Lattice-enabled nuclear reactions in the nickel and hydrogen gas system

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Thousands of lattice-enabled nuclear reaction (LENR) experiments involving electrochemical loading of deuterium into palladium have been conducted and reported in hundreds of papers. But, it appears that the first commercial LENR power generators will employ gas loading of hydrogen onto nickel. This article reviews the scientific base for LENR in the gas-loaded Ni–H system, and some of the tests of pre-commercial prototype generators based on this combination.

Keywords: Gas loading, hydrogen, lattice enabled nuclear reactions, nickel.

Introduction

LENR generally 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 lattice-enabled nuclear reactions. Many experiments have shown that these reactions can occur when protons (P) or deuterons (D) are brought together with the lattices of various metallic materials by a variety of processes. Hence, there are three choices to be made prior to performing a LENR experiment: (i) which hydrogen isotope, P or D, (ii) what metallic element or alloy, and (iii) the means of causing interactions between the hydrogen isotopes and the metals.

The first approach to producing LENR involved electrochemical loading of D into Pd. Fleischmann and Pons were electrochemists, familiar with the remarkable ability of Pd to absorb P or D. In the mid-1980s, they were interested in the possibility of producing energy by nuclear fusion and so did experiments with heavy water D_2O (ref. 1). Measurements of heat generated in those experiments could not be explained by chemical reactions, and the nuclear reaction term 'cold fusion' was applied to the results. While 'cold fusion' is still used by some people, the mechanisms occurring in such experiments now generally go by the acronym LENR.

Most experiments in the field have been done with the Pd–D system and electrochemical loading. There have also been notable heat-producing electrochemical experiments with the Ni–H system[2]. Gas loading of P onto Ni has also received much attention, and is likely to be commercialized first in the coming years. The advantages of gas loading were summarized in a review of the approach[3]. That line of research for the Ni and H system started early in the field during the mid-1990s, and is the topic of this article.

The second section briefly compares some nickel and palladium characteristics, which are relevant to LENR. The third section reviews some of the pioneering research on gas loading of the Ni–H system by Piantelli and his colleagues. Current commercialization of energy generators based on the Ni–H system by small companies is treated in the fourth section. The final section summarizes the possible advantages of production of energy using LENR. It also mentions the steps that must be taken to achieve commercially viable LENR power generators.

The test results from commercial prototypes reviewed in section 4 are provided mainly from the available documents and web postings. The reviews in this article are not endorsements of the reported results nor of the conclusions of the authors. It is important to note that what was done and found in the tests is generally contentious, with stern critiques by competent scientists and others. A much longer paper would be required to fully summarize the on-going debate.

Nickel and palladium

These two elements are in the same column of the periodic table, so they have some similar properties. They have the same face-centered cubic crystal structures, but different band structures and different phase diagrams with hydrogen. Both elements have many isotopes, ten for Ni (five stable) and nine for Pd (five stable). Hydrogen is much more soluble in palladium than in nickel, the ratio being about 10^5 at 500 K, and even greater at ordinary temperatures[4]. This means that the interaction of hydrogen with nickel tends to be confined to the near-surface region. Hence, the use of nanometre-scale materials, where most atoms are on or near the surface of the active materials, is attractive. The nanomaterials might be powders, that is, individual particles, or features on the surfaces of larger materials. The latter approach will be discussed below. The occurrence of LENR on material surfaces makes both the introduction of reactants and the

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removal of products much easier than if the reactions happen within the bulk of materials. The very large difference in price for the two elements is important commercially, about US$ 15/kg for Ni and US$ 27,000/kg for Pd. The low cost of H_2 compared to D_2 is another reason for commercial interest in the Ni–H system, compared to the Pd–D combination.

