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Review Article

Hot and Cold Fusion for Energy Generation

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Abstract

Sixty years of research on hot fusion have cost more than $ 20 B. Only one of the dozens of experiments has barely reached breakeven, the point at which the energy produced is equal to the energy spent for its production. Twenty years of work on "cold fusion" cost less than $ 0.2 B. Energy amplifications exceeding 10 for the palladium–deuterium system, and more than 100 for the nickel–hydrogen system, have been reported, but not verified. Hot fusion is understood and may result in large power plants in several decades. "Cold fusion", now called Low-Energy Nuclear Reactions (LENR), remains a scientific mystery. If adequately funded, LENR could lead to safe, non-radioactive, green, small, distributed nuclear energy sources in less than two or three decades, well before hot fusion can produce commercial power.

Keywords: Cold fusion, Condensed matter nuclear science, Fusion energy generation, Hot fusion, Low-energy nuclear reactions, Nuclear energy generation

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1. Introduction

There are many enduring concerns in the modern world. Energy is certainly one of them. The relentless increase in the world's population, and the increase in the per capita use of energy in most countries, both force attention to old and new sources of energy. More and more people are on average needing more and more energy.

It is possible to group sources of energy into four categories. The first category includes materials and technologies that are already heavily used. They are three types of fossil fuels, coal, oil, and gas, and nuclear fission in large reactors. Overall, these established sources of energy provide over 90% of the power in the US. The environmental drawbacks of fossil fuels are well known. Nuclear fission is relatively benign environmentally, and is beginning to make a comeback in the US after three decades of stagnation.

The second group is often called "alternative" sources. They include "renewable" reservoirs of energy, notably solar, wind, and tidal energies, as well as hydroelectric and geothermal sources, and biomass. Most of these sources

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of energy tend to be best in particular regions, which are rarely near high population density areas. Hence, long power lines are needed to deliver the energy from such sources to consumers. Solar and wind energy have grown rapidly in recent years. Continued growth can be expected in the coming decades as the prices of both photovoltaic devices and wind generators continue to decline. In the US, these alternative sources provide less than 10% of the country's energy needs. Few people expect them to grow enough in the near future to significantly erode the large fractional positions of the sources in the first category. Growth of alternative energy sources will be mostly absorbed by increasing population and the growing demand for more energy per individual.

The third group of energy sources is distinguished by two characteristics, well-established experimental demonstrations and a lack of commercialization. Included in this category are hot and cold nuclear fusion, the subjects of this paper. Hot fusion due to the energetic collisions of light nuclei is well understood theoretically, as well as robustly demonstrated experimentally. The nuclei of main interest are the heavy isotopes of Hydrogen (H), namely Deuterium (D) and Tritium (T). The characteristics and history of hot fusion are sketched in Section 2.

"Cold fusion" is the historic name for the ability to produce nuclear reactions at relatively low energies (temperatures). The name is, at least, misleading and may be entirely wrong. The topic is now called Low Energy Nuclear Reactions (LENR) by many researchers. It is part of the field of Condensed Matter Nuclear Science [1]. The subject is well established experimentally, but not understood theoretically. The features and history of LENR constitute the third section of this paper. Both hot fusion and LENR are fields of scientific research now. They are decades away from commercialization, and later, possibly becoming of fractional importance as energy sources for both developed and developing countries.

The last of the groups of energy sources is populated by a few concepts, which have yet to be robustly demonstrated as energy generators, but may someday become such sources. That is, there is little or no experimental basis for believing now that they will emerge as sources of energy on any time scale. The best known conceivable source in this class is probably Zero Point Energy (ZPE) [2]. The idea behind ZPE is to draw energy from the large reservoir of fluctuations in all of space. Reports of demonstrations of such postulated effects and sources should be monitored. However, from engineering and commercial perspectives, it is unrealistic to expect the emergence of practical ZPE or other such energy sources for a half-century.

Another way to put into perspective the variety of power generators is to consider the source of their energy. Fossil and biomass fuels release energy by the occurrence of chemical reactions. There are several types of nuclear reactions that also yield energy, and they will be considered below. The remaining currently practical energy sources depend on three general reservoirs of energy, the motion of matter (wind, falling water and tides), thermally hot matter (geothermal and solar thermal) and light (solar photovoltaic). The focus here is on existing and potential nuclear sources of energy. But, since they involve reactions, as do the burning of various fuels, we can usefully compare chemical and nuclear energy sources.

Table 1 is a summary of the means of initiating reactions, their propagation and the possibility of fast energy releases for the different types of reactions. Of the four types of listed reactions, the least is known about LENR.

It should be noted that the situation for fission reactions is qualitatively different than that for fusion reactions in two ways. First, spontaneous radioactive decay can result in fission of a few heavy nuclides. Second, neutron-induced fission, as in ordinary nuclear reactors, does not involve an electrostatic barrier because the neutrons are not charged and, hence, are not subject to Coulomb repulsion. However, there are two primary requirements for sustained neutron-induced fission reactions to produce energy. The first is that the neutrons incident on a heavy nucleus must have appropriate energies, called thermal energies, because they are low in equivalent temperature. The second is that the heavy nuclides have to be sufficiently numerous and close enough to each other to use the neutrons emitted during fission reactions to induce other fissions. Control rods in fission reactors absorb neutrons to tune the rate of reactions and the power output. In short, the requirements of supplying energy for most chemical and nuclear reactions do not apply to neutron-induced fission reactions. But, they have these other requirements on neutron energies, and the density, mass and arrangement of the nuclear fuel.

Before reviewing hot and "cold" fusion, it is worth considering the recent data on the sources and uses of energy in the US, shown in Fig. 1 [3]. Focusing on the US is done simply because the information is conveniently available, and that country is a disproportionally large consumer of energy. The dominance of coal, oil, and gas as chemical energy sources is clear from this diagram. The three primary uses of energy are shown as (a) residential and commercial, (b) industrial and (c) transportation. Non-fuel uses are mainly chemical processes, such as production of plastics. Despite all the recent emphasis on electric cars, the use of electricity for transportation was fractionally miniscule in 2002. Another very large-scale feature of the diagram is the fact that over half of the energy is unusable due to thermodynamic and other inefficiencies, such as heat leaks and electrical resistances. It is clear that energy conservation is attractive and relatively near-term way to help somewhat to balance the energy "books". But, it cannot be a total solution to the energy needs of any one country or the world.

