Energy gains from lattice-enabled nuclear reactions

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The energy gain of a system is defined as the ratio of its output energy divided by the energy provided to operate the system. Most familiar systems have energy gains less than one due to various inefficiencies. By contrast, lattice-enabled nuclear reactions (LENR) offer high energy gains. Theoretical values in excess of 1000 are possible. Energy gains over 100 have already been reported. But, they have not yet been sustained for commercially significant durations. This article summarizes the current status of LENR energy gains.

Keywords: Energy, energy gain, LENR.

Introduction

LENR most commonly stands for low energy nuclear reactions. But 'low' is a relative and unclear term; so LENR is used in this article to represent the more precise descriptor lattice-enabled nuclear reactions. Such reactions can occur when protons (P) or deuterons (D) are brought together with the lattices of various metallic materials by a variety of processes. Electrochemical loading of D into Pd was the initial means of producing LENR[1]. However, gaseous loading of P onto Ni has also received much attention, and is likely to be commercialized first in the coming years[2]. Because of LENR, a revolution in energy generation is expected by many informed people.

A quarter of a century of experimental research has shown that it is possible to induce nuclear reactions with chemical energies. This remarkable capability is contrary to accepted theoretical physics, and is still not understood. However, it is well established empirically. Output energies from LENR experiments have exceeded what is possible from chemical reactions by factors of well over 100 in some cases[3]. Power densities far in excess of those in fission reactor fuel rods have been observed[4]. The products of nuclear reactions have often been reported[5]. Evidence for the production of tritium, a radioactive isotope with a short half life, is especially strong[6]. The correlation of produced helium with excess energy was discovered and reviewed by Miles[7]. Neutrons from LENR experiments cannot result from chemical reactions[8]. By themselves, they show that nuclear reactions occur in LENR experiments. Other empirical evidence, such as the appearance of craters on the surfaces of materials in LENR experiments, can be explained by the release of nuclear energies[9].

The large published literature of experimental data on LENR shows that this method of producing energy has some attractive advantages. These include high energy densities and gains, with freedom from significant prompt radiation, residual radioactivity and greenhouse gases. And, it appears that kilowatt LENR power generators can be widely distributed, i.e. off the grid. They offer the prospects of being cost-effective. Electricity production at 2 US cents/kWh has been projected. These potential advantages, as well as safe long-term operation, regulatory approval and market acceptance, remain to be demonstrated commercially. However, LENR offer the best combination of prospects of any foreseeable new energy source.

The input to most LENR experiments is electrical power, usually at low (chemical) voltages. Integration of the input power over the course of an experiment gives the total input energy, the denominator in the energy gain. The output of such experiments is thermal power, commonly measured by calorimeters. It includes both the input power and the power generated by LENR. Its integration for the duration of the experimental run gives the total output energy, the numerator in the energy gain.

Reliability and full control of power production are clearly needed for commercialization of LENR. It must be noted that in most LENR experiments to date, the produced power varied for unknown reasons during a run. Willful control of the power generated by LENR remains a challenge for both scientific understanding and practical applications. However, recent progress has been made on such control for a prototype product that generates power levels in the kilowatt range[10]. It will be discussed below.

We consider the energy barriers to both chemical and nuclear reactions in the next section. Theoretically possible and published LENR energy gains are discussed in the following section. Reports of fast energy releases in LENR experiments are summarized in the penultimate section. The concluding section looks ahead to commercialization of LENR.

Reaction barriers

When it is desired to produce chemical or nuclear reactions, it is necessary to bring the reactants together under

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the proper conditions with an initiation energy E_I to cause the reaction. Then, for exothermic reactions, energy E_R is released. This is indicated schematically in Figure 1. A key factor is the existence of an energy barrier between the initial and final energy levels.

The existence of an activation energy has both good and bad effects. Without such an energy barrier, undesired reactions could proceed spontaneously. Runaway combustion and nuclear reactions would occur. But, if one wants to induce reactions to produce energy or chemicals, reaction barriers are an impediment.

The key factor for both chemical and nuclear reactions is the fact that the activation energy is on the same scale as the released energy, eV for chemical reactions and MeV for nuclear reactions. The barrier to chemical reactions exists because energy must be provided to a system of molecules in order to rearrange the atomic constituents. The relatively low temperature (energy) of the flame from a match is sufficient to ignite a chemical fuel, such as wood, which produces a few eV per reaction. The barrier in the nuclear case is due to the electrostatic (Coulomb) repulsion of the two positive ions, which tends to keep them apart and unable to react. In the case of hot fusion, hard-to-contain, hundred-million degree plasmas are needed, so that their ions have kinetic energies with a significant fraction of an MeV. Then, they can overcome the Coulomb barrier and induce fusion reactions that release MeV of energy. The big news for LENR is that eV-scale chemical energies are sufficient to release MeV nuclear energies. With LENR, it is not necessary to employ very hot plasmas, with their fast particle velocities, in order to induce nuclear reactions.