Research by Piantelli and colleagues

Late in 1989, Piantelli was conducting a biophysics experiment at the University of Siena, when he serendipitously discovered that the combination of H_2 gas and Ni could produce heat. Within a year, he reproduced the phenomenon a few times. He formed a collaboration with Habel and Focardi in 1990. They published the initial results of their work in 1994 (ref. 5). The trio used thermometry, rather than calorimetry, to prove that power was being generated in their experiments. They measured 44 W of excess power for a period of 24 days, for an excess energy of 90 MJ. Two years later, Piantelli, Focardi and three others reported additional preliminary evidence of excess power[6]. In that work, they used calorimetry as well as thermometry to obtain the values for excess power in two cells. Two methods sometimes, but not always, gave comparable values for excess power. Nonetheless, substantial excess powers were obtained for all cases. Two years later, the same team published more details on their ability to produce power by LENR[7]. In that paper, they noted that two cells ran for periods of 'about 300 days', and produced excess energies of 600 and 900 MJ respectively.

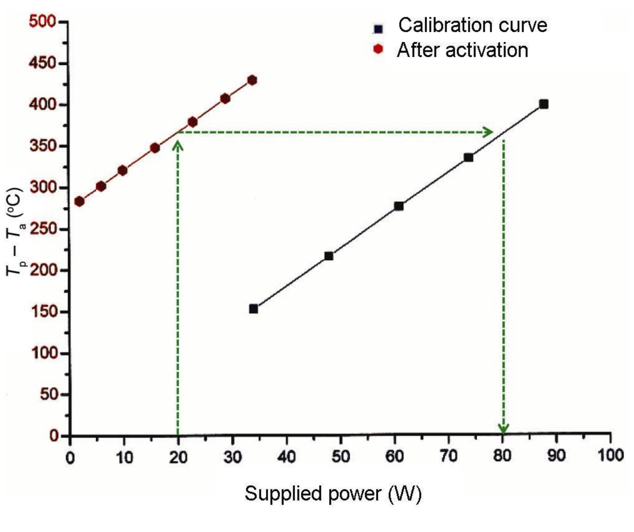

Figure 1. Temperature (T_p) in the core of the experiment relative to ambient temperature (T_a) for two cases, a calibration curve and a Ni rod that had been activated. Only 20 W of input power is needed for the activated rod to attain the same temperature as produced by 80 W of power input for the calibration run. This indicates an excess power of 60 W for the 20 W of input electrical power.

At a conference in 2010, Piantelli presented a paper entitled 'proton reactor'[8]. It contained a graph showing the results of thermometry measurements of excess heat in the Ni–H gas system (Figure 1). It is seen that the comparison of temperatures for the calibration run, with those from an experiment with activated Ni material, indicates an excess power of 60 W. Given 20 W of input power, the power gain was a factor of four = (20 + 60)/20.

The work by Piantelli and his colleagues attracted widespread attention of other researchers. It also stimulated multiple attempts to commercialize the Ni–H gas loading approach for the generation of energy by LENR. The commercial activities, which have been made public, are reviewed in the next section.

Current commercialization

The successes of Piantelli and his colleagues in producing heat by LENR, and the advantages of gas loading of protons onto nickel, have generated substantial technical and investment interest in commercialization of the process. A few relatively new and small companies are seeking to develop prototypes of products. Their status and activities, and results of tests of some their prototypes, are reviewed in this section.

Piantelli's companies

In 2011, Piantelli founded the company Nichenergy to develop LENR generators[9]. The next year, he formed another company Metalenergy to raise money by selling stock to acquire the capital needed for commercialization of his technologies[10]. Little has been heard from these companies recently, so their status and plans are now unclear.

Companies related to Rossi

Andrea Rossi has been involved with a few companies before and after he began work on commercialization of LENR. One was a company he owned in Italy called EON srl, which modified diesel engines for large generators. There, he had a LENR system that produced heat for the factory. The system was claimed to save 90% on the cost of keeping the place warm during a six-month period[11]. Rossi has had a long association with a company in New Hampshire called Leonardo Corporation, and a related and newer enterprise named AmpEnergo, Inc. Recently, Rossi sold some rights to a new company in North Carolina, Industrial Heat LLC.

