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Cold Fusion - The Heat Source
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ABSTRACT

Metals and alloys interact with hydrogen, deuterium, and other elements and mechanisms to induce and propagate cracks in the bulk. A primary source of heat in the experiments of Martin Fleischmann and Stanley Pons is the surface energy of the fractured surfaces inside the bulk of the palladium electrode. Other secondary heat sources are described in this article. Albeit unintentionally, the energy responsible for the production of excess heat was stored in the system, and is not a new chemical or fusion reaction.

This paper shows that the reported phenomenon is not "nuclear fusion," that the system is not fully enclosed, that the "maximum" amount of heat which can be derived does not justify commercialization, and that the energy mechanism responsible for the excess heat can be explained in classical terms.

1. INTRODUCTION

Experiments by Stanley Pons and Martin Fleischmann (1) demonstrated that excess heat can be generated in a palladium-deuterium system at room temperature. In these tests, sheet, rod and cube palladium (Pd) electrode samples were used in heavy water (99.5% D_2O + 0.5% H_2O) solutions. The excess heat led the experimenters to conclude that "hitherto unknown nuclear process or processes" (1) were responsible for the excess enthalpy. This led to great interest in the possibility of "cold fusion" as an ideal source of energy.

In the short period following the Pons-Fleischmann discovery, several centers in the United States and abroad reported the generation of excess heat in similar experiments. Others have not been able to emulate the heat production.

While the heat generation appears to be real, the fusion reaction is not so clear. Neutron counts, tritium, helium, and other fusion by-products were variable, inconsistent with theory, or non-existent.

The perplexity surrounding "cold fusion" is mainly due to the inability to account for the excess heat by chemical or nuclear reactions.

This matter can be resolved using classical means by recognizing that the "system" which is used in the Pons-Fleischmann experiments was not a closed system. Interaction with the external environment was hidden, albeit accidentally, and this was the source of the paradox.

In the next sections, I will describe the likely source of heat, the interaction with external environment, the "mechanical" energy source, and other related matters.

2. THE STRENGTH OF METALS AND ALLOYS

Metals and alloys are characterized by the presence of very large number of microcracks in the bulk. The fine cracks cause considerable reduction in the theoretical cohesive strength of materials as derived by the Griffith theory (Appendix A).

The measured strength of materials reflect the chemical and physical bonds in the bulk less the effect of the area of the cracks and stress concentrations produced by the sharp cracks.

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3. THE HEAT SOURCE

Atomic, molecular, and grain bonds can be destroyed by different mechanisms, including, fracture, melting, or chemical attacks. When a metal sample is fractured across the bulk, two new surfaces are produced, Fig. 1. The process involves crack initiation and crack propagation. The crack may propagate along grain boundaries (intergranular) or across the grains (transgranular), Fig. 2.

The energy required to produce two new surfaces across the grain is a function of the number of atoms involved in the process. As the crack propagates through the metal, energy is released and absorbed by local deformation in the fractured surfaces. The amount of heat released in the process can be calculated using the expression:

$$H = AU_a$$

where, H is the heat imparted to the system, A is a constant with a value of 1.00, and U_a is the cohesive bond energy of the two layers of atoms involved at the two surfaces. The description here applies to transgranular fractures.

If the fracture is intergranular, then the released energy is lower than for the transgranular case; and so will the released heat be lower. Where the sample is immersed in a liquid, the energy released to that environment is:

$$H = AU_g$$

where, U_g is the cohesive bond energy of the grain boundaries involved in the process.

4. THE OPEN SYSTEM - TIME EFFECT

The validity of the Pons-Fleischmann experiments relies heavily on the assumption that the Pd-D electrolysis cells is a closed system, Fig. 3. Here, heat, or energy, does not flow into or out of the system, and the system is presumed to be independent of the environment. But this is not the case.