The ability to reduce activation barriers for chemical reactions by the use of catalysts is familiar. It is less widely known that the catalysis of nuclear reactions is also possible in an established process called muon-catalysed fusion[11]. The radius of a hydrogen atom, with a muon in place of the normal electron, is 285 fm. This small radius leads to increased fusion rates, because the distance over which tunnelling must occur to result in a nuclear reaction is much smaller than for normal atoms. Hence, the tunnelling probabilities and associated nuclear reaction rates are greatly increased (catalysed). A very basic question regarding mechanisms for LENR is how the Coulomb barrier is reduced by catalysis or otherwise entirely avoided.

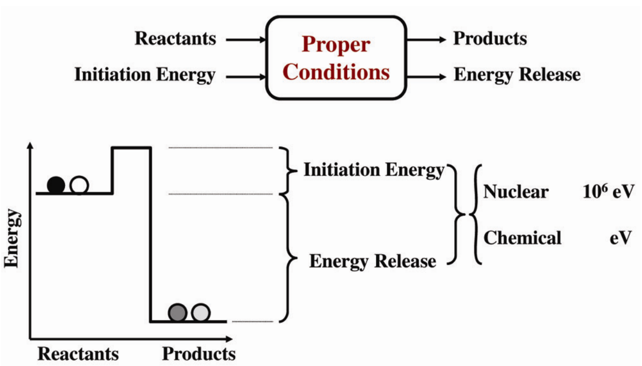

Figure 1. General characteristics of exothermic chemical and nuclear reactions. The initiation energy E_I is generally within a factor of ten of the released energy E_R for chemical reactions and varies widely for nuclear reactions.

There has been one experimental determination of the activation energy needed to induce LENR. Storms[12] performed electrochemical loading of D into Pd as a function of temperature. He found that the excess power due to LENR followed the Arrhenius equation[13], familiar for chemical reactions, with an activation energy of 0.6 eV. That is, initiation energies E_I on the chemical eV scale sufficed to produce nuclear energy releases E_R. This is encouraging for the energy gains in expected commercial LENR generators.

Potential and reported LENR energy gains

If it is possible to trigger the release of about 1 MeV of nuclear binding energy by the use of a chemical energy on the scale of 1 eV, then an energy gain of 1 million is conceivable. That would require success in surmounting the barrier to LENR for each attempt. The energy gain would be as high as $E_R/E_I = 10^6/1 = 10^6$. Because of thermal vibrations and other factors, achievement of such a high success rate is unlikely. But, what if it turns out to be possible to induce one LENR with a 1000 attempted barrier crossings? That would result in an energy amplification of about 1000. Such a value might seem inconceivable now. However, if LENR generators become reproducible, controllable, safe and successful in the market, their performance will be improved over the years. Consider the integrated circuit, with only a few transistors on a chip about 60 years ago and over 5 billion transistors on some current chips. One might object to that comparison because of the immense commercial importance and impact of microelectronics on computations and communications. Trillions of USD have been spent on microelectronics. However, if the cost of heating and electricity could be reduced by even a factor of 10, it is highly likely that LENR would become widely used and a very large global business. The availability of distributed generators would have the most dramatic impact on lifestyles and health in developing countries.

Those who blanch at the possibility of energy gains of 1000 might demand evidence for their expectation. Because of many and diverse experiments conducted since the 1989 announcement by Fleischmann and Pons, there is already a significant database for high LENR energy gains. Some of those data will now be reviewed. There are numerous reports of significant energy gains in LENR experiments. The earliest was a report in 1991 by Mills and Kneizys[14] of a gain of 37. They performed electrolysis in a light water (H_2O) electrolyte with a nickel cathode. One of the most famous reports of a high LENR energy gain came from a former Israeli company, Energetics Technologies[15], which conducted electrochemical experiments with Pd and a heavy water (D_2O) electrolyte. The experiments were distinguished by having a complex ('superwave') electrical input and also an ultrasound transducer to excite the cell. Figure 2 shows plots of the input electrical power and output thermal power for about 20 h. The two powers are similar at a fraction of 1 W for the first 4.5 h of the run. Then, the output power increased rapidly to 18 W, and varied erratically (uncontrollably) for 15.5 h, reaching a maximum of 35 W. The average power was 21 W and the energy gain a factor of 26.