Rossi's systems go by the name E-CAT (Energy CATalyser), where the catalysis is presumably the separation of hydrogen molecules into hydrogen atoms. Their interaction with nickel-based materials must lead to protons being on, or in the near-surface region of the nickel. There have been tests of various versions of the E-CAT systems during the past five years, which involved people from outside of Rossi-related companies. In 2009, there was a test in New Hampshire with a closed-loop water heater system, which was observed by visitors. The following year there were two more tests by scientists from outside of Rossi's companies. One was in New Hampshire and another in Virginia. Both used single-pass mass flow calorimetry. Those three tests were not publicized, in contrast to several later tests. In 2011, there were four announced tests of E-CAT systems (Table 1). The data were collected from diverse websites, some of which are no longer available. The data are similar, but not identical to the information now on the web[9].

A test of a 1 MW system containing many E-CAT modules was conducted on 28 October 2012. Lewan counted 116 such modules, but Rossi stated that 107 were used[12]. The system reportedly generated an average of 479 kW of power[13]. There was and remains much controversy over the methods used to conduct the tests just cited, and the fact that detailed reports based on them were not published.

By contrast, an important report of the results of three E-CAT tests performed in late 2012 and early 2013 was published in May 2013 by Levi *et al.*[14]. The 31-page document provides some information on one high temperature test, and many details about two subsequent quantitative tests. In all three tests, the E-CAT HT (for high temperature) devices were mounted in open air and measured with infrared cameras. They consisted of concentric cylinders. The outer cylinder was supported by a metal frame. The inner cylinder contained the active material. It was described only as 'a small amount of hydrogen loaded nickel powder plus some additives'.

During the initial run in November 2012, the active material was concentrated at two distinct locations axially. Figure 2 shows an image of the device during operation. The two hot regions near the ends of the outer cylinder are clear. Less obvious, but still measurable are multiple temperature variations around the circumference of the imaged cylinder. Quantitative analysis of their geometry showed that they corresponded to positions of the 16 resistive heater coils within the device. That is, the images are consistent with a central source of energy, which casts shadows of the cooler heater coils on the outer cylinder.

Table 1. Dates, durations and details of E-CAT tests announced during 2011

Date	Duration (h)	Power level (kW)	Energy gain
14 January	1	10	23
11 February	18	16	135
29 March	6	4.4	15
28 April	3	2.3	8

The input power to the 'primer' resistor coils was 1 kW during the November test. It stimulated reactions in the active material, which led to melting of the inner steel cylinder and 'surrounding ceramic layers'. The temperature measured on the exterior of the outer cylinder was approximately 680°C.

The December 2012 test used an E-CAT HT, which was somewhat similar to the earlier device, but has some important differences (Figure 3). The outer cylinder was silicon nitride ceramic, 33 cm in length and 10 cm in diameter. Another inner cylinder was corundum, which housed the resistor coils. In this case, there were only three such coils, and the input power was limited to 360 W. Inside the structure with the heater coils was an AISI 310 stainless steel cylinder 3 mm thick and 3.3 cm in diameter. Two AISI 316 steel end caps were fitted to the long cylinder using differences in thermal expansion of the two types of steel.

The E-CAT HT was already in operation when the team started the December test. This did not prevent them from obtaining quantitative electrical input and thermal output power data. However, it did preclude their measurement of the weight of the active materials before and

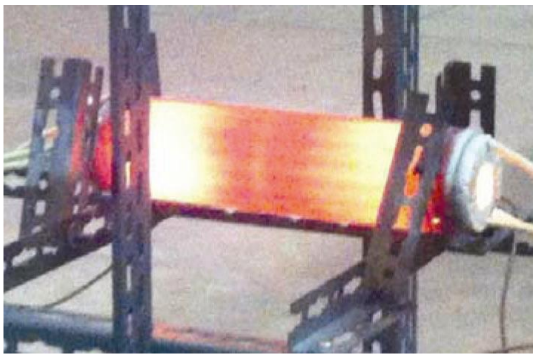

Figure 2. Visible image of an E-CAT HT during November 2012 prior to its self-destruction by internal melting.

