually with dimensions on millimeter and centimeter size scales. However, total areas for the finer, more complex micro- and nano-scale materials used in many experiments are unknown.

Certainly, the set of three graphs is not necessary to make estimates of the power or other four factors that appear in Figure 6. If all four of the factors are known, computation of the power is straightforward. For example, a total area of 100 cm^2, an active fraction of 10%, an areal reaction rate of 10^{13} Hz/cm^2, and a reaction energy of 24 MeV would yield a power output of about 4 W, where the conversion factor of 1.6×10^{-19} J/eV was used. In a similar fashion, it is possible to calculate the total area needed for a specific desired power output. If an output power of 1 kW was desired for the same active fraction, areal reaction rate, and energy per reaction, then a total surface area of one-fourth of a square meter (2.5×10^3 cm^2) would be required. In such a case, effective heat removal would be needed to prevent temperatures greater than an LENR reactor could withstand.

The total area and the energy per reaction are not zero. The total area is controllable, even if it is not known precisely. The particular reaction in an experiment, with its characteristic released energy, may eventually be under con-

trol. If there is no nuclear power in a particular LENR experiment, then either or both of the active fraction or the areal nuclear reaction must be zero. Again, it is difficult to overemphasize the importance of understanding and controlling these two quantities. The use of surfaces structured on the nanometer scale might enable the needed control, or at least, improve the performance of a LENR device.

5. LENR and Nano-Technology

It is interesting that the independent development of a robust experimental case for the existence of LENR was contemporaneous with the explosive growth in nano-technology, as shown in Figure 2. This timing was accidental and not causal. But, it has led to an opportune situation, where many nano-materials are now available for exploitation in LENR experiments. Further, the numerous tools of nano-scale research are candidates for use in LENR experiments. Both of these points are addressed in this section.

There are at least two reasons for LENR experiments to be viewed as a part of nano-science and -technology. The first is simply the size scale of the materials that are and can be involved in the production of energy by LENR. If LENR occur on or near the surfaces of materials, the maximization of surface area for a given amount (volume or weight) of the substrate material will be economically compelling. Section 4 and the Appendix address the case for using nano-meter sized materials. As already noted, nano-meter scale particles have been used in very successful LENR experiments.[4] However, there are many other opportunities for LENR experiments with nano-scale materials. Figure 10 gives micrographs of nanometer-scale Pd and Ni structures from the recent literature. Many nano-scale materials relevant to LENR are already commercialized. However, their cost is a current and possibly durable concern. Widespread use of LENR-based reactors would drive down material costs.

The second reason why LENR can be viewed as a part of nano-science and nano-technology is less certain now. It is possible that the active areas on the surface of a LENR substrate have lateral dimensions below a micrometer. The difficulty in understanding the essential parameters that determine the outcome of LENR experiments might be due to appropriate conditions existing in only very small surface regions for very short times. Such regions might turn on and off during an experiment, and might vary widely in size and duration. There is little direct experimental evidence for sub-micrometer active regions being important. Diagnostic equipment with the needed spatial and temporal resolution has not been brought to bear in LENR experiments.

Because of funding limitations, many clear possibilities for the spatial and temporal study of the surfaces of cathode materials before, during, and after LENR experiments have yet to be used. This applies to micro-scale tools as well as those of prime use in nano-scale research. For example, it is possible to immerse high-power microscope objectives near cathodes in LENR experiments in order to obtain images with sub-micrometer spatial and sub-millisecond time resolution. It would also be quite straightforward to perform light scattering experiments, such as Raman spectroscopy, on active cathodes with micrometer spatial and sub-nanosecond temporal resolution. A few experiments have been done in which X-rays are used to probe the surface and interior of cathodes during electrolysis. They can provide spatial resolution on the order of 10 micrometers and time resolution of less than one second. So, some basic and some advanced tools of material science at the micro-scale should be used for LENR experiments. One recommendation of the review of LENR by the U.S. Department of Energy in 2004 was to employ modern research tools for the analysis of materials in LENR experiments.[12]

The same shortfall in utilization, and similar opportunities, apply to the tools of nano-technology. The use of an Atomic Force Microscope (AFM) to examine the surfaces of cathodes within electrolytes during active LENR experiments would not be simple, but should be feasible. The AFM has the spatial resolution to address some of the fundamental questions regarding conditions at the surfaces of solids in LENR experiments. If it happens that the nuclear active regions are stable for the time that it takes to scan a small region of a surface, then the temporal resolution of a submerged AFM would also be germane. Scan speeds of 10 micrometers per second translate into the ability to scan a 1 micrometer long line in about 100 msec.

