Excess of Power in Deuterium-charged Palladium

IN SUMMARY

■ **PROCESS AND STATUS OF THE RESEARCH** – Evidence of power generation during electrochemical loading of palladium with deuterium was first announced by M. Fleishmann and S. Pons in 1989. The achievement was not confirmed by the international scientific community because of the low reproducibility of the experiments. Since then, research on anomalous effects in metal deuterides has continued at laboratory scale and included a wide spectrum of topics. A satisfactory level of reproducibility and better material control have been achieved in the last years, due to advances in material science. US laboratories have recently undertaken a review of the experimental outcomes. All the scientific and quality targets of the review have been met or exceeded. However, a theoretical explanation of the phenomenon is not yet available. Increasing knowledge of metal-hydrogen systems in the unexplored region of high stoichiometric ratios could pave the way to better understanding.

■ **PERFORMANCE AND COSTS** – Power and energy gains up to *thousands* percent and up to some KeV (thousands of electron-volt) per particle have been observed in experiments with good reproducibility. In absolute value, the excess of power ranges from some tens mW (a level well above the detection capability of the instruments) up to some tens of Watt. The power density at the Pd cathode observed in some experiments reached several hundreds watt per cubic centimeter, a value well above that occurring in nuclear power stations. Further developments of the research require investment in equipments and expertise higher than those available in preliminary studies. The cost of a typical 5-year R&D project involving 5 professionals and related instruments is estimated to be around 15 million euro. Cost estimates of the energy eventually produced by the process are premature as the technology is at an early stage. No assessment of potential applications is available.

■ **RESEARCH DIRECTIONS, POTENTIAL & BARRIERS** – In principle, the process could have important implications and huge impact on the future energy system. However, its fundamental physics needs to be explained and its scientific feasibility needs to be confirmed. Technology and economic feasibility are beyond the scope of current R&D studies. At present, any discussions on potential applications are speculative. Moderate investment in specific projects could help advance the knowledge in this field and could result in a very high benefit-to-cost ratio in the future, as compared to higher investment in other energy technologies.

PROCESS AND STATUS – Some metals have a large hydrogen solubility and among them palladium is the most studied. The dissolution of the deuterium (hydrogen isotope) into palladium may be achieved using either high gas pressure or an electrochemical loading process under cathodic polarization of a palladium electrode with an alkaline electrolyte. A typical electrolysis cell with a platinum anode and a palladium cathode can be used for such a process. The generation of power and energy in excess to the energy input during the process of electrochemical loading of palladium (Pd) with deuterium (D) was first announced by M. Fleishmann and S. Pons in 1989 (M.Fleishmann, S.Pons, Electrochemically Induced Nuclear Fusion of Deuterium", J. Electroanal. Chem. Vol. 261, (1989) pp. 301). The international scientific community did not confirm the experimental achievement because of the low reproducibility of the experiments. Most scientists believed that the phenomenon was due to inaccuracy in calorimetric measures. However, following the first experiments, excess of heat has been observed by different groups working in different labs and using a number of calorimeters based on varying operating principles. The idea that the excess of heat was due to inaccuracy of calorimetric measures has been carefully considered, checked and ultimately rejected (M. C. H. McKubre, F. L. Tanzella, I. Dardik, A. El Boher,T. Zilov, E. Greenspan, C. Sibilia and V. Violante "Replication of Condensed Matter Heat Production" Edited by the American Chemical Society – in press). The conditions under which the excess of heat occurs remain of interest. A sound theoretical explanation of the phenomenon is not yet available. Increasing knowledge of metal-hydrogen systems in the unexplored region of high stoichiometric ratios could help understanding. Typical considerations in the scientific debate are summarized as follows: **a)** The excess of power is observed only when loading palladium with deuterium, but never with hydrogen; **b)** Bursts of excess of power are unidirectional (i.e., negative power gains never observed); **c)** In many experiments, the energy gain is in the order of thousands eV per particle of electrode (D+Pd, assuming a loading ratio close to 1/1). Such level of energy cannot be explained by a chemical process since the energy level of chemical bounds is in the order of a few eV; **d)** Unknown mechanisms for chemical energy storage could in principle lead to very low-rate energy storage into the system, with power level too low to be detected by the calorimeter. Stored energy could then be released very fast (at once) such that an apparently high excess of power is detected. If so, to ascribe the effect to a chemical process, the total specific energy must be in the order of a few eV per particle of electrode;