In 2002, nuclear fission contributed somewhat over 8% of the total energy source, and lead to about 20% of the US electricity generation. In France, almost 80% of electricity is generated by nuclear fission energy. The US is finally embarking on the construction of new fission reactors as old reactors retire and the use of electricity continues to grow. The US Department of Energy projects that the country will need 28% more electricity by 2035. Maintaining the current 20% nuclear fraction would require building about one reactor per year starting in 2016 [4].

Nuclear reactions other than fission, including hot fusion and LENR, are now where fission reactors were over 50 years ago. Even if their development, demonstration and commercialization proceeded quickly, they are decades away from starting to impact the energy balances in the US and elsewhere.

Section 2 summarizes the characteristics, history and status of hot fusion. Similar factors for LENR constitute in Section 3.

2. Hot Fusion

2.1. Background on nuclear reactions

Nuclei can be grouped into two major classes, stable nuclei and radioactive nuclei, which decay at rates characterized by a half-life. The spontaneous decay of a single radioactive nucleus is not strictly a nuclear reaction because two nuclei or quanta do not come together to react. There are many types of nuclear reactions that do involve the interaction of two nuclei (or nuclei and neutrons or gamma rays). The number of possible binary nuclear reactions can be simply computed. Since there are 256 stable isotopes for 80 of the elements in the periodic table, the number of possible reactions of stable nuclei is the square of 256, or 65,536 [5]. Reactions of unstable nuclei are possible, so the total number of potential nuclear reactions is very large, possibly exceeding 1,00,000. An interactive chart of the stable and unstable nuclides is on the web [6].

Table 1. Comparison of the initiation, propagation and runaway scenarios for chemical, fission, fusion and low-energy nuclear reactions. Fusion reactions can be produced in accelerator experiments, but they have no prospect of being practical energy sources. Tokamaks are the primary machines for production and confinement of very hot plasmas. Eventual commercial power plants for fusion energy will be Tokamaks. They might attain burning conditions some day. HAD represents "Heat After Death", the production of energy in a LENR experiment after the input energy is terminated.

Reactions initiated by		Propagating reactions	Runaway reactions
Chemical	Flame	Burning	Explosions
Fission	Slow neutrons	In nuclear reactors	Atomic bombs
Fusion	Very hot plasmas	Possibly in Tokamaks	Hydrogen bombs
LENR	Unknown	Possibly HAD	Unknown

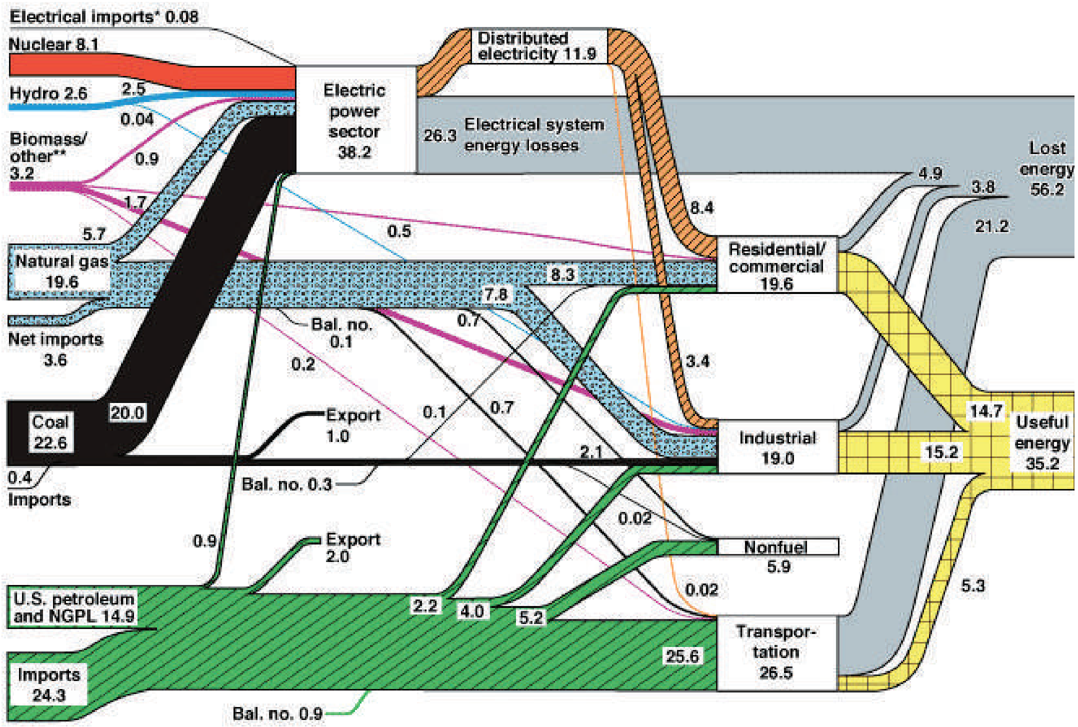

Figure 1. Diagram showing the sources (*left*) and sinks (*right*) of energy in the US for the year 2002 [3]. Since it happened for that year, the US energy consumption was about 97 quads, the numbers on this graphic are approximately percentage points. "Biomass/Other" (3.2 quads) includes wood, waste, alcohol, geothermal, solar and wind sources. A quad is an energy unit equal to 10^{15} British Thermal Units (BTU) or 1.055×10^{18} J. Equivalents of 1 quad are conveniently available on Wikipedia: http://en.wikipedia.org/wiki/Quad_%28energy%29.

Most of the possible binary reactions are simply termed nuclear reactions. However, reactions at the extremes of light and heavy elements are of practical interest and have special names. Both of these types of reactions are generally exothermic, that is, they yield energy. The splitting of heavy nuclei, notably isotopes of uranium and plutonium, due to neutron impact is termed fission, as already noted. It is the basis of the over 400 nuclear power reactors now in use around the world [7]. Fission power reactors already have a history of over a half-century. The reactions of very light nuclei go by the name of fusion. Fusion reactions are the basis of hypothetical large power plants that might become productive in a few decades.