Before the palladium electrodes were used in the tests, the sheet, rod and cube Pd samples underwent a series of production steps which included melting, cooling, working, alloying, and other processes. These treatments introduce a variety of effects in the metal, some of which are exhibited only with time. A classic example of these locked-in stresses is shown in Fig. 4 (2). The rod shown in the figure may be considered to be in a state of equilibrium and free of external forces. In reality, the strains associated with the locked-in stresses represent locked-in energy which can remain in the sample for a long time, ready to be released by a variety of mechanisms. There are several other metallurgical factors which store strain energy in metals and alloys, and several mechanisms which can release the stored energy. These are the subject of other articles and seminars.

The mechanical energy stored in materials is usually released in time as the material seeks a minimum energy condition. The energy can also be released artificially, suddenly or slowly. The stress relaxation curves (2) shown in Fig. 5 demonstrate some fundamental behavior as function of time and temperature.

The release of stored strain energy is reflected in the reduction of the strength of the material. Typical strength reductions versus time are shown in Figures 6, 7, and 8 for materials exposed to corrosive, hydrogen, and operational environments (3, 4, and 5 respectively). A typical characteristic of these and other studies of metal behavior is the high initial rate of decline of strength with time.

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The reduction in strength represents a release of stored energy which is converted into heat as described above.

In this sense, the Pons-Fleischmann system is not truly contained as required by the laws of thermodynamics. The interaction with external environment is exhibited by the recovery of characteristics which were stored in the palladium samples during the processing and fabrication cycles, Fig. 9.

5. HYDROGEN AND DEUTERIUM EMBRITTLEMENT

Hydrogen- and deuterium-metal systems were studied at length in the last three decades (6 and 7). The load carrying capacity of metals and alloys is significantly reduced by the attack of molecular or atomic hydrogen. The attack of hydrogen on metals is termed hydrogen embrittlement (HE). Hydrogen, deuterium, and other elements induce and propagate cracks in the bulk of metals. Hydrogen- or deuterium- induced and propagated cracks produce new surfaces inside the bulk of the material, which is the source of heat as described above. The cracks propagate discontinuously, at times resulting in quick fracture, and at other times, delayed fracture.

The severity of hydrogen attack is dependent on the crystallographic structure of metals and alloys. The more open body-centered cubic (bcc) metals are more susceptible to hydrogen attack than the hexagonal close-packed (hcp) or, the more closed, face-centered cubic (fcc) crystal structures. Interstitial and substitutional atoms, and point defects occur in greater abundance in the open, than the closed, atomic structure.

Fracture toughness tests of several alloys (8), in vacuum and hydrogen environments, showed the degradation effects of hydrogen, Table-1. The values shown here indicate the varying influence of hydrogen on different alloys. Actually, the influence of hydrogen on the strength of materials can also be different for similar alloy samples. This is shown in Figures 10 and 11 for steel-4130 and titanium Ti-6Al-4V samples.

Figure 11 shows that the strength of titanium samples was always affected by hydrogen, but to a lesser degree than the worst steel-4130 samples. The steel samples, on the other hand, showed greater strength reduction, in some instances, and no reduction in others, Fig. 11. These figures will be interpreted further in later sections.

The effect of deuterium on the strength of materials is known to be more severe than hydrogen (9).

As proposed earlier, the excess heat measured in the Pons-Fleischmann and other experiments was merely the conversion of stored mechanical energy in the palladium, titanium and other electrodes into heat as new surfaces are formed in the bulk of the material.

Is there a maximum enthalpy, or heat content, that can be derived from the stored mechanical energy? Or, is the energy unlimited?

6. THE MAXIMUM HEAT CONTENT

"Enthalpy generation can exceed 10 W cm^{-3} of the palladium electrode; this is maintained for experiment times in excess of 120 h, during which typically heat in excess of 4 MJ cm^{-3} of electrode volume was liberated," said Pons and Fleischmann (1). In a congressional hearing, April 26, 1989, it was indicated that considerable heat can be generated from the system in 1,000 or more hours. This is simply an extrapolation from the reported measurements.