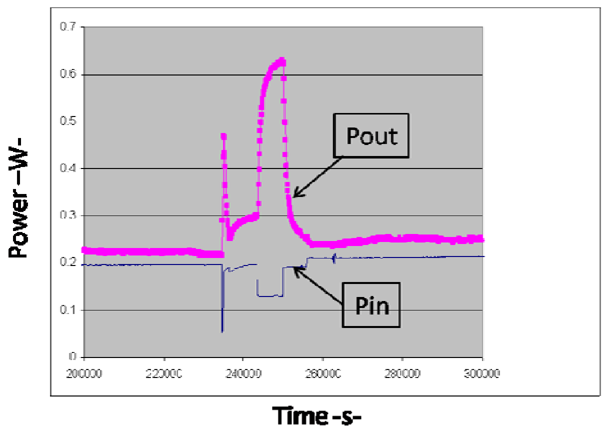

Fig-1 - Excess of power observed at the ENEA labs using deuterium (D_2O 0.1M Li)

e) It has also been considered that the energy storage might occur into the electrolyte where the number of particles is larger than in the electrode. If so, the effect should be observed not only with Pd cathodes, and even if hydrogen is used instead of D; **f)** Energy from recombination of oxygen (O) with D or H into the cell can be excluded since in many experiments the pressure of the cell is monitored and observed to be constant during the occurrence of the excess of power. Most accurate experiments are carried out with sealed cells equipped with a catalyst that recombines the gases produced by the electrolysis, thus leading to a constant value of the pressure into the cell); **g)** Under-evaluations of the input power can be excluded in all the experiments using a closed cell under galvanostatic DC operation (constant current). In such experiments, the input power is exactly the scalar product between voltage and current; **h)** If the energy excess is explained in terms of chemical reactions occurring in the cell, then at the end of the experiment, one should observe reaction products, which were never observed.

In 1991, the excess of power was demonstrated to be a threshold effect that occurs if a very high stoichiometric ratio between D and Pd is achieved (K. Kunimatsu, N. Hasegawa, et al. - *Deuterium Loading Ratio and Excess Heat Generation during Electrolysis of Heavy Water by a Palladium Cathode in a Closed Cell Using a Partially Immersed Fuel Cell Anode;* and C. H. McKubre, S. Crouch-Baker, A. M. Riley, S. I. Smedly, F. L. Tanzella, *Excess Power Observation in Electrochemical Stusies of the D/Pd System; the Influence of Loading* – Proceedings Third International Conference on Cold Fusion, Nagoya (Japan) October 20-25, 1992 (p.5 and p.31). On the basis of such an input data it was evident that the achievement of the loading ratio was not a simple task. Different lots of palladium from the same producer, showed a completely different behavior in terms of loading. This evidence was a trigger that moved the research into the field of material science in order to identify the mechanisms acting on the hydrogen isotopes loading into the palladium lattice. The result of the study allowed to understand that the stress field created by the absorption of hydrogen into the lattice increased the chemical potential of the solute (hydrogen or deuterium). Such an increase may limit the hydrogen isotopes solubility (Physical Review B, Vol.56, N.5 1997/2417-2420, work mainly developed at ENEA Frascati Research Center). Then a proper metallurgy was studied in order to limit the stress field into the lattice during the hydrogen loading. The experimental activity carried out with palladium having the appropriate metallurgy revealed a loading reproducibility close to 100%. This step forward has largely improved the reproducibility of the excess of heat and allowed to understand that high loading was a necessary condition to observe the phenomenon, but not sufficient.

