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# Cold Fusion – The Heat Mechanism

by

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Reprint from *Journal of Fusion energy*, Vol. 9, No. 3, p. 345, 1990

**SPECIAL ISSUE**: U.S. Department of Energy Workshop on Cold Fusion
Phenomenon, Part II
Plenum Press, New York and London

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# Cold Fusion — The Heat Mechanism

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The assumption that deuterium, and not palladium, is the fuel in the Pons-Fleischmann experiments(1) led to high expectations of cold nuclear fusion. The conversion of mechanical energy to heat was neglected in studying the phenomenon. Considerable strain energy is stored in metals when processed from the ore. The initiation, growth, and propagation of cracks in the bulk disturb the energy balance within the metal. Deuterium induces and propagates cracks in metals and alloys, including palladium. The sudden discharge of fracture energy during crack propagation generates considerable heat. The abundance of deuterium in cracked palladium will not continue the heat-generation process. The confident figures-of-merit of cold fusion have been based on the small energy input to the electrolytic cells and do not consider the substantial energy required to process (by melting) the palladium from the ore, or to recycle the cracked electrode samples. In this paper, the work-of-fracture is shown to be the likely mechanism responsible for the excess heat in cold fusion.

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**KEY WORDS:** Cold fusion; heat mechanism; deuterium-palladium; hydrogen embrittlement; fracture energy.

## INTRODUCTION

Considerable heat was liberated from the palladium-deuterium (Pd-D) system by Stanley Pons and Martin Fleischmann.(1) As conventional chemical or physical processes could not account for the substantial heat, the heat mechanism was proposed to be nuclear fusion of deuterium in the palladium (Pd) bulk. The fusion by-products reported to date have been minimal, variable, inconsistent with theory, or non-existent. Anyway, the heat mechanism in cold fusion has not been identified with certainty.

This matter may be resolved by classical means if we recognize that specific energy terms, and associated work, were neglected in the study of cold fusion. Considerable strain energy is stored in metals and alloys when processed from the ore. The energy balance is disturbed when cracks nucleate, grow, and propagate within the bulk. Deuterium induces and propagates cracks in palladium and other metals and alloys. The sudden discharge of fracture energy during crack propagation generates considerable heat. The heat produced by the work-of-fracture can be substantial and can account for the excess enthalpy reported in cold fusion experiments. The maximum amount of heat from the process is also calculated and is shown to be finite. When all energy terms are considered, including the substantial energy required to process the palladium electrodes from the ore or to recycle the cracked electrode samples, the break even in cold fusion is found to be much less than 100%, and not 1000% or, the expected, one million percent reported by the original experimenters. This paper also demonstrates that palladium, and not deuterium, is the fuel in cold fusion.

## 2. THE EFFECT OF MICROCRACKS

Metals and alloys contain many microcracks in the bulk. The fine cracks cause considerable reduction in the theoretical cohesive strength of materials. This is demonstrated in the well-known Griffith theory (2) which explains why the strength of materials is orders of magnitude less than the theoretical values. The measured strength is the theoretical value less the effect of the microcracks. Cracks induced and propagated by deuterium in the palladium bulk have the same effect of strength reduction. The energy terms associated with the strength reduction of palladium in deuterium, for example, must be considered in the overall energy balance of the cold

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[1] This and related work have been fully sponsored by the author; Technical Consultant, Herndon, Virginia 22071.

fusion experiments. This can be done by measuring the strength of the palladium electrodes before and after exposure to the deuterium or hydrogen environments, and calculating the corresponding energy.

## 3. DEUTERIUM AND HYDROGEN EMBRITTLEMENT

Before we calculate the amount of heat that can be liberated by the work-of-fracture, relevant characteristics of deuterium- and hydrogen-induced cracks in metals are cited. Hydrogen-induced failure is known as hydrogen embrittlement, and extensive database is available on the subject.(3) Deuterium embrittlement is similar to hydrogen embrittlement, but the embrittling effect of deuterium is greater than that of hydrogen, in some cases by about 30%.(4)

Deuterium-induced cracks propagate discontinuously. This suggests a zipper mechanism, where cracks nucleate, grow, propagate, and are then stopped by some obstacle in the material, only to repeat the cycle again. The grain boundary is the most likely obstacle to the continuous propagation of intergranular (along the grain boundary) and transgranular (across the grain) cracks.

Embrittlement can proceed without externally-applied loads, but this does not mean that loads are not present. Forces are provided by the residual stress in the material and by the embrittlement mechanisms, such as, dislocations interaction, hydride or molecular precipitates, etc. The primary mechanism for crack growth and propagation is the stress concentration at the tip of the crack and the strain energy associated with the very high stresses. Embrittlement is more influenced by the microstructure of the material than by the kinetics of transport of hydrogen or deuterium in the lattice. For example, the final stage of crack propagation happens at such fast speeds, with which hydrogen or deuterium transport cannot compete.