There were many attempts in two laboratories[16] to reproduce the performance shown in Figure 2. Several runs showed substantial energy gains. The highest energy gain seen in those replication experiments was 70. This can be compared with the target gain of only 10 for the International Tokamak Experimental Reactor, a hot fusion project that is now taking tens of years and tens of billions of USD to complete.

In March 2010, Focardi and Rossi[17] posted on the web the results of several experiments done in Bologna by loading H_2 gas onto nickel materials (Table 1). It is seen that some of the input and output energies are relatively large for those LENR experiments. But, the really significant data are the remarkable magnitudes of their reported energy amplification factors, which range from a low of 80 to a high of 415. The authors reported that the run with a gain of 80 was anomalous (due to contamination of the fuel).

The highest energy gain report from an LENR experiment is from Mizuno and Toriyabe[18]. They were operating a relatively large electrochemical cell, which exploded about 1 min after the power was turned on. 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 than a chemical event.

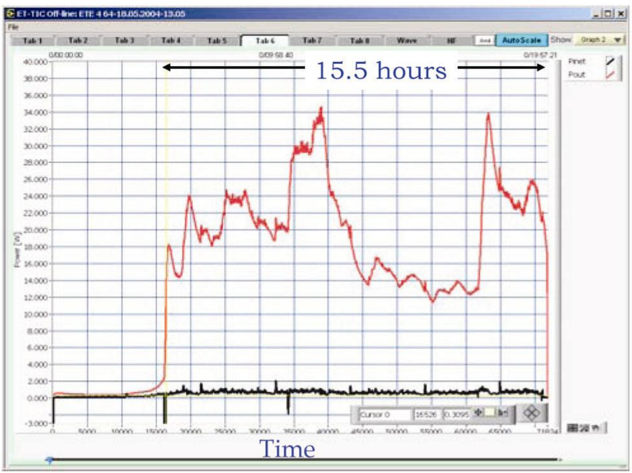

Figure 2. Plots of power in (black) and out (red) for an experiment that gave an energy gain of 26. The vertical scale is in W up to 40 W (2 W/division).

An even higher energy gain has been reported in an experiment apparently unrelated to LENR, but possibly caused by LENR. Kamada and his colleagues[19] implanted P and D into separate thin Al foils at relatively high doses. Because of the low solubility of hydrogen isotopes in Al, the implanted atoms were trapped near where they come to rest. Hence, high densities of P and D were produced. When the samples were viewed under a transmission electron microscope, images and diffraction patterns showed that Al near the D-rich regions melted. The samples with P did not show similar behaviour. The energy necessary to produce the melting, and the energy deposited by the electron beam up to the time of melting, were both computed. The ratio of these two energies gave the energy gain. The authors wrote 'the energy gain… amounts to more than 1×10^5'. The reaction time was estimated to be one-tenth of a nanosecond. In later papers, Kamada considered many mechanisms for this observation, including cold fusion. He concluded that the melting mechanism was due to the action of a spin–flip phonon maser action of the deuterium nucleus induced by a stimulated Raman process[20]. That work deserves more consideration, in particular, an energy analysis for the production of maser action.

It must be emphasized that the energy gains over 100 listed above have not been adequately validated by either independent detailed examination of the experiments that produced them or by their repetition. This does not mean that they are wrong. The normal requirement for reproducibility of laboratory experiments will be difficult to satisfy if all of the controlling parameters are not yet understood.

Fast LENR energy releases

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. Several instances of runaway and even explosive LENR experiments have been reported. Some will be cited here.

Table 1. Date, duration and details of gas loading experiments that reportedly had very high energy gain

Date	Duration	Method	Input (kWh)	Output (kWh)	Energy gain
28 May 2008	1–1.5 h	Steam production and make-up water	0.2	83	415
11 June 2008	1–1.5 h	Steam production and make-up water	0.806	165	205
2 September 2008	1–1.5 h	Steam production and make-up water	0.5	40	80
17 February–3 March 2009	15 days	Thermometry with a heat exchanger	5.1	1006.5	197
5 March–26 April 2009	53 days	Thermometry with a heat exchanger	18.54	3768	203
24 June 2009	?	Thermometry in a closed loop	0.018	3.23	179

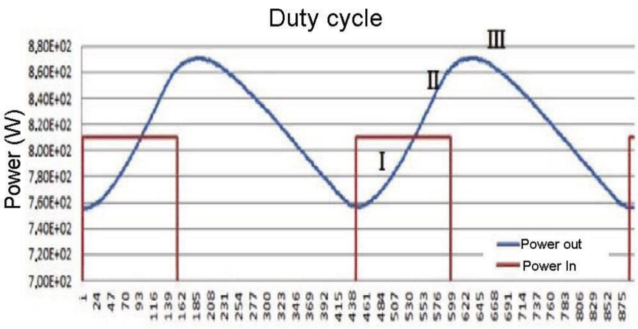

Figure 3. Temporal variation of E-CAT input (red) and output (blue) powers for two heating cycles. The horizontal axis is from 1 to 875 sec, and the vertical axis from 700 to 880 W.