More recently, in spite of different calorimetric systems and different instrumentation used in the experiments, three research labs (two institutions from the United States and ENEA) obtained similar results using Pd specimens prepared at the ENEA labs (ENEA Fusion Dept. - Progress Report 2006). Samples belonging to these lots of specimens produced excess of power in all of the three research labs. Such a result has been achieved through an extensive work for preparing Pd specimens to ensure the achievement of a threshold D/Pd loading ratio close to one (atomic fraction), with about 100% reproducibility. The result also represents the achievement of the transferred reproducibility: samples belonging to a specific lot, with specific characteristics, have produced excess of power in all the Institute where the

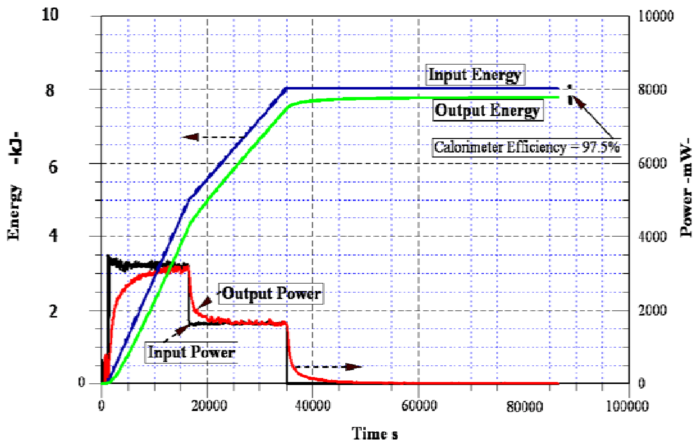

Fig. 2 – Experiment with hydrogen (H_2O 0.1 M Li): No excess of power is observed (calorimeter effic. 97.5%)

experiments have been carried out. At present, material science studies are mainly focused on identifying other palladium characteristics - in addition to the high hydrogen solubility - which may increase the reproducibility of the occurrence of the excess of powerproduction. The ongoing R&D effort is expected to allow a complete identification and qualification of the material to be used. Most work focuses on surface characteristics, texture of the material and purity level of the rough metal.

A typical excess of power, with the output power curve exceeding the input power, is shown in the Figure 1, while the Figure 2 shows the typical behavior of the calorimetric system when the experiment is carried out by using light water and no excess of power is observed (the output power curve never exceeds the input power).

The Figure 1 also shows an input power reduction during the excess of heat production. This is due to the galvanostatic (constant current) operating mode of the power supply. During the excess of power the electrolyte temperature increases (as it is also monitored with different instruments). And the impedance of the electrolyte decreases. As a consequence, to maintain the current at the set point value, the power supply reduces the voltage and this produces the reduction of the input power. As the experiment is carried out in a closed cell, the galvanostatic mode ensures that the input power is correctly estimate as the scalar product between current and voltage. The output power is obtained by a precise measurement of the coolant fluid input/output temperatures (by platinum thermometers) and by flow rate high-precision measures. The uncertainty is estimated to be in the range ± 15 mW. The Figure 3 shows the calorimetry laboratory at the ENEA Frascati labs.

PERFORMANCE AND COSTS - The excess of power usually occurs with gain level ranging from 5% to some thousand percent. In absolute value, the excess of power ranges from some tens mW (a level well above the detection capability of the instruments) up to some tens of Watt. The reasons for such different experimental results are currently under investigation. They may somewhat depend on material science aspects that are under clarification. The timing of power release also deserves further investigations as the excess of power can be observed in a few hours as well in several days, following the achievement of the loading threshold. The large power gain and the power density observed in some experiments could enable potential energy applications. Power density at the Pd cathode reaches several hundred watt per cm^3 , a value well beyond that occurring in nuclear power stations. An excess of power of about 500 % observed at ENEA Frascati is shown in Fig.1 (M. C. H. McKubre, F. L. Tanzella, I. Dardik, A. El Boher,T. Zilov, E. Greenspan, C. Sibilia and V. Violante, *Replication of Condensed Matter Heat Production,* American Chemical Society, in press). In the experiment, the input power was 0.125 W while the output was above 0.6 W. The cathode consisted of a 20x10mm, 50µm-thick Pd foil.

Since research is still at an early stage, any considerations of feasibility and costs of practical applications are premature.