Fusion reactions were initially studied using directed ion beams striking targets in accelerator experiments. When it became possible to heat and confine very hot plasmas, in which the random thermal motions of ions have sufficient momenta to induce nuclear reactions, energy production from multi-million degree plasmas could be sought. The very hot nuclei have to be confined, so the plasma does not cool, and net energy production results. This is done in either of two primary ways. The first uses very strong magnetic fields to restrain rather dilute plasmas, so it is called "magnetic fusion". The second involves producing conditions in very dense materials that can lead to significant numbers of fusion reactions before the plasma explodes and cools. The inertia of the ions provides a short time before the plasma is too cold to support hot fusion reactions, so this method is called "inertial fusion". Such fusion can be induced by very high-power lasers or by electrical discharges.

Two equivalent units are used to characterize ion kinetic energies (for beams or in plasmas) or ion temperatures (in plasmas). Ion kinetic energies are usually expressed in electron volts (eV). Plasma temperatures are given in degrees Kelvin (K). In plasmas, there are distributions of the kinetic energies for all of the particles. The hotter the plasma, the higher is the maximum of the distribution in energy terms. The conversion factor between kinetic energies and plasma temperatures is 1 eV = 11,604 K. Hence, a particle energy of 1 eV (the energy obtained by one electron accelerated by a potential drop of 1 V) is equivalent to the peak energies of particles in a plasma with a temperature of 11,604 K. The surface of the sun has a temperature of about 6000 K, or roughly 0.5 eV, for example.

2.2. Hot fusion reactions

There are many types of fusion reactions between the isotopes of hydrogen, helium, lithium and beryllium. We consider two of them, first, fusion between two deuterons, because of its envisioned relevance to LENR, and then deuterium–tritium fusion, because of its practical importance for hot fusion energy production. Figure 2 shows cartoons of the particles involved in two D–D reactions and the variation of reaction probabilities (cross sections) with kinetic energy for these two reactions [8]. Note that D–D fusion requires higher energies and has much lower cross sections compared to D–T fusion. Fusion between two deuterons is not a practical approach to hot fusion because relatively high energies (temperatures) are required. By contrast a deuteron and triton have peak reaction rates at much lower energies. This greatly relieves the requirements for both heating and confining the plasma in which the particle kinetic energies are

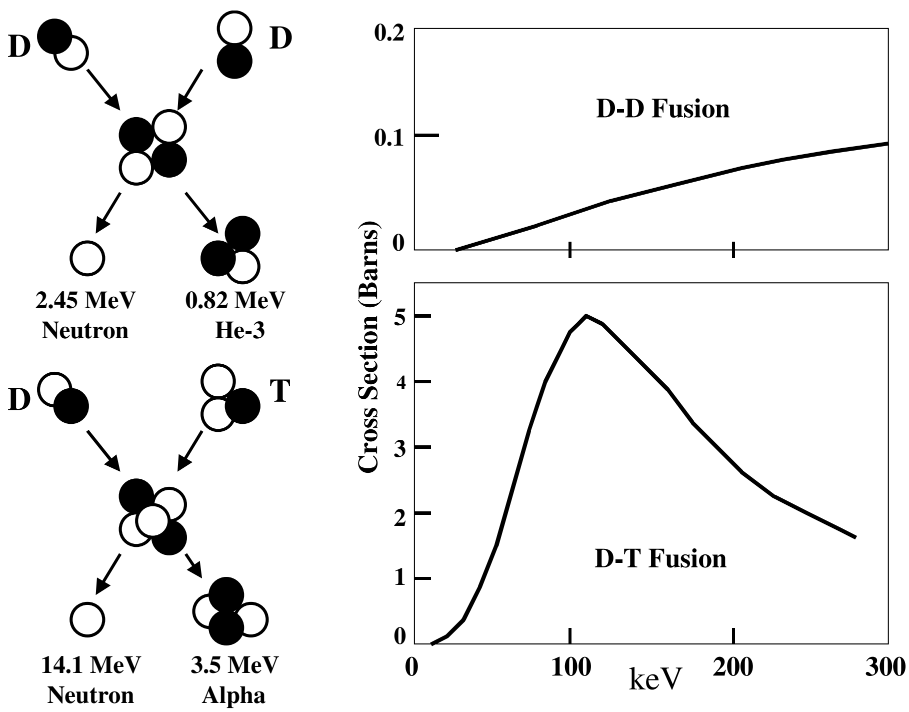

Figure 2. *Top left*: A schematic showing the particles and exit energies for one branch of D–D fusion. Table 2 provides all the outcomes of D–D fusion. Protons are shown in black and neutrons in white. *Bottom left*: A schematic of the reactants, product particles, and exit energies, for D–T fusion. *Right top and bottom*: The cross sections for D–D and D–T fusion. One Barn is 10^{-24} cm^2.

great enough for power production.

The term fusion, as applied to reactions of two deuterons, is actually somewhat odd. Consider the outcomes of D–D reactions shown in Table 2. In almost all of the deuteron–deuteron "fusion" reactions, the incoming nuclei do not fuse in the ordinary sense of the word. For only one reaction in 10 million is there actual fusion (joining) of the two deuterons to form a helium nucleus, which is called an alpha particle. Then, the excess energy is emitted as a 23.5 MeV gamma ray. Most of the time, the energy that is produced by D–D reactions is carried off kinetically by the reaction products. Table 2 also contains the particle and energy accounting for D–T fusion, which will be used in potential commercial hot fusion power plants.

2.3. The Lawson criterion and progress in hot fusion

The "fusion" of light elements in very hot plasmas is understood both conceptually and quantitatively. This permits the computation of the conditions which must be met to produce energy, that is, to get out more energy than is needed to produce and maintain the plasma. There are three critical plasma parameters, the density, the temperature and the lifetime. The density is crucial because higher densities lead to more frequent collisions and, hence, more reactions. The temperature is important because it determines the particle velocities and, hence, the energies with which they collide. Those energies in turn determine the reaction cross sections, as shown in Fig. 2. The plasma lifetime is significant because it measures the time available for fusion reactions. If it is very short, the same energy is needed to create the plasma, but there are relatively few reactions. That is, there is no hope of net energy production for short-lived magnetically confined plasmas. The challenge to plasma physicists and engineers is to achieve high values of all three critical parameters simultaneously within a Tokamak.