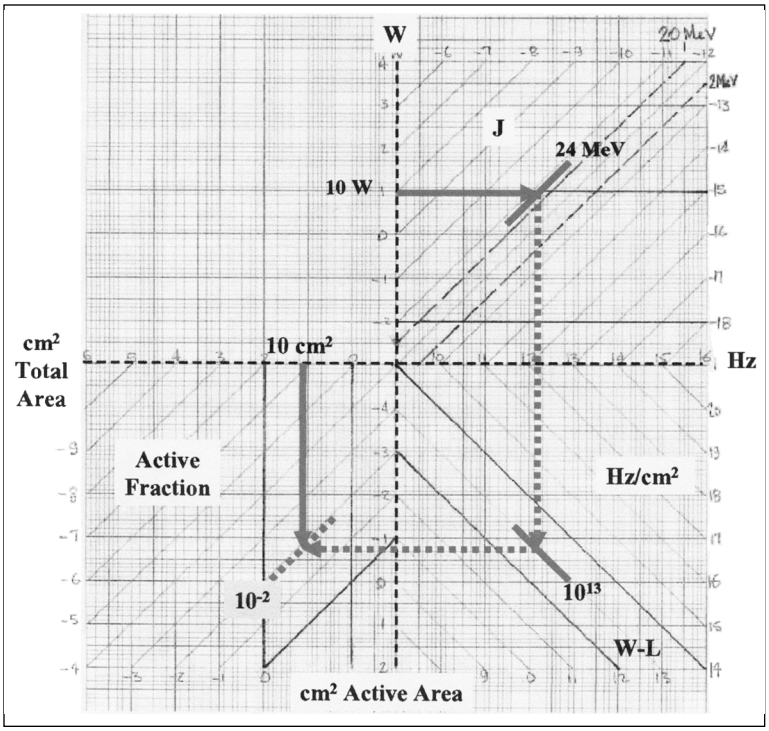

Figure 9. Illustration of how an active area fraction of 1% can be determined, if the other factors and parameters have the indicated values.

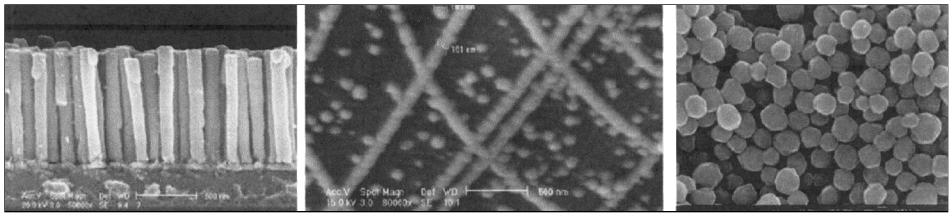

Figure 10. Micrographs of nano-structured materials relevant to LENR. Left: Pd nano-wires about 100 nm in diameter.[9] Center: Pd nano-particles about 100 nm in diameter, many of them grouped to form nano-wires.[10] Right: Commercial Ni nano-particles generally near 200 nm in diameter.[11]

There are other techniques for analyzing nanometer scale materials that do not involve high resolution, but average over large areas, that is, over many particles. Catalysis scientists have developed an array of methods for measuring the surface areas of materials with very small particle sizes.[13] Apparently, such techniques have not yet been used for the study of the dependence of the output of LENR experiments on the total areas of the cathodes for micro- and nano-meter scale materials.

Applying new tools to LENR experiments will be challenging, especially for probes immersed in a liquid electrolyte or in a plasma. Possible impurity contamination, and the need for proper electrical connections, are among the challenges for the contemplated measurements. However, major hurdles have already been overcome in LENR experiments. Performing precision calorimetry in electrochemical experiments is a prime example.

In short, few members of the wide array of surface diagnostics now of use in micro-meter and nanometer-scale research, and in practical catalysis studies, have been employed in LENR experiments. This is primarily due to lack of financial support. Many of the tools and techniques are expensive. The need for employment of modern experimental tools seems urgent. It is widely thought that materials conditions are central to understanding LENR. That is, until the composition and structure of the solids in LENR experiments are probed with sufficient spatial, temporal, energy, and momentum resolution, it is not possible to demonstrate directly the basic mechanisms and processes active in the experiments.

The use of new fine-scale probes of LENR experiments should permit both pursuit of existing questions and the discovery of new, unexpected phenomena. There are many related questions that can be addressed with the proper tools. It is well known that the structures, including lattice constants of nanometer-scale materials, are different than those of the bulk of the same materials. It is unclear now whether variations in lattice constants will improve or degrade the production of LENR. Similarly, it is well understood that the local order in amorphous materials is quite similar to the local order within ordered samples of the same materials. But, here again, it is not known confidently now, either experimentally or theoretically, if the long range structure of materials is relevant to LENR.