RESEARCH DIRECTIONS AND INVESTMENT – A research project on Excess of Power Production in Metal Deuterides has been supported by the Italian Ministry of the Economic Development and carried out in 2005 and 2006 by ENEA. The research activity was mainly oriented to enhance the knowledge in material science in order to obtain the clear evidence of the phenomenon, with significant reproducibility and very high signal/noise ratios. During the two-year project, theoretical investigations have also been performed. The project enabled to improve both the expertise and the equipment of the laboratory. All the targets of the projects have been successfully achieved. Several experimental campaigns have been runned during this period with reproducibility exceeding 50%. All the results have been confirmed in other countries by laboratories cooperating with ENEA and described in detailed reports to the Italian Ministry of the Economic Development. They may pave the way to further developments, know-how and patents. A moderate level of additional investment in specific laboratory instruments as well as in technical expertise is required to inject in the current working groups an appropriate level of interdisciplinary including primarily material science and solid state physics. Experimental efforts should focus on improving: ■ the reproducibility of the process; ■ the amplitude of the signal (i.e. the power and energy gain); and ■ the lifetime and predictability of the occurrence of the energy release. To achieve the first objective, reproducible Pd specimens are needed with well characterized material features. A laboratory-scale specimen production facility could significantly help the understanding process. The second objectives could be achieved by establishing a co-relation between the amplitude of the signal and the specimen features mentioned above. This is also the key to improve lifetime and predictability of the process. Experiments have demonstrated that in some specimens the excess of power is suddenly produced once the loading threshold is achieved. This could be correlated with the specific status of the material. The lifetime of the excess of heat production could also be affected by unavoidable modifications of the material produced by the electrochemical process. Investigations of theoretical aspects should support all the steps of the experimental work. A systematic laboratory approach should include: ■ cathode production with controlled characteristics; ■ calorimetric measures on a significant number of specimens to produce an acceptable statistics; ■ samples characterization before and after the experiments, and during the Pd loading process. The required instruments include: ■ Pd melting system with control of the level of impurities; ■ Rolling system with controlled thickness; ■ Annealing system under controlled temperature and atmosphere; ■ Chemical and physical surface treatment systems; ■ Surface analysis instruments (TOF SIMS, AFM with in situ test option, SEM + EBDS, EDX); ■ Metallurgic analysis instruments: (XRD, TEM, mechanical test, optical

Fig. 3 - Calorimetric laboratory at ENEA Frascati

profiler); ■ Chemical analysis instruments (ICP Mass, nuclear activation analysis); ■ Electrochemical characterization based on cyclic voltammetry and impedance spectra analysis; ■ Flow calorimetry with typical sensitivity from 10 mW to 20 W; ■ Beta spectroscopy; ■ Mass spectrometry; X ray detection system.

The cost of a typical 5-year R&D project involving 15 professionals and related instruments is estimated to be around 15 million euro

POTENTIAL & BARRIERS - In principle, the process under investigation could have important implications and huge impact on the future energy system. However, the fundamental physics of the process needs to be understood and its scientific feasibility needs to be confirmed. Moderate investment could help advance the knowledge in this field and could result in a very high benefit-to-cost ratio in the future, as compared to higher investment in other energy technologies. A general skepticism produced by first announcements and expectations generated by media in 1989 could still be a barrier to R&D investment in this field.

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Major R&D players

● SRI (USA); ● Energetics LtD (USA); ● Energetics Technologies (Israel); ● Osaka University (Japan); ● Sapporo University (Japan); ● SPAWAR Systems Center CA USA; ● ENEA (Italy); ●INFN (Italy).