In 1985, Fleischmann and Pons were running an electrochemical experiment with a cathode, which was a cube of Pd 1 cm on a side. One night, it melted and destroyed the set-up, as documented in their 1989 paper[1]: '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 1544°C), part of it vaporized, and the cell and contents and a part of the fume cupboard housing the experiment were destroyed.' A hole was produced in the concrete floor below the experiment that was about 8 inch wide and 3 inch deep[21]. That incident was not an explosion.

There are two papers which document explosions in LENR experiments, in addition to the event described by Mizuno and Toriyabe and reviewed above. In 1992, Zhang and his colleagues described three explosions in electrolytic Pd–D experiments[22]. The cathode was a hollow Pd tube. They analysed one of them and wrote 'it is not a chemical explosion but a cold fusion explosion'. Biberian[23] had an experiment, also using a hollow Pd cathode, end in an explosion. He then did experiments to see if the explosion could be due to recombination of deuterium and oxygen. They failed to simulate the initial explosion. 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 noted by Arata and Zhang[24], and by Srinivasan[25].

Rossi was quoted as having observed numerous explosive events during the development and testing of E-CAT devices. On 21 July 2011, a report in Pure Energy Systems News[26] 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.' In an interview, Christos Stremmenos[27] stated that there were explosions during E-CAT tests in Bologna, fortunately all at night.

Craters less than 100 μm in diameter have often been observed in cathodes after electrolytic LENR experiments. Examination of craters shows evidence of melting. Production of craters requires only small energies, 1 mJ or less[9], but they form on times scales of less than 1 μs (ref. 28). Craters are evidence of micro-explosions in LENR experiments.

In summary, it appears that LENR reactions are capable of fast release of energy. Hence, the means to control them in commercial generators are critically important. Put another way, it is necessary to balance the production of LENR energy, possibly at high gains, with the ability to both control the level of power production and prevent runaway events. In some ways, this situation resembles the control that is needed for fission reactors.

A recent report on testing of E-CAT devices provided encouraging evidence of the control of LENR energy production[10]. The devices were heated by electrical pulses, the magnitude, duration and spacing of which were controllable. Figure 3 shows the time histories of the input electrical and output thermal power. It is seen that after the input power was turned on, more power was being consumed than was produced in phase I, a situation that reversed during phase II. Then, after the input power was stopped, the output power declined in phase III. The shape of the output power curve is significant. During heating, it is concave upward, the opposite of the behaviour of a heated resistor. That indicates a potential runaway situation. The character of the output power curve during cooling is concave downward, again opposite the behaviour of a normal hot object, which cools quickly at first and more slowly later. This controllability has a highly desirable feature. Failure of the input heating power system would lead to prompt shutdown of LENR power production. Hence, meltdowns would be avoided, a good feature even with the absence of radioactive materials in a LENR reactor.

Conclusion

The contrast of energy amplification by LENR with ordinary generation of energy is stark. Consider the production of electricity by burning coal, which produces 60% of the electricity in India and 40% of US electricity. The overall process involves three energy conversions (each with inefficiencies): (i) chemical to thermal (with possible incomplete combustion and heat losses), (ii) thermal to mechanical (with heat losses and friction), and (iii) mechanical to electrical (with friction and hysteresis losses). Each step is also encumbered by the thermodynamic Carnot inefficiency. The point is that the current production of even heat, but especially electricity, involves significant energy losses, in contrast to the energy gains in LENR. The high gains and high temperatures, which some LENR prototypes have exhibited, bode well for future electricity production.

The overall situation regarding LENR involves science, engineering and commercialization. Theoretical understanding of LENR remains to be achieved. However, significant experimental evidence shows that LENR can have very large energy gains. Both theoretical considerations and empirical evidence for LENR are discussed in other articles in this special section. Importantly, LENR are not encumbered with the problems of fossil fuels (notably greenhouse gases) and other nuclear means of energy production (with their prompt radiation and residual radioactivity). The engineering of LENR experiments during the past 25 years has become very sophisticated. In contrast, the engineering of commercial prototypes is still relatively crude. This might change in the coming few years. Commercialization of LENR will require several steps. These include the development of reliable and controllable prototypes, beta testing, design and production of products, and their safety and regulatory clearances. Conventional and new means to exploit power produced by LENR will be needed. Whatever the commercial timescale, LENR energy promises major benefits for humankind in future decades and beyond.

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