In 1955, Lawson derived the criterion that bears his name. It was published in 1957 and applies to deuterium–tritium fusion. He found that the triple product of density, temperature and plasma lifetime must exceed 10^{21} to achieve energy breakeven. The units are m^{-3} for density, keV for temperature, and seconds for time. A compact derivation of the Lawson Criterion is available on the web [9]. Steady increases in the triple product have been achieved in the last half century in large and expensive hot plasma experiments. That history is shown in Fig. 3 along with a similar curve for growth in the number of transistors in leading-edge microelectronics and the energy of accelerators for high-energy physics [10]. It appears that the Japan Torus (JT-60) experiments have already achieved the Lawson Criterion. However, the values for the JT-60 device are based on deuterium–deuterium experiments. Were those experiments done instead with deuterium–tritium plasmas, an energy gain of 25% was calculated. Tritium is expensive and radioactive, so it was not used in the JT-60 experiments.

While progress in both hot fusion research and microelectronics might appear similar, there is a vast difference in the impact of both trends. To date, all of the high temperature plasma devices were energy sinks, requiring more energy to run than they produced. Figure 4 shows the annual costs of hot fusion research in the US [11]. They total to over $ 20 B in current USD for the second half of the last century. There has been no energy return on investments in hot fusion yet. Such will probably be the case for another few decades. Financial returns for past funding of hot fusion are

Table 2. The branching ratios (fractions), and the emitted quanta and their energies (in MeV), for the fusion of two Deuterons (D) with three outcomes, and the fusion of a deuteron and triton (T) with one outcome. Alpha is short for Alpha Particle, the nucleus of a Helium atom.

Reaction	Partners	Fraction	Emitted	Energy	Emitted	Energy
D	D	0.5	Neutron	2.45	He-3	0.82
D	D	0.5	Proton	3.03	H-3	1.01
D	D	10^{-7}	Alpha	0.082	Gamma	23.5
D	T	1.0	Neutron	14.1	Alpha	3.51

even more remote.

By contrast, the progress in microelectronics has enabled the computer and communication revolutions, which have created vast new industries and already changed the world. The amount of value from production and use of computers of all sizes, and the internet and wireless industries, is immense and may be inestimable. Even if hot fusion succeeds grandly on a scale of a few decades, it might attain only a niche status in the overall generation of energy. That is, it must compete with many other energy sources. Meanwhile, the melding of information technology and humans will have advanced greatly.

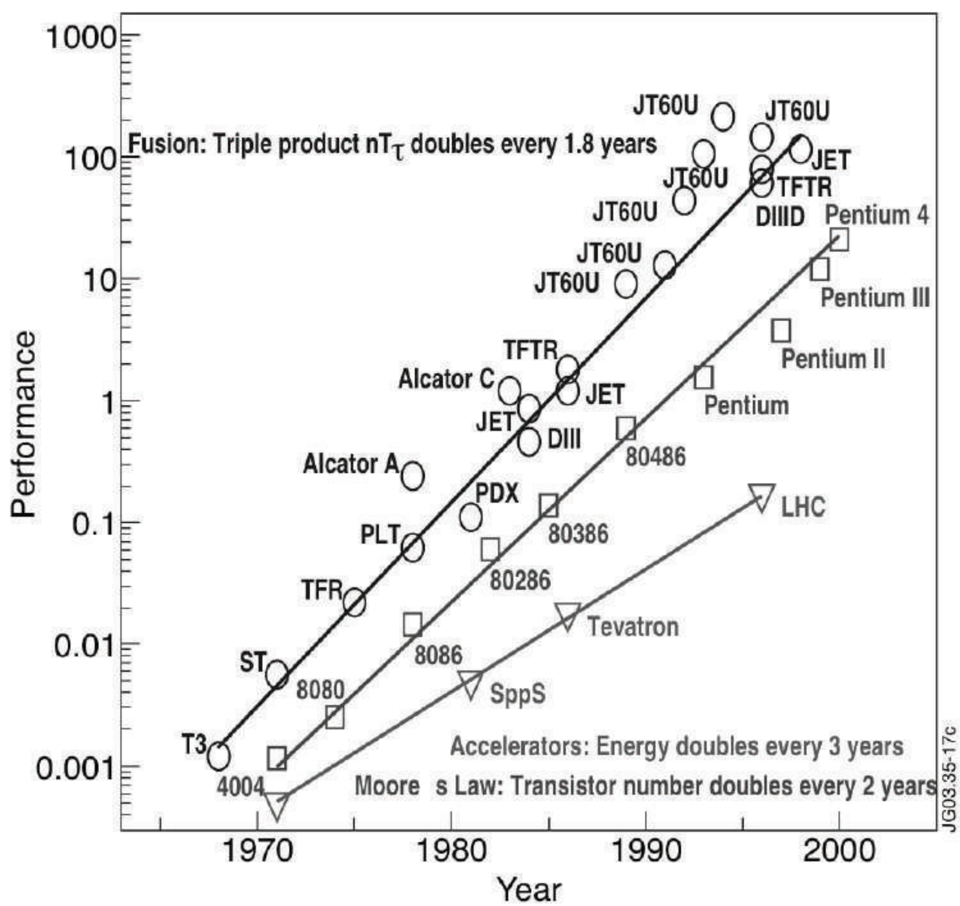

Figure 3. History of the increase in the Lawson Triple Product, the number of transistors on computer chips (Moore's law) and the energy of particle accelerators [10]. The Lawson Criterion is achieved at the value of 100 on the left-hand vertical scale of this graph. High-energy particle accelerators advance slower than the other technologies because of the immense cost per facility.