Tab 1 - ENEA Relevant R&D Activity

Processes and technologies under development
Technology for producing palladium foil having very high hydrogen solubility. The materials produced by means of the specific treatment (rolling + annealing) is showing nearly 100% reproducibility for hydrogen (deuterium) loading up to 1 (atomic fraction). Experiments using this material revealed excess of power production during electrochemical loading with significantly reproducible evidence of the effect either at ENEA labs and in other labs using palladium prepared by ENEA.
R&D and Demonstration Plants
Given the basic level of the research no demonstration plants exist but only experimental apparatus to perform sophisticated calorimetric measures and material characterization.
R&D Objectives and Achievements
Reproducibility of the experiments and results of excess of power. Technology and methods for specimen preparation. The ENEA research and activities are considered as the most advanced in these specific fields of material science.
R&D Resources
Two researchers and two technicians. Budget for personnel and instrumentation 250 KEuro/Y
Collaborations and External Funding (if any)
SRI International (CA) USA, Energetics (NJ) USA, Roma La Sapienza University
Patents, Major Publications, Articles, Citations, Congress and dedicated web sites
● ENEA Italian Patent: Procedimento metallurgico per aumentare la capacità di assorbimento dell'idrogeno da parte di alcuni metalli come il palladio, il nichel e le loro leghe RM 2004 A 000437. ● G.K. Hubler, Anomalous effects in hydrogen-charged palladium - a review - PII: S0257-8972(07)00302-7, DOI: doi: 10.1016/j.surfcoat.2006.03.062 - Reference: SCT 13322 - Peer reviewed paper on International Magazine Reporting ENEA results to appear in: *Surface & Coatings Technology.* ● V. Violante, A. Torre, G.H. Miley, G. Selvaggi, 3-D Analysis of the Lattice Confinement Effect on Ions Dynamics in Condensed Matter and Lattice Effect on the D-D Nuclear Reaction Channel. Fusion Technology 39 (2001) 266-281. ● V. Violante, P.Tripodi, C. Lombardi, Le Conoscenze Attuali sulla Fusione Fredda, La Termotecnica, Marzo (2001) 67-72. ● V. Violante, G.H. Miley et Al., Recent Results from Collaborative Research at ENEA-Frascati on Reaction Phenomena in Solids, Transac. American Nuclear Soc., 83, 361(2000). ● P.Tripodi, M.C.H. McKubre, F.L. Tanzella, P.A. Honnor, D. Di Gioacchino, F. Celani, V. Violante, Temperature coefficient of resistivity at composition approaching PdH. Physics Letter A 276 (2000) 1-5. ● V. Violante, Lattice Ion Trap Confinement for Deuterons and Protons: Possible Interactions in Condensed Matter. Fusion Technology 35 (1999)361-368. ● V. Violante, A. Torre, G. Dattoli, Lattice Ion Trap: Classical and Quantum Description of a Possible Collision Mechanism for Deuterons in Metal Lattices. Fusion Technology 34(1998) 156. ● V. Violante et Al., Consequences of Lattice Expansive Srtain Gradients on Hydrogen Loading in Palladium. Phys. Rev. B, Vol. 56, N. 5 (1997) 2417-2420. ● V. Violante et Al. Deformations Induced by High Loading Ratios in Palladium-Deuterium Compounds, J. Of Alloys and Compounds, 253-254 (1997) 181-184. ● L. Bertalot, V. Violante et Al. Study of Deuterium Charging in Palladium by the Electrolysis of Heavy Water: Heat Excess Production. Il Nuovo Cimento, 15, N.11 (1993) 1435-1443. ● V.Violante, A. De Ninno, Lattice Ion Trap: A Possible Mechanism Inducing a Strong Approach Between Two Deuterons in Condensed Matter. Fusion Technology 31 (1997) 219-227. ● R. Felici, V. Violante et Al., In-situ Measurement of the Deuterium (Hydrogen) Charging of a Palladium Electrode During Electrolysis by Energy Dispersive X-Ray Diffraction, Review of Scientific Instruments, 66(5) (1995) 3344-3348. ● V. Violante et Al, Study of Deuterium Charging in Palladium by Electrolysis of Heavy Water. Fusion Technology 26(1994) 1304-1310. ● V.Violante et Al., Deuterium Charging in Palladium by the Electrolysis of Heavy Water: Measurement of the Lattice Parameter. - Transactions of Fusion Technology, 27(1994) 122-125. ● Citation: Surface & Coatings Technology (2007), doi: 10.1016/j.surfcoat .2006.03.062.

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