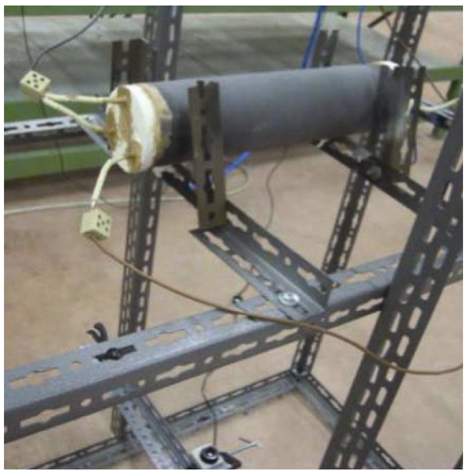

Figure 3. Visible image of E-CAT HT with the white electrical leads on the left and the IR camera on the floor.

Table 2. Power, energy and other parameters for two published tests of the E-CAT HT. The input powers do not include those consumed by the conditioning or control circuits. That is, they are the powers that actually entered the E-CAT devices

Quantity (units)	December 2012	March 2013
Test duration (h)	96	116
Consumed mass of the fuel (g)	<236	1
Maximum outer temperature (°C)	765	326
Radiated power (W)	1568	459.8
Convection power (W)	466	281.5
Correction to power (W)		75
Total output power (W)	2034 ± 203	816 ± 16
Average input power (W)	360	283.5
Excess power (W)	1674	532.5
Power gain = P_{out}/P_{in}	5.6 ± 0.8	2.9 ± 0.3
Excess power density (W/kg)	7093 ± 709	5×10^5
Total output energy (Wh)	1.96×10^5	9.5×10^4
Energy in (Wh)	0.35×10^5	3.3×10^4
Excess energy (Wh)	1.61×10^5	$6.2 \pm 0.4 \times 10^4$
Energy gain = E_{out}/E_{in}	5.6	2.88
Excess energy density (Wh/kg)	$6.81 \pm 0.7 \times 10^5$	6×10^7

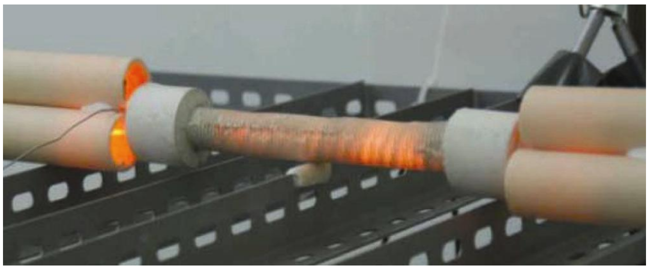

Figure 4. Photograph of an E-Cat during testing in 2014.

after the test. They obtained a high estimate of the mass of the fuel material by weighing parts of a 'perfectly similar' device that was available. They weighed two objects – (a) a complete assembly consisting of the inner 310 steel cylinder containing a charge of the fuel material with the 316 steel end caps, and (b) only the empty long cylinder without end caps. The difference was 236 g. A much smaller and more realistic fuel weight would have been obtained if the end caps were included in the second weighing. However, the overestimate of the fuel mass makes the later calculations of power and energy per kilogram of fuel very conservative.