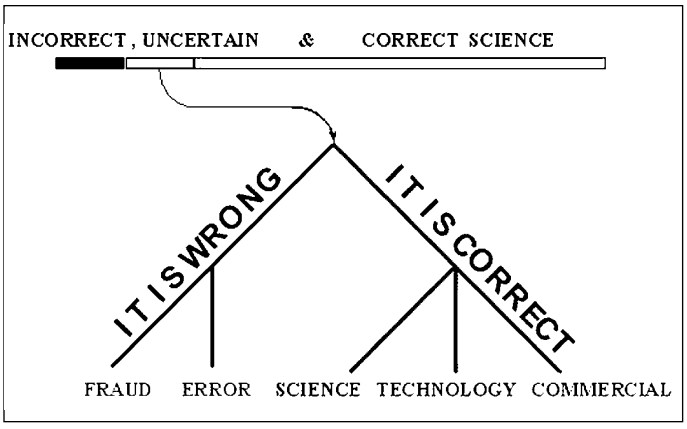

Figure 11. Subjects sometimes begin in the uncertain area between incorrect and correct sciences. They can turn out to be all wrong, or at least partially or entirely correct. After almost two decades of experimental research, it is now clear that LENR represents a valid area of scientific inquiry. That is, not all of the experimental reports in the field can be dismissed as lies or mistakes.

It is possible that detection of the conditions for LENR would become a new sub-field of nano-science and -technology. What if it were possible to detect in real time the formation of small craters and other fine and fast features during LENR experiments? Such measurements would add to the long list of remarkable studies now being made in nano-science and -technology.

6. Conclusion

Early in the study of LENR, many people thought that all the reports were wrong, the result of fraud or errors. Because of the strong experimental basis that now exists, it is clear that lies or mistakes cannot account for all the published results. One of the two branches in Figure 11 has been pruned off. Hence, now there is at least new science, which could rejuvenate the old field of nuclear physics. It remains to be seen if technological capabilities or engineering designs will result from the new science.

The design and manufacture of practical sources of energy, materials, and radiations will not merely be the application of existing engineering practices. Most current sources of energy, notably combustion and fission fuel rods, are three-dimensional in nature. If surface reactions are the dominant mode for LENR, then the flows of energy and matter will be quite different than for current combustors and reactors. There will certainly be commonalities in the basic science and in some of the computer codes used for design and simulation. However, an energy source based on LENR might be quite like an automobile radiator with a large surface area to enable the transfer of significant energy even if the temperature gradients are not large. Whatever practical configurations prove to be, new reactor engineering practices will be needed to turn the current science of LENR into distributed, commercial sources of energy. Those thermal sources, when coupled with thermoelectric materials, can provide electrical power as well as hot water.

Appendix: Surface Areas in Relation to Material Volumes

The area of the surface of the cathode in an electrochemical loading experiment can vary widely both in absolute basis and in relation to the volume of the cathode material. If the geometrical shape of the cathode is fixed, increasing the volume will increase the surface area. However, it is more effective to alter the geometry of the cathode for a fixed volume of material. This section examines three geometries with materials having different size scales, which have been used in LENR experiments. Then, means are presented to increase the solid surface area, as the shape of a cathode with a fixed amount of material is varied.

Figure 12 shows photographs of LENR cathodes on three size scales. The classical electrode is a solid cylinder of palladium or its alloys with a diameter on the scale of millimeters, such as that made by Imam.[14] Co-deposition of palladium and deuterons leads to a material with much higher surface area per cubic centimeter or gram, as shown in the work of Szpak and his colleagues.[15] The largest surface area per volume is gotten for material with dimensions of nanometers, with the work of Arata and Zhang providing one of the few examples.[16] In going from the regular solid electrode form to progressively finer materials, there are both advantages and disadvantages, as noted in Figure 12. The increase in area, and possibly the number of nuclear reactions, and

the decrease in loading times, are the major advantages. Rapid removal of heat, products and high escape rates for radiations can also be advantageous. However, unless particular assessment techniques are used, the actual surface area is not known for the micro- and nano-meter scale materials. This is not to say that the areas of the fine-scale materials cannot be measured. As noted earlier, the methods of catalysis can be used to quantify the surface areas of finely divided materials on a mass (per gram) basis.[13]