## 4. EXCESS HEAT CONTENT, EXCESS ENTHALPY

A significant amount of heat was liberated from the palladium-deuterium system in the Pons–Fleischmann experiments: "4 MJ $cm^{-3}$ of electrode volume."(1). The surplus heat is not explainable by conventional chemical or physical processes. The excess enthalpy, however, can be shown to be the result of coversion of the mechanical energy of fracture into heat.

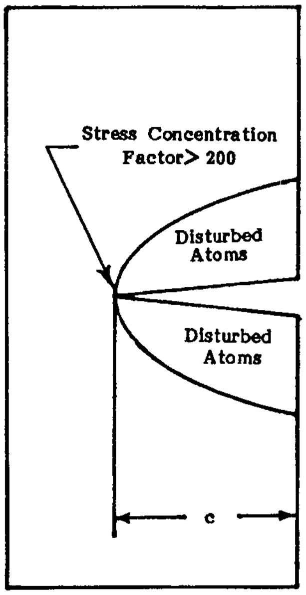

**Fig. 1.** Many layers of atoms are disturbed near a crack tip.

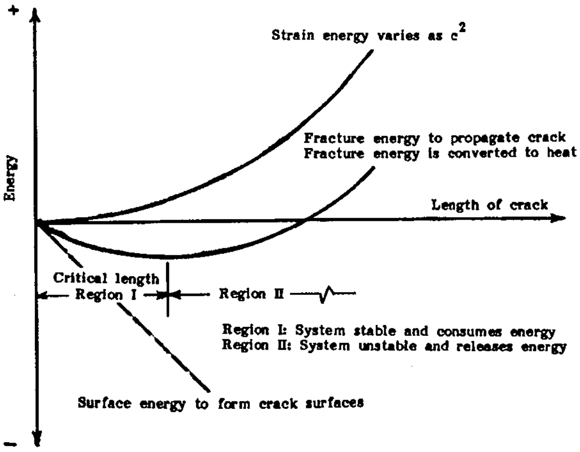

**Fig. 2.** Interaction of surface, strain, and fracture energy terms during crack growth and propagation.

Consider the typical crack geometry shown in Fig. 1. A complex triaxial state of stress exists near the crack tip. In an elasto-plastic material, such as palladium, many layers of atoms are disturbed in the vicinity of a growing crack. As the crack grows, the surface energy is proportional to the crack length, $c$. The strain energy increases as $c^2$ (area of disturbed atoms indicated by shaded area). The relationship between strain energy, surface energy, and fracture energy during the growth and propagation of a crack is shown in Fig. 2, where $c_c$ is the critical Griffith crack length. Below $c_c$, crack growth is stable and the system consumes energy. Beyond the critical length, considerable work (of fracture) is done, and crack growth is rapid and can, sometimes, be explosive. The work done can be estimated from the Griffith equation,

$$W = \frac{\pi c_c s^2}{2E}$$

where $s$ is the stress, and $E$ is the modulus of elasticity, for Pd $1.23 \times 10^{11}$ N/m$^2$. It is not necessary to include nonlinear terms in the modified Griffith equations as the simplified equation is sufficient to determine the order of magnitude of heat that can be generated by the fracture work, or to calculate how millions of joules may be liberated from a small palladium volume. To calculate the work-of-fracture, we must first examine the state of stress at the tip of the crack.

Geometric discontinuities in materials produce stress concentration near crack tips. A theoretical stress concentration factor, $K_t$, for an elliptic hole, of length $2c$ ($c$ is the length of a crack) and width $2b$, is given by

$$K_t = 1 + 2\frac{c}{b}$$

The stress concentration factor for a crack several angstroms wide and several microns long is greater than 1000. As the atomic bonds at the crack tip break, the stress concentration effect is transferred to the next bonds, and so on. The stress concentration for a microcrack (2 microns long and 1 angstrom tip radius) was modeled and computed at about 200.(5) The stress concentration effect in the vicinity of a microcrack is insensitive to the method of load application, i.e., whether the load is applied externally or internally. In the calculation of the fracture energy, the more conservative stress concentration factor of 200 is used in this paper. Yet, to calculate the fracture energy, the number of cracks in the palladium electrodes must first be determined.

The number of cracks in a palladium electrode cannot be counted after the Pons-Fleischmann type experiments. However, the strength reduction of palladium after exposure to deuterium can be used to estimate the number of sites where cracks propagated in the bulk. Such measurements were not reported in cold fusion experiments. The reduction of ultimate strength of palladium, for hydrogen to palladium concentration of 0 to 1, was measured in a NASA study.(6) For H/Pd ratio of 0.6, the ultimate strength of 76 ksi (520 MN/m$^2$) was reduced to 44 ksi (300 MN/m$^2$), a strength reduction of 220 MN/m$^2$. For this reduction value, the critical crack length is estimated at about 47 microns, the grain size level, which controls the discontinuous crack propagation in embrittlement as mentioned earlier.