Input electrical power and energy measurements were performed with a PCE-830 power and harmonics system from PCE Instruments. The group made estimates of the radiated heat from the temperatures obtained from the infrared cameras. They did not have the actual emissivities of the E-CAT HT outer surface, but made assumptions during the data analysis that reportedly led to underestimates of temperatures and radiated power. Power lost due to convection was also estimated. The overall performance of the E-CAT in the December test is summarized in Table 2. It is seen that the average power and energy gains are 5.6. The error estimates in Table 2 are stated and rationalized by the authors of the test report.

The test run in March 2013 involved another version of the device labelled E-CAT HT2. The device had a new control system. It permitted applying continuous power to the E-CAT HT2 for the 2 h that it required to reach 'self-sustaining' operation. After that, the power was on for 2.5 min and off for 5 min for the remaining 114 h of the run. Overall, the ratio between average power and peak power into the device was 35%.

After the 116 h run, the test team used the same device, but with the inner cylinder, its end caps and the active material replaced with an empty duplicate inner cylinder. They powered this with the resistive heaters to temperatures near 300°C, that is, those during the 116 h test run. They were able to determine that the output power obtained during the test was underestimated by 75 W. That is the source of the correction listed in Table 2 for the March test.

There are some data in Table 2 that deserve particular attention. The first is the four- and five-day duration of the tests. These were the longest tests of E-CAT systems for which detailed data were available. The other is the relatively high power levels, both in and out, compared to most other experiments on LENR. Excess powers of 1.6 and 0.5 kW are near what is needed for commercial home heaters. A report critical of the practices and results of the 2012–2013 E-CAT tests is available on the web[15].

A second detailed report on testing of an E-CAT was published in October 2014 by the same team, plus one additional scientist and five others, who supplied supporting measurements[16]. The 52-page report deals with a single E-CAT system, which was tested both without and with the active material. A photograph of the new system is shown in Figure 4. It is a cylinder of unstated internal construction 2 cm in diameter and 20 cm long, which was covered with corrugated alumina. The triangular ridges on the outer alumina surface, 2.3 mm high and 3.2 mm at their base, improved convective heat transfer to the air. The system had two smooth alumina end caps, 4 cm in both diameter and length. To the left and right of the E-CAT were a trio of alumina cylinders, through which passed the leads from the three-phase electrical supply. The ends of the inconel resistors, which penetrated the end caps to heat the E-CAT internally, stuck out into the alumina tubes and heated them. The fine cable to the Type K thermocouple inside of the E-CAT is visible on the left in Figure 4. Alumina cement held the three hollow end tubes to each other on both ends, and also isolated the E-CAT from the metal frame.

Electrical power was supplied continuously to the E-CAT in this test. It was again measured with the PCE 830 instruments, this time with one instrument before and another after the control system. The electrical determinations apparently were not tested against a known resistive load or other power measurement instrumentation. Radiative energy from the E-CAT was determined as in the earlier tests using infrared thermometry, specifically two Optris PI 160 thermal imagers. It would have been better to also employ short-wavelength infrared imagers in addition to the long-wavelength devices that were used. Energy that escaped from the E-CAT by convection was computed. Calibration of the method for computing the convective heat losses against measurements from a simple cylindrical system might increase confidence in their correctness. Electrical data and IR camera images were recorded at 0.5 Hz. The temperature-dependent emissivity of alumina and a self-consistent computational procedure were used to make sure that the radiative power was correctly estimated for subdivided areas along the E-CAT, its end caps and the alumina tubes. However, the spectral variations of the emissivity were not considered.

A 23 h run was made without fuel in the E-CAT, which the authors termed a 'dummy' run. For that operation, the input power was measured to be 486 ± 24 W, and the output radiative and convective power was 446.36 ± 10.60 W. Taking the extremes of the errors, the methods used overestimated the electrical power supplied to the unfuelled E-CAT, or underestimated the thermal output by 14%. If those variations also applied to the E-CAT during the fuelled test, then the errors provide conservative estimates of performance. It must be noted that the test with the unfuelled E-CAT was performed with input powers, output powers and temperatures substantially lower than those during the test with the fuelled reactor.