Turning now to ways to increase the areas for a given volume of materials, there are two approaches conceptually. In the first, the material is cut into progressively smaller pieces, with each cut producing more surface area without the addition of any volume. This is illustrated in Figure 13. Starting with a cube one centimeter on a side, regularly-spaced cuts parallel to one pair of sides will produce layers. Further cuts parallel to another pair of sides yields rods. Finally, cuts orthogonal to the first two sets of slices gives particles. The analytical expressions for the total surface areas of the layers, rods, or particles are given in Figure 13 as a function of N, the number of entities in each case. It can be seen from the expressions that, for all three cases, the area per volume scales linearly with N. In the limit of large N, the scaling for layers is 2N, for rods 4N, and for particles 6N. That is, there is a gain of a factor of a few (2 or 3) if the number of directions of the cuts is increased from one to two or three. The biggest gain is due to having large values of N, that is, by making numerous cuts. For example, in the case of particles, micrometer-sized particles have a value of $N = 10^4$, while nanometer-scale particles have $N = 10^7$. Particles with sizes of about 10 nanometers have a surface to area ratio of about 6×10^6 with units of cm^2/cm^3.

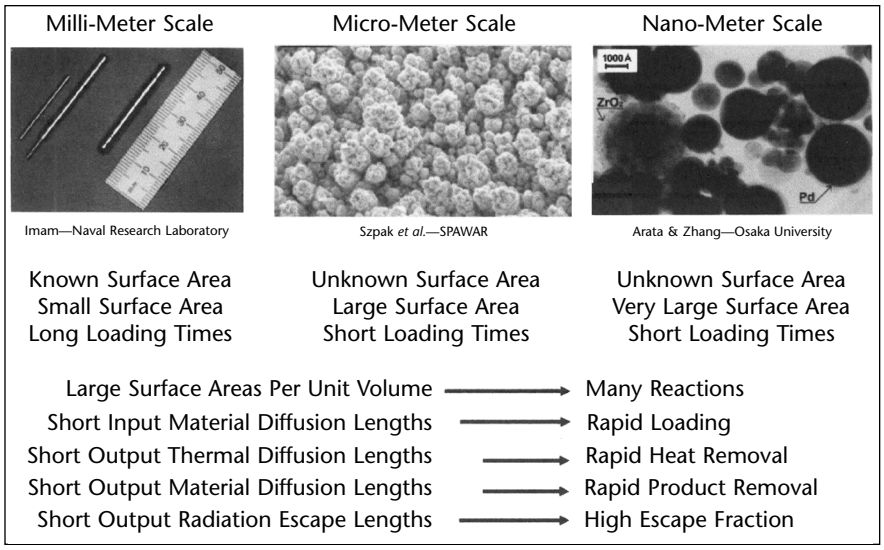

Figure 12. Photographs of Pd cathode materials from various LENR experiments on size scales of millimeters, micrometers, and nanometers. The favorable and unfavorable aspects of each type of material are listed in the middle. Experimental determinations of the total areas of micro- and nano-meter scale materials are needed. The implications of having large surface areas and small particles are given at the bottom of the figure. They are generally favorable for engineering of LENR reactors.

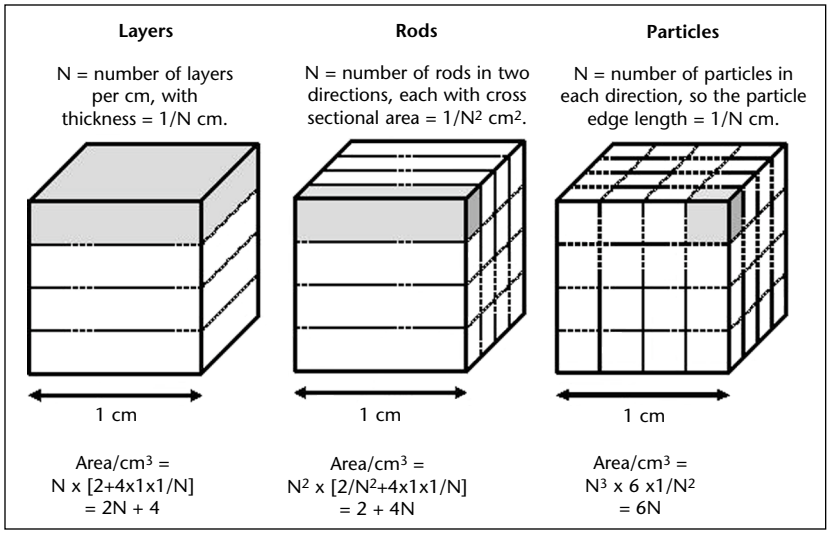

Figure 13. The number of layers, rods, or particles and the total surface area per cubic centimeter that result from one, two, or three sets of regularly-spaced cuts parallel to the faces of the original solid cube.