If the heat measured in the Pons-Fleischmann experiments is produced by the conversion of stored mechanical energy, as internal surfaces are formed, then a maximum "heat content" can

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be calculated for a cross sectional area within a given electrode. For this, we will use a palladium-hydrogen example.

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Variation in the yield and ultimate strengths of palladium as function of hydrogen-palladium atom ratio (from 0 to 1) is shown in Fig. 10. The ultimate strength for pure palladium is given at about 75 ksi and, at a ratio of 0.6, a minimum of 44 ksi is approached. In this study, a hydrogen ratio of more than 0.6 reduces the ultimate strength by 31 ksi, and a completely brittle fracture occurs (11). In this example, the cracks induced and propagated by the hydrogen in the palladium bulk reduced the strength by 31 ksi. We can now convert this value to obtain the maximum heat that can be generated from a palladium sample saturated with hydrogen.

The equivalent force on a 1 cm^2 area is about 21,400 newtons. To calculate the work done by this force, we use a distance of 10 angstrom units as representative of the distance where "interatomic forces between two separating crystal planes are important" (12). The work done here is 0.0000214 N-m, or watt-sec. The velocity of crack propagation of brittle fracture, about 5 x 10^5 cm/sec for the palladium sample, is then used to determine the total power that can be delivered by the propagation of the crack a distance of 1 cm:

$$(0.0000214 \text{ watt-sec})/(5 \text{ x } 10^5 \text{ sec-1}) = 4.28 \text{ Watts}$$

which is of the order of magnitude of the excess enthalpy reported by Pons and Fleischmann (1).

The surface energy per unit area can multiply by a factor of 100 to 1,000 (13) depending on other metallurgical parameters. Here, output of tens or hundreds of watts may also be possible.

As mentioned earlier, cracks propagate discontinuously in the hydrogen or deuterium environments; and the energy is released incrementally. The release of energy is commensurate with the crack(s) propagation, namely, each time a crack is propagated and arrested, its energy installment is released; and so on.

The high initial rate of decline of strength with time in the hydrogen and deuterium environments releases more energy in the first hours of operation in the Pons-Fleischmann type experiments. As time goes on, the crystallographic and other conditions which cultivate the fracture process diminish, and the energy generation process comes to an end. For example, if a hydrogen assisted brittle fracture extends across the full 1 cm^2 electrode area, the circuit is interrupted and the process of power extraction is stopped.

7. THE INCONSISTENT EXPERIMENTAL RESULTS

Some centers, in the United States and abroad, were able to reproduce the excess heat phenomenon, while other centers were not. Those who were able to reproduce the phenomenon reported differences in level from that obtained by Pons and Fleischmann. The inconsistent heat production can be explained from data presented earlier in this article.

Figures 10 and 11 show the behavior of steel-4130 and titanium-6Al-4V in hydrogen environment. The steel samples show considerable variation in the load to failure in hydrogen. All the samples tested in air failed at about 4.2 KN, and one specimen in hydrogen failed at about half of that load, 2.2 KN. The distribution for the remaining samples shows an increasing number as the air environment is approached. Note that some specimens showed no effect at all, failing at the load to failure in air. In contrast, all the Ti-6Al-4V alloy samples failed below the load for the air samples, but deviation was less pronounced than the steel samples.

As described in the previous section, the amount of heat generated in the Pons-Fleischmann type experiments is dependent on the amount of internal surface energy released during the propagation of cracks in the bulk.

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Suppose the steel samples shown in Figure 10 were distributed to 26 centers to be used in the electrolysis experiments. It is clear from the figure that some centers will report no "heat," others will report moderate levels, and only two or three will report considerable heat content.

Another interesting observation is that "all" the titanium samples showed reduction in strength when placed in the hydrogen environment. It would therefore be expected that the alloy is very likely to produce the heat effect discussed above. Also, titanium, a transition metal, is similar to palladium.