Importantly, Rossi was present and involved at key times during the tests of both the unfuelled and fuelled E-CAT. He was there, when the unfuelled test was started, and ramped the power up to the level requested by the authors, and at the end of the dummy test. Rossi was also present for fuel insertion, reactor start-up, reactor shutdown and fuel removal. His presence naturally concerns people who want an entirely independent test of the E-CAT technology.

The fuel used in the test of 32 days was 1 g of 'hydrogen loaded nickel powder plus some additives, mainly lithium'. The authors of the 2014 report wrote that it was 'plausible' that the fuel was mixed with $LiAlH_4$. Composition of the fuel was tested before and after the 32-day run, as will be summarized below after presenting and discussing the energy data.

The 32-day run with the fuelled E-CAT included two periods of different performance. The first was about 10 days long with approximately 800 W of input power and 2400 W of output power, that is, about 1600 W of power due to LENR. The temperature of the E-CAT was about 1260°C during this period. Then, the input power was increased to about 900 W for the second part of the test run of 22 days duration. During that time, the output power was near 3200 W, so the LENR power was about 2100 W. The temperature then was 1400°C. The Coefficient of performance, defined as the ratio of the total output power divided by the input power, was near 3.2 for the first phase of the test and 3.6–3.7 for the rest of the run.

The authors of the 2013 and 2014 reports on E-CAT testing gave the power and energy densities that follow from the measured results. The March 2013 data from Table 2 are 5×10^5 W/kg and 6×10^7 Wh/kg = 2.2×10^5 MJ/kg, both based on 1 g of fuel. The data from the 2014 report are $2.1 \times 10^6 \pm 10\%$ W/kg and $5.8 \times 10^6 \pm 1\%$ MJ/kg, if 1 g mass of the fuel is used in the denominator. These values are vastly higher than what can be attributed to chemical reactions. If the overall mass of the 2014 E-CAT of 452 ± 1 g were used, the values just given would be proportionally smaller. But, they would still exceed the capabilities of even the most energetic fuels and energy storage systems.

One of the main features of the latest report by the Levi collaboration was the nuclear analyses of the nickel-based fuel prior to and after the 32 day run. Beforehand, the distribution between ^{6}Li and ^{7}Li was found to be normal, specifically 93% ^{7}Li. After the run ^{7}Li was substantially depleted, where secondary ion mass spectrometry (SIMS) gave 7.9% and inductively coupled plasma mass spectroscopy (ICP-MS) gave 42.5%. The large disagreement between analytical methods does not mask the apparent depletion of ^{7}Li. Major depletion of ^{58}Ni and ^{60}Ni and the build-up of ^{62}Ni were also measured. For example, ^{62}Ni in the unused fuel was 3.6%, whereas the used fuel has 98.7% of that isotope according to SIMS and 99.3% from ICP-MS. Only 10 mg of the fuel, that is, 1% of its mass was taken for analysis. That small amount raises questions about whether the sampling was representative of the average compositions. But, it does not necessarily cast doubt on the large changes in isotope ratios. The possibility that molecular rather than atomic ions influenced the reported isotope ratio results remains unexplored.

Like the results from the 2013 report by the Levi group, the 2014 report has generated much discussion[17]. However, these new isotope data, as well as the production of powers that are far beyond what chemistry can explain, burden the critics to explain how they can be rationalized without LENR.

Progress on the performance of E-CAT systems over the past few years is noteworthy. The 2011 test durations were only parts of one day. The 2013 Levi *et al.* report detailed operation for most of a week. The latest report from that group cited operation for over one month. However, reliable and controllable operation for well over one year is needed in commercial products.

Defkalion Green Technologies (DGT)

DGT is another company attempting to commercialize the Ni–H system. DGT started in Greece, and now has laboratories in Vancouver and Milan. The company had an agreement with Rossi, which ended in August 2011. Then, they proceeded independently of Rossi. The DGT approach to producing prototype LENR generators has not been tested publically or quasi-independently as often as the E-CAT systems. Information on the company and some of its activities is available on the web[18].