The second approach to increasing the surface area of a fixed volume of cathode material is to deform it, for example by flattening it into a square sheet or pulling it into a wire with a square cross section. For reference, gold leaf is about 100 nanometers in thickness.[17] Flattening one cubic centimeter into a thin film with a thickness of 100 nm would give a square area with a side that is about 3 m long. The total surface area of the film would be about 20 square meters. Stretching the cubic centimeter into a wire that has a square cross section of 100 nm would yield a wire, which is 10^8 m long with an area of 40 square meters. It is clear that having one or two dimensions on the scale of nanometers results in very large total areas per cubic centimeter of material, whether the starting volume is cut up or deformed.

References

1. Storms, E. 1991. "Review of Experimental Observations about the Cold Fusion Effect," *Fusion Technology*, Vol. 20, p. 433.

2. Letts, D. and Cravens, D. 2006. "Laser Stimulation of Deuterated Palladium: Past and Present," in Hagelstein, P.L. and Chubb, S.R., eds., *Condensed Matter Nuclear Science: Proc. of the 10th International Conf. on Cold Fusion*, World Scientific, pp. 159-170.

3. Swartz, M.R. 2006. "Photo-Induced Excess Heat from Laser-Irradiated Electrically Polarized Palladium Cathodes in D_2O," in Hagelstein, P.L. and Chubb, S.R., eds., *Condensed Matter Nuclear Science: Proc. of the 10th International Conf. on Cold Fusion*, World Scientific, pp. 213-225.

4. Arata, Y. and Zhang, Y.C. 1992. "Reproducible 'Cold' Fusion Reaction Using a Complex Cathode," *Fusion Technology*, Vol. 22, p. 287.

5. Iwamura, Y. *et al*. 2006. "Observation of Nuclear Transmutation Reactions Induced by D_2 Gas Permeation through Pd Complexes," in Biberian, J.-P., ed., *Condensed Matter Nuclear Science: Proc. of the 11th International Conf. on Cold Fusion*, World Scientific, pp. 339-350.

6. Storms, E. 2007. *The Science of Low Energy Nuclear Reaction*, World Scientific.

7. Nagel, D.J. In Press. "Powers, Materials, and Radiations

from Low Energy Nuclear Reactions on Surfaces," *Proc. of the 13th International Conference on Cold Fusion* (June 2007).
8. Widom, A. and Larsen, L. 2008. "Theoretical Standard Model Rates of Proton to Neutron Conversions Near Metallic Hydride Surfaces," http://arxiv.org/PS_cache/nucl-th/pdf/0608/0608059v2.pdf.
9. Kim, K. et al. 2006. "Pulsed Electrodeposition of Palladium Nanowire Arrays Using AAO Template," *Materials Chemistry and Physics*, Vol. 96, pp.278-282.
10. Shi, Z., Szpunar, J.A., and Wu, S. 2005. "Morphological Characterization of Self-Assembled Pd Nanowires by Electroless Deposition," *Microscopy & Microanalysis*, 11 (Suppl 2).
11. 200 nm Ni particles from Nano Dynamics, Inc. (http://www.ndmaterials.com/nickel.php).
12. U.S. Department of Energy, 2004. "Report of the Review of Low Energy Nuclear Reactions," December 1, http://www.newenergytimes.com/DOE/DOE.htm.
13. Condon, J.B. 2006. *Surface Area and Porosity Determinations by Physisorption: Measurements and Theory*, Elsevier Science.
14. Dominguez, D.D., Hagans, P.L., and Imam M.A., 1996. "A Summary of NRL Research on Anomalous Effects in Deuterated Pd Electrochemical Systems," Report NRL-MR-6170, January 9.
15. Szpak, S. *et al.* 2005. "The Effect of an External Electric Field on Surface Morphology of Co-deposited Pd/D Films," *J. of Electroanalytical Chemistry*, Vol. 580, pp. 284-290.
16. Arata, Y. and Zhang, Y. 2006. "Development of Compact Nuclear Fusion Reactor Using Solid Pycnodeuterium as Nuclear Fuel," in Hagelstein, P.L. and Chubb, S.R., eds., *Condensed Matter Nuclear Science: Proc. of the 10th International Conf. on Cold Fusion*, World Scientific, pp. 139-157.
17. http://hypertextbook.com/facts/1999/JeniferVilfranc.shtml, Gold Leaf Thickness.

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