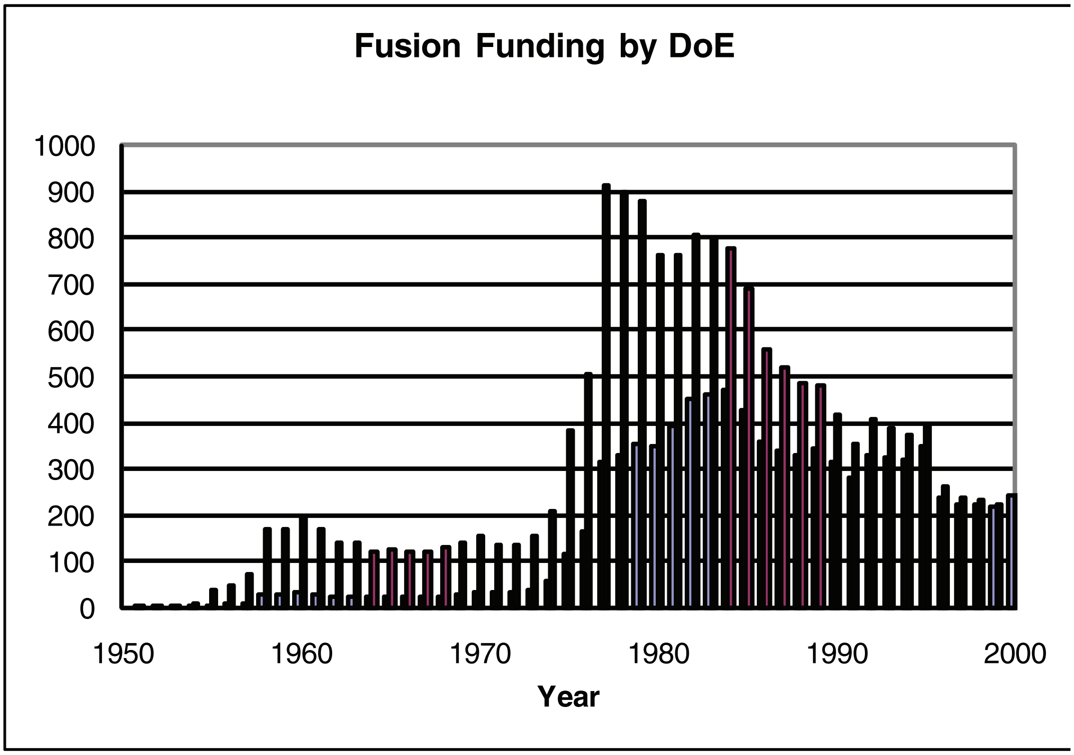

Figure 4. History of the funding of hot fusion research by the US Department of Energy over five decades at the end of the last century [11]. The vertical axis is millions of USD. The shorter bars for each year are actual ("then year") dollars. The longer bars are inflation-adjusted to the year 2000. The effect of the oil price shock in the early 1970s due to decisions of the Organization of Petroleum Exporting Countries is evident.

2.4. Status and prognosis for hot fusion research

Having reviewed the history of hot fusion, what is its current status and expected progress in the coming decades? Table 3 gives a terse history and prognosis for the major current and planned hot fusion machines.

Figure 5 shows the largest magnetic and laser inertial machines for hot fusion research. The total capital and

Table 3. Actual and projected energy gains for experimental Tokamaks with D–T plasmas. The value for JT-60 was computed for D–T plasmas based on its actual performance with D–D plasmas. The years for the projected machines are conservative. That is, building and successful operation of ITER, DEMO and PROTO may occur substantially later than shown. The energy gain goal for PROTO, if it is actually to be built, is to be determined (TBD).

Machine	Goal	Year	Energy gain	Reference
JET	Research	1997	0.7	[12]
JT-60	Breakeven	1998	"1.25"	[13]
ITER	Ignition of burning	>2020	10	[14]
DEMO	Steady-state electricity generation	>2030	25	[15]
PROTO	Prototype commercial power sation	>2040	TBD	[16]

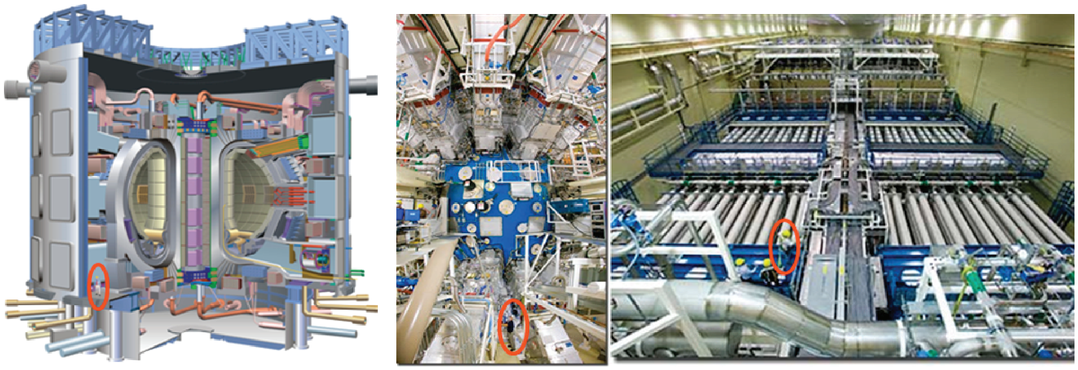

Figure 5. *Left*: Drawing of the International Thermonuclear Experimental Reactor, a Tokamak hot fusion facility being built in France [17]. Center: Photograph of the laser target chamber for the US National Ignition Facility (NIF), an inertial fusion facility in early operation at the Lawrence Livermore National Laboratory. *Right*: Photograph of one of the two 400-foot-long NIF laser bays [18]. The ovals indicate people in the drawing for ITER and the pictures for NIF.

operational cost of these facilities is very great. The projected costs for International Thermonuclear Experimental Reactor (ITER) exceed $ 15 B. Those for the US National Ignition Facility (NIF) will likely be greater than $ 3 B. Neither machine will produce useable energy, let alone electricity.

There are many potential scenarios in the long-term competition for part of the escalating energy market. Assuming that hot fusion does achieve energy gain values high enough to be commercially valuable, its large central power plants might augment or replace some fission reactors. Mining of uranium might yield fission fuels for centuries. The deuterium fuel for hot fusion is available from water, and would be adequate for millennia. However, large hot fusion reactors will be expensive to operate and they will produce nuclear waste. So, it is also possible that increased use of distributed solar and wind energy will keep hot fusion nuclear reactors from ever becoming a major source of energy. Recent and largely unenthusiastic perspectives on the history, status and prospects for hot fusion are available [19,20].

Imagine that it is 100 years ago, and the subject was transportation rather than energy. Arguments over possible outcomes were similar to current uncertainties over the future of nuclear and other sources of energy. What would be the types of engines for moving people and goods? The sizes, configurations and number of cylinders were central issues. The best fuels were also uncertain. Now we know two things. The first is that almost all options under consideration at the outset of the transportation revolution have some role to play currently. The second is that fast turbines, which enable modern jet airline transportation, where not a major part of the historic discussion in the early 1900s. Water turbines were common and gas turbines were demonstrated. However, the materials needed for high-speed gas turbines were not available a century ago. Will anything emerge in the field of energy production, as did fast turbines in the field of transportation? Could it be Low-Energy Nuclear Reactions? If so, when might that happen?