The work-of-fracture can now be calculated using the Griffith equation. For a critical crack length of 50 microns, a strength reduction of 220 MN/m$^2$, and a 200 stress concentration factor, the work-of-fracture is found to be 1.24 MJ/m$^2$, which is much greater than the typical surface energy of less than 1 J/m$^2$ for most metals and alloys, including palladium.

The enormous work done during the fracture process is proposed to be the heat mechanism in cold fusion and is, most likely, the primary energy term which was neglected in the study of the phenomenon.

When two or more cracks nucleate within several atomic radii, it is possible for these to coalesce into one crack which, eventually, propagates along a grain boundary or across the grain. The maximum number of locations where cracks can nucleate and propagate across 1 cm$^2$ palladium interface is $200^2$, which corresponds to 50 microns separation. The number of locations is then adjusted using the strength reduction ratio of 220/520, and the heat liberated from cracks at all possible locations is found to be 2.1 MJ/cm$^2$.

Similar calculations for deuterium (30% greater effect than hydrogen) gives a work-of-fracture of 5.5 MJ/cm$^2$. Cracks can also propagate in the third orthogonal direction within a palladium cube sample, in the process, producing more heat. It follows that the heat liberated in the Pons-Fleischmann experiments (4 MJ/cm$^3$) is only a fraction of the maximum amount of heat that be released by the fracture process.

Deuterium- or hydrogen-induced cracks can eventually break a metal sample in two, where the full ultimate strength across the fracture is lost. Using the ultimate strength of palladium, the work of fracture 6.9 MJ/m$^2$. If cracks propagate at all possible locations and in all three directions, then the maximum heat that can be liberated is 27.6 MJ/cm$^2$ or 5520 MJ/cm$^3$. This condition is highly unlikely, but it demonstrates the tremendous potential for heat generation by the fracture of metals.

The crack length of 50 microns is the major assumption made in the above analysis. This assumption does not affect the final outcome much as long as crack propagation occurs on the grain, and not the atomic distance and size level. It was noted in Ref. 1 that heat production in cold fusion is "markedly dependent on electrode volume." Of course, if the volume increases, the fracture locations increase, and so will the heat.

## 5. EXPERIMENTAL VERIFICATION

If only the surface energy (less than 1 $J/m^2$) is involved in the fracture of metals, then the heat produced in the fracture of 1 $cm^2$ rod in tension will be small. However, appreciable work is involved when the substantial fracture energy (more than $10^6$ $J/m^2$) is considered, and detectable heat, to the touch, may be liberated. Based on calculations in this paper, the author demonstrated that hot-to-the-touch condition occurs on the fracture surfaces of metals in simple tensile tests. Strain energy is released and stored near crack tips, then suddenly discharged when the cracks propagate through the bulk. The heat on the fracture surfaces is felt immediately after, and not before, break-up of the metal sample. Of course, if a 1-cm sample can be pulled apart quickly and in succession at 10- or 50-micron intervals, then considerable heat will be generated: an accelerated cold fusion experiment.

Integrated tensile-calorimetric experiments under controlled strain rates and other conditions will lead to better understanding of the heat mechanism in cold fusion.

## 6. TIME EFFECTS — RAPID CORROSION

Deuterium or hydrogen embrittlement of metals is a corrosion process, and is time dependent. The general behavior of embrittlement in time is shown in Fig. 3. The initial interval (A) shows no effect as the kinetics of deuterium or hydrogen transport in the bulk predominate. This idle period is followed by an accelerated strength reduction interval (B). During this period, many sites are available for the fracture process. Eventually, less and less sites are available for crack nucleation and propagation and the fracture process and heat generation stop. This behavior is similar to that reported in cold fusion to date, where an initial idle period, for the absorption of deuterium into palladium, is followed by heat generation and, finally, by a dormant stage when the heat generation process stops.

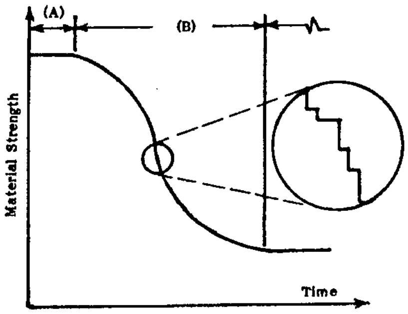

Fig. 3. Typical behavior of embrittlement with time showing delayed, accelerated, and dormant fracture periods. Energy release is incremental (inset).