During the 18th International Conference on Cold Fusion (ICCF-18), DGT demonstrated their Release 5 (R5) reactor in two separate runs performed in Milan. Information was streamed to the conference site over the internet. Prior to the runs, the DGT Chief Technology Officer, John Hadjichristos, provided a tour of the laboratory. He described both the test set-up and the protocol to be employed. For the first run, the reactor was filled with argon. That run was performed to show that the diagnostics for the measurements, both the input electrical power and the output thermal power, were working properly. Hydrogen filled the reactor during the second run of 3 h duration. The performance during that run was conveyed to Michael Melich by phone, who had arranged the demonstration. He reported to the conference that the maximum output power measured by the flow calorimeter was 5.2 kW, with an input power near 2 kW. That is, there was a power gain of about 2.6 at some unstated time during the run. There was no written report from DGT on the runs during ICCF-18. However, there is significant information on the internet[19]. A report critical of the claim of power production by DGT during ICCF-18 is also available[20].

DGT has made an interesting statement in 2012 about the ability of isotopes of nickel to participate in LENR[21] – 'We realized that ^{58}Ni, ^{60}Ni, ^{62}Ni and ^{64}Ni stable isotopes were "willing" to participate … while ^{61}Ni was not'. No supporting evidence for this assertion has been posted or published. It contrasts with the last report from long-term testing of an E-CAT, where major depletion of both ^{58}Ni and ^{60}Ni and enhancement of ^{62}Ni were reported. DGT has decided not to communicate further with the public until the launch of its pre-commercial R6 generator.

Hydrogen Engineering Applications and Development Company (HEAD company)

A new Japanese company made its initial public presentation at the 2014 Cold Fusion/LANR colloquium at MIT in March of 2014 (ref. 22). Their development work involves use of both Ni and Pd with H_2, D_2, H_2O and D_2O gases. They prepare Ni mesh material in a prototype reactor by sequentially heating the material, subjecting it to a plasma discharge, heating it in the gas of interest and, finally, heating the material in a vacuum. This sequence is repeated four or five times. It produces nanoscale particles on the surface of the Ni mesh materials. Then, the gas of interest is introduced and a plasma is created during the experimental run.

The team at the HEAD Company conducted 73 tests during 2013, and reported on 45 of them at the MIT Colloquium. In one run lasting 35 days, they obtained a maximum excess power of 75 W. The reported energy gain (output thermal energy divided by input electrical energy) was 1.9 for a total excess energy of 108 MJ. Roughly three-fourth of the experiments gave excess power.

Conclusion

Despite arguments over the validity of prototype test data, the evolving character of commercialization efforts, and uncertainties over the current activities of the two Piantelli companies, Industrial Heat, DGT and HEAD, some conclusions can be drawn about the field of LENR. They are solidly based on published experimental results from many experiments.

It is clear from a quarter of a century of empirical data that energy generators based on LENR could offer some remarkable potential advantages. Experiments have shown that LENR are free of three major problems, intense prompt radiation, residual radioactivity and greenhouse gases. The very high energy densities and gains that have been measured indicate that power production might be significantly cheaper than for fossil fuels and nuclear fission. Small LENR generators, with powers in the kilowatt range, could be off the grid and widely distributed. Their impact in developing countries might be immense, similar to the effects of cell phones in regions that never had phone service.

It is highly likely that the availability of commercial LENR generators, no matter how potentially attractive, is at least a few years away. The development of robust prototypes of products, their long-term testing to determine reliability, their regulatory approval and customer acceptance all remain to be achieved. It might be that having the word 'nuclear' in the name proves to be a detriment to both governmental approvals and consumer acceptance. However, the many possible advantages of LENR might prove to be unstoppable.

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