3. Low-energy Nuclear Reactions

3.1. Background

The term “low energy” is part of LENR because of the fact that it is possible to induce nuclear reactions at energies and equivalent temperatures that are dramatically lower than those needed for ordinary nuclear reactions, fusion included. We noted in the last section that energies of at least tens of keV, that is, temperatures exceeding 100s of millions of degrees K are needed to overcome the Coulomb barrier for fusion reactions to occur. Much higher energies are needed for nuclei with higher charges. But, it has been found experimentally that it is possible to induce exothermic LENR in both light and heavy ions at rather ordinary temperatures. The corresponding energies are well below 0.1 eV.

Many books give myriad details on LENR. A useful compilation is on the web [21]. The architecture of this section is similar to that of the last section on hot fusion. The goal of the section is to give highlights on the characteristics, status and prognosis for LENR.

3.2. Types of LENR

In very general terms, the specific materials, the equipment and the protocols in LENR experiments have varied widely. Materials in LENR experiments are quite diverse. But, in all cases, either a proton or deuteron is loaded on to or into a solid lattice. The hydrogen isotopes can come from a liquid (electrochemical loading), a gas (high pressure and elevated temperature loading), a plasma (mostly glow discharges, but also arcs) or an ion beam (from an accelerator).

The material system used by Fleischmann and Pons in the pioneering experiments in the late 1980s was Pd as the solid lattice and deuterium as the hydrogen isotope. Most of the experimental work in the field has been done using this system, including electrochemical, gas, plasma and beam loading. Early in the field, some experimenters worked with the Ni and H system and reported getting excess heat, indicative of nuclear reactions. This system has also been the core of numerous experiments, but many fewer than for the Pd–D combination.

The signatures of nuclear reactions are also varied, but can be categorized. The first and most important is the generation of heat at levels far beyond what can be explained chemically. Energy output is the most likely to be a practically important result of LENR. It is the focus of this paper. We will survey energy gains for the Pd–D and Ni–H systems below.

There are other measured signals that indicate nuclear reactions can occur at low temperatures. One is “nuclear ash”, the elemental residues of the reactions. Helium and tritium are the dominant examples of nuclear reaction products. There are several reports of a correlation between heat and helium production in LENR experiments. The first was by Miles [22]. The most detailed was by McKubre and his colleagues [23]. The correlation of heat and helium remains contentious, as do most aspects of LENR, both experimental and theoretical.

The production of heavy elements in LENR experiments has been widely reported. The term “transmutation” is applied to this kind of output from LENR. In 2003, Miley compiled a list of 15 laboratories in six countries, which reported transmutations in LENR experiments [24]. Such experiments are difficult because they require trace element analyses both before and after the LENR experiments. Such analyses are generally complex and expensive.

Fast charged particles, which also cannot be produced chemically, have been observed by many investigators. For example, Lipson and his colleagues reported the emission and measurement of 3 MeV protons and 11–20 MeV alpha particles from Pd/PdOD_x and TiD_x [25].

Besides heat, nuclear ash and energetic particles, there are some infrequently measured low-energy phenomena that can also be interpreted as evidence of nuclear reactions. They include the emission of sound and infrared radiation, and the production of micro-craters. Such measurements must be verified in experiments that involve parametric variations of the materials and conditions used. Until then, they provide only weak but suggestive evidence for LENR.

The variety of means to load hydrogen isotopes onto and into a lattice and the classes of ensuing measurements is given schematically in Fig. 6. It must be emphasized that the number of experiments that can be classified into each of the 16 boxes varies greatly. Most work has been done with electrochemical loading from liquids and heat measurements using a wide variety of calorimeters.

3.3. Criteria for LENR

We saw that there are three critical plasma parameters, the density, the temperature and the lifetime, for energy production in hot fusion. The Lawson Criterion gives the requirements on the Triple Product of these three factors quantitatively

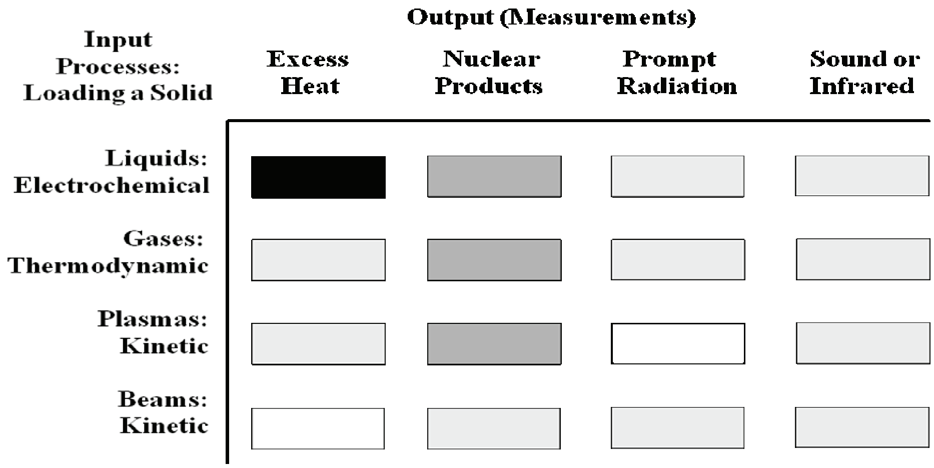

Figure 6. The four means to bring together a solid lattice and hydrogen isotopes (*left side*) and the four classes of measurements that indicate the occurrence of LENR (*top row*). The darker shading indicates the combinations with the most experiments.

for net energy production by D–T fusion. The question naturally arises: are the conditions for LENR known similarly, and are they quantified? In other words, is there the equivalent of a Lawson Criterion for LENR? The answer now is no. The fundamental roadblock is the lack of understanding of LENR, both conceptually and quantitatively. Around two dozen theories of LENR have been published, but none of them has been adequately tested against the results of LENR experiments. The present lack of theoretical understanding does not mean that a criterion specifying quantitative conditions for achievement of LENR will never be developed. In fact, there has been major progress toward the development of such a criterion.