8. VERIFICATION IN ACCELERATED TESTS

Verification of the Pons-Fleischmann experiments has been complicated by several factors. Some scientists complained that insufficient details, to duplicate the tests, were given by the discoverers. Some estimated that it will take days, weeks or, even, months before the hoped for "cold fusion" can be confirmed or rejected.

The heat produced by new surfaces in an internal fracture within the bulk can be verified with simple experiments. Standard tensile tests of specimens of different alloys and different diameters at different strain rates can quickly provide estimates of the amount of heat that can be generated by the formation of two new surfaces. Calorimetric tests can be integrated into the tensile tests to measure the thermal product.

The fracture surfaces of a one-inch diameter tensile specimen of a high strength alloy, including palladium, should be hot-to-the-touch immediately after fracture; before the heat imparted to the separated surfaces is dissipated.

The author will conduct these experiments at the first opportunity of laboratory availability.

9. IS COMMERCIALIZATION FEASIBLE?

In the Congressional hearing on "cold fusion," a possible commercial device was described by the team from the University of Utah. The device is a closed system, which depends on circulation and ionization of deuterium for the production of heat.

The heat production mechanism briefly described in this article requires specific crystallographic and other conditions in the electrode material. These conditions are altered in time, particularly, in the first hours of operation. For example, the more efficient the system, the more is the proliferation of cracks in the bulk. The metallurgical conditions which nourish the production of heat must be restored to the electrode material. Restoration may require melting, cold or hot working, or other metallurgical processes which require considerable energy to promulgate.

The question "Is commercialization feasible?" can be answered by comparing the energy required to restore the metal electrode to the energy obtained from "cracking" of the bulk.

The accelerated tests proposed in the previous section can be used to obtain a quick answer.

10. A SIMILAR CONVERSION SYSTEM

The initiation and propagation of cracks in hydrogen and deuterium environments have been related to many factors, including, hydrides and molecular precipitates, surface, lattice and dislocation interactions, and others. Perhaps, the most prominent feature of hydrogen-induced fracture failure is that "all forms of embrittlement are extremely sensitive to variations in the microstructure of the embrittled metal" (14). This common feature points to the importance of crystallographic structures and interactions to the conversion of mechanical energy into other forms.

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In this article, I described, albeit very briefly, interactions within the crystal structure of metals and alloys that can lead to the release and conversion of mechanical energy. This, however, is not unique to the recently reported "excess heat" experiments. The interaction of stress and strain with the atomic crystal structure is known to result in the direct conversion of mechanical energy to other forms: "Direct conversion of mechanical energy into electrical energy is possible by utilizing the phenomena of piezoelectricity ..." (15).

When compressive load is applied to a crystal with low symmetry, electrical charges develop on the axis of load application. Mechanical strains can also be produced in these crystals when an electric field is applied. This phenomenon, piezoelectricity, is used in microphones, transducers, loudspeakers, and other devices. A crystal with high asymmetry can thus operate as a generator or as a motor.

The phenomenon reported in the Pons-Fleischmann experiments must also be studied in light of the piezoelectric effect to establish the role of atomic arrangements, Pd, Ti, H, D and others, in the heat generation behavior.

11. THE ENERGY MECHANISM

This article provides a possible explanation for the heat source in the recently reported Pons-Fleischmann electrolysis experiments. The extensive database in hydrogen embrittlement is used to describe some mechanisms and effects involved. The theoretical and experimental hydrogen-metal system studies did not (consciously) extract deuterium from the hydrogen environment in tests. As a minimum, deuterium was involved in these earlier tests in a ratio consistent with the abundance of the deuterium in the natural or test environments. The validity of my proposal is enhanced by the fact that the effect of deuterium on embrittlement has shown the same effect as that of hydrogen, but with greater severity. Also, some