The power in the Pons-Fleischmann experiments was estimated at more than "10 W $cm^{-3}$ of the palladium electrode,"(1) but for only 120 hours. Extrapolating to 1000 or more hours at the same power rate is not valid simply because the fracture work that can be done is limited. Of course, considerable power can be generated if the fracture energy is released in shorter periods. For a given set of parameters, explosive crack propagation is known to occur in metal structures, such as ships, bridges, and aircraft. The suddenly fused and partially vaporized palladium sample in the Pons–Fleischmann experiments may be explained by the known short-time release of fracture energy. The explosive crack propagation can be violent enough to produce traces of fusion by-products.

As mentioned earlier, deuterium-induced cracks propagate discontinuously. Here, the fracture energy is released incrementally (see inset in Fig. 3), which may explain the heat pockets in the calorimetric cells, reported in the Pons–Fleischmann tests. As time goes on, the conditions which cultivate the fracture process diminish, and the heat generation process comes to an end. This is, perhaps, why in 5.5 years (nearly 50,000 hours), only the 120 hours, or less, time-samples have been cited by the original experimenters.

## 7. THE FUEL IS PALLADIUM, NOT DEUTERIUM

When all the locations susceptible to crack nucleation and propagation in the palladium (or other material) are exhausted, the metal is, theoretically, burnt out. In order for the cold fusion process to continue, the crystallographic structure, required to produce more cracks and more heat, must be restored. The palladium electrodes must then be recycled (by melting) to continue the heat generation process; and the efficiency estimates must take this energy overhead into account.

Professors Pons and Fleischmann projected figures of merit of 1000%, and expect one million percent thermal yield, from their process. This is based on the "joule heat or total energy supplied to the cell"(1) and the amount of heat liberated in the cells. As described above, the small energy supplied to the cell is not the only, or even primary, input involved. The efficiency of cold fusion must take into account the considerable energy required to process the metal electrodes from the ore, or to recycle the cracked palladium electrodes by melting.

From the analysis in this paper and other relevant considerations, we may conclude that palladium, and not deuterium, is the fuel; just as coal, and not air (oxygen), is the fuel in that combustion. And just as combustion ceases when coal is turned to ashes, so the heat generation in cold fusion ceases when palladium is all burnt, or cracked. The abundance of air, in the case of carbon ashes, or deuterium, in the case of the cracked palladium, will not continue, or restart, the burning process.

There is a net entropy increase in both processes. Coal burning is irreversible as heat cannot be made to flow back into the ashes to reproduce coal. The exhausted structure of palladium can be restored after embrittlement and heat generation, but only by melting. The ability to recycle the exhausted metals makes the heat generation by cold fusion a reversible process. In accordance with the second law of thermodynamics, the net entropy change in cold fusion (between the electrolytic cell and the furnace) must be zero. It then appears that the cold fusion process may not be a viable source of energy. Recognizing that palladium, and not deuterium, is the fuel in the Pons-Fleischmann system will lead to better study and applications of the phenomenon.

## 8. CONCLUSION

The heat mechanism in the Pons–Fleischmann experiments was identified as the fracture work of cracks induced in palladium by deuterium. The work-of-fracture was calculated and shown to correspond to the excess heat measured in the cold fusion experiments. The maximum heat that can be liberated from the process was shown to be considerable, but finite. Only a fraction of break even, and not 1000% or more, has been achieved from cold fusion to date. Other characteristics of the process were also presented, such as the identification of palladium, and not deuterium, as the fuel in the process.

When conducting cold fusion experiments, using palladium, titanium, nickel, or other metals and alloys, it will be useful to measure the strength of the electrodes before and after exposure to deuterium. The strength reduction can be used to estimate the energy absorbed by local deformation in the fractured surfaces so that experimental-theoretical correlation can be established. It is also important to carefully identify the processing technique of the electrode material to establish the likelihood of embrittlement and fracture energy conversion to heat. Detailed metallographic analysis of the palladium samples will yield useful information. The phenomenon, now popularly known as cold fusion, will find uses for heat storage in special applications, but the process must first be controlled. A similar process, the piezoelectric effect, converts mechanical energy to electrical energy, but only in asymmetrical crystals. Unlike piezoelectric devices, metal-burning devices will store energy in the bulk of a greater variety of metals and alloys for use when needed.

Numerous chemical, physical, and mechanical processes in the palladium-deuterium system affect the results, but not the order of magnitude, of this study.

## ACKNOWLEDGMENT

The author wishes to acknowledge useful discussions with Dr. Andrew Meulenberg, Jr., and the opportunity provided by the Continuing Engineering Education Program of the George Washington University to consolidate related work in a short course, "Cold Fusion—Engineering Perspectives." which will be given at the University on January 29–31, 1990.

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