The most fundamental requirement for the occurrence of LENR seems to be the need for a solid lattice to be the host for the protons or deuterons. This is in stark contrast to the situation for energetic and high temperature nuclear reactions. In beam experiments, the lattice provides a holder for target nuclei, but is not a requirement for the occurrence of nuclear reactions. Put another way, crossed ion beams in a vacuum system also lead to high-energy nuclear reactions. In hot plasmas, there is no lattice because the particle energies are sufficiently great to melt, vaporize and ionize the atoms that might initially be part of a solid lattice.

There has been much discussion about the location of the sites at which LENR occur. It is not finally decided whether LENR occur only on the surfaces of lattices, only within them or in both locations. Much evidence indicates that surface reactions are dominant, but there is no consensus. Similarly, many studies have employed materials with particle sizes on micrometer and nanometer scales, in addition to the millimeter-scale electrodes usually used in LENR experiments. Several experiments indicate that the use of nano-scale particles favors the production of LENR, but here also the "jury is still out". Despite all these uncertainties, there is a good start on determining the criteria required for production of LENR.

McKubre and his colleagues have done over 100,000 h of precision calorimetry in LENR experiments. They presented [26] a provocative relationship based on their measurements, which gives the variations in excess power P_{xs} in electrochemical LENR experiments with three quantities, which will be defined in the following paragraphs. K is an unknown proportionality constant in this equation.

$$P_{xs} = K(I - I_0)^2(X - X_0)\mathrm{d}X/\,\mathrm{d}t.$$

The first factor in the McKubre equation is the value of the electrochemical current density I passing through the cylindrical cathode surface beyond a value near 100 mA/cm^2 = I_o. It was found that P_{xs} scales with $(I–I_o)^2$. Experimental current densities about an order of magnitude greater than 100 mA/cm^2 have been employed. The maximum values of I are not well defined. Power supplies capable of delivering very large currents can be built, so there is no imminent equipment limit. Heating of electrochemical cells might be the first factor that limits the increase of electrical current density. But, heating has been shown to favor excess power production in some experiments.

The second parameter is the loading factor, specifically, the ratio of the number of deuterons to the number of Pd atoms within a Pd cathode, that is, X =D/Pd. The excess power scales linearly with values of X in excess of $0.85 = X_o$. It has been difficult to achieve and maintain values for X substantially above unity in electrochemical experiments. Then, $(X–X_o)$ is near 0.15. Other (non-electrochemical) experiments have reported values for X near 2. Hence, $(X–X_o)$ can range from zero to somewhat above unity.

The third parameter in the equation for the Pd–D electrolytic system is the rate of change of the loading X. The higher $\mathrm{d}X/\mathrm{d}t$, where t = time, the higher the excess power. In the experiments that lead to the discovery that P_{xs} scales linearly with the rate of change of the loading factor, the value of dX/dt was not a control parameter. It varied capriciously, leading to the observed correlation. If there were, indeed, some way to willfully increase the rate of loading $(+\mathrm{d}X/\mathrm{d}t)$ and deloading $(-\mathrm{d}X/\mathrm{d}t)$ for D in Pd, P_{xs} might be enhanced. But, it is not easy to estimate the maximum achievable values. The rate of diffusion of D in Pd might provide an extreme limit on the values of $\mathrm{d}X/\mathrm{d}t$. But, that rate is remarkably high. The rate of ingress and egress of D is clamped to the electrochemical current. Possibly, the use of power supplies that rapidly vary their applied currents for constant voltage (potentiostatic) electrolysis, would favor large values of $\mathrm{d}X/\mathrm{d}t$ and, hence, high values of P_{xs}.

The above conditions on loading, current density through a cathode surface and rate of change of loading are probably necessary, but not sufficient conditions for full control of LENR in electrochemical experiments. Analogous criteria for gas, plasma and beam loading experiments remain to be developed.

We must note that a criterion, or rather multiple criteria, for the occurrence of LENR is not the same as some measure of ways to optimize the production of energy by LENR. While the Lawson breakeven criterion for energy production in hot fusion is available, a recipe for optimization of hot fusion energy production does not exist now. There are inevitable limits on hot plasma densities, temperatures and lifetimes. Until these limits and trade-offs between them are known, it is not possible to provide the conditions for optimization of hot fusion energy production. The situation is similar to the operation and efficiency of an automobile. It is relatively easy to state what is needed to make a car work. It is more complex to ascertain how to get the best gas mileage, which depends on both the design and the operation of a car. In short, now we are waiting for the complete criteria for occurrence of LENR. Knowledge of the conditions for net energy production and for optimization of energy production may not be available for several years, or even longer.

3.4. Status of LENR

3.4.1. *The palladium–deuterium system*

There are about three dozen experimental papers on the Pd–D system, which present the values for both the output and input energies, so an energy gain can be computed. For most of them, the energy gains (energy out divided by energy in) are less than 1.5. Such relatively low values raise questions about the possibility of chemical effects, and experimental errors, especially drifts in long-term experiments. A short summary of a few of the more noteworthy measured LENR energy gains is given in Table 4. None of these experiments has been adequately replicated. Note that the first two of these experiments involve relative small (<1 MJ) energies.

3.4.2. *The nickel–hydrogen system*

The field of LENR was started with Pd–D experiments, and most of the experiments in the field have been done with that system. However, there have been many reports on experiments with the Ni–H system, which first got attention in the early 1990s. It is attractive since Ni is much cheaper than Pd and H_20 is also less expensive than D_20. In the recent past, Focardi and Rossi have reported spectacular energy gains in the range from 80 to somewhat over 400 from Ni–H experiments [30]. They tabulated the results of six experiments during the period from mid-2008 to mid- 2009. Figure 7 is a plot of their reported input and output energies.

There are three remarkable features of these data from the Ni–H system. The first is the immense energy amplification factors. Ordinarily, a factor of 25 is adequate for commercialization of an energy source. That gain is enough to overcome thermodynamic, conversion and transmission losses. Gains in the range of 80–400 bode well for the practical applications of LENR.

The second noteworthy factor is the relatively large amounts of energies going in and out of the system. Pd–D experiments rarely have powers exceeding 100 W as input and output, and integrated excess energies seldom exceed 1 MJ. The highest of the Focardi–Rossi input energy exceeds 30 MJ with the associated output energy in the 3 GJ range. These are very large values for LENR experiments. The last important feature of the new Ni–H data in Fig. 7 is the approximate linearity of the output energy with the input energy. This indicates that, with some thermal lag, the input energy may be the much-needed control parameter for LENR energy source output.

The important power–time histories (power input and output) from the Rossi Ni–H experiments are not available. Additional information on this provocative work is in an international patent application [31]. However, that application does not teach how to produce LENR and realize high energy gains. The immense reported gains for the Ni–H system share an unfortunate feature with the high energy gains in the Pd–D system. They have not been reproduced by other experimenters nor even robustly verified.

4. Conclusion

The overall contrast between hot and "cold" fusion is remarkable. It is a fact of scientific history that hot fusion experiments have been conducted for 60 years by hundreds of physicists and engineers at a cost exceeding \$ 20 B. But, they have barely achieved energy breakeven. Experiments having costs, which will double the investment in hot fusion, are planned for the next few decades. Both their uncertain outcomes, and competition from other sources, make the eventual practical importance of hot fusion inscrutable.

Hot fusion is understood scientifically, and a great deal of the engineering needed to realize hot fusion power plants is already done. It is possible that large central hot fusion power plants might be supplying electrical power before 2050, a century after research in the area took off. Like current fission power plants, the grid will be used to distribute power that huge hot fusion plants might eventually produce. Their operation will activate large amounts of materials near the plasmas, which will be heavily bombarded by neutrons. Hence, future hot fusion plants will leave behind significant radioactive waste, as do present fission plants.

In stark contrast, LENR (then called "cold fusion") experiments reached breakeven after less than 10 years of experimentation by two people, Fleischmann and Pons. The total cost of LENR research to date is probably well under

Table 4. Reports of high-energy amplifications from some Pd–D LENR experiments.

Authors	Year	Energy in (kJ)	Energy out (kJ)	Energy gain	Ref.
Fleischman and Pons	1991	22.5	102.5	4.5	[27]
Sun, Zhang and Guo	2003	28.3	131	4.6	[28]
Dardick et al.	2003			6.7	[29]

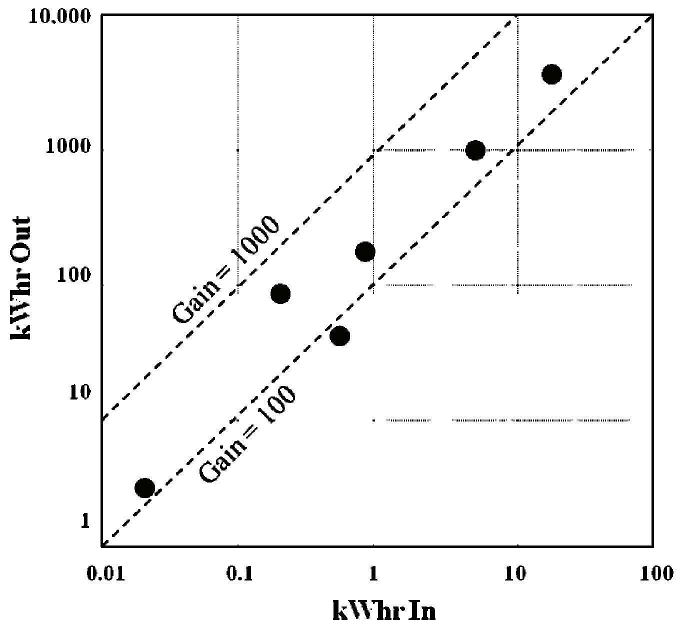

Figure 7. The output energies as a function of input energies reported in the recent Focardi–Rossi paper [30]. 1 kWh = 3.6 MJ. The very high gain values are noteworthy. If they are verified or reproduced, they would prove to be historic.

$ 0.2 B. Very little support is available for LENR at present. Given that the field has the potential to produce a new and clean source of energy, this situation is anomalous. If practical sources based on LENR are promising, why is the scientific study of LENR not being pushed hard? The most fundamental reason is lack of attention by the mainstream scientific community. Funding agencies, major investors, patenting organizations, and the editors of both scientific journals and magazines, are all waiting for the scientific community to adequately engage the voluminous literature on LENR and then legitimize the field as a part of science. However, few scientists with the appropriate expertise are willing to thoroughly examine the available information. And, several well-recognized ex-scientists continue to disparage the field for unknown reasons.

LENR are not understood now. None of the many theories has been adequately tested. However, the empirical database in the field, which is mostly public, makes it possible to contemplate the following possibilities.

- The new sources would be safe during their operation because LENR do not emit high intensities of dangerous prompt radiation (neutrons or gamma rays).
- There is ample experimental evidence that LENR do not produce significant residual radioactivity, so generators based on these reactions would not generate dangerous waste.
- No green house gases are emitted during the operation of LENR experiments.
- LENR generators do not have to be big or expensive. However, they might be scalable for larger applications, both mobile and fixed.
- The sources could be distributed, even powering individual homes and, hence, relieving the electrical distribution grid of some load.

The sizes of potential LENR sources of power and energy are naturally key to possible applications. Now, neither the physical size nor the power output of potential LENR sources is clear. Some people envision such sources being the size of batteries for personal electronics. They might be desk sized and supply enough power for an individual home. Powers ranging from watts to more than kilowatts have been discussed. One of the main issues for commercial LENR power sources is already known from experience with fuel cells. The ancillary equipment for electronic, fluidic and thermal functions can be relatively complex. Put another way, even if a vessel in which LENR could be confidently produced at an attractive cost were available now, engineering it into widely useful and reliable products would be challenging.

While it is possible to project the performance of magnetically confined hot fusion experiments, this cannot be done now for LENR experiments. Until reproducibility and controllability of such experiments are improved, and the active mechanisms are understood, confident theoretical scaling of LENR power and energy gains will remain essentially impossible. However, despite the current shortcomings for LENR, the prospect of many applications, in addition to the vexing scientific riddles in the field, should spur research. One application in particular could be historic. The production of clean water by either desalination of seawater or distillation of contaminated river waters would have immense global health benefits. The availability of distributed sources of nuclear energy for clean water production is a wonderful vision for the future of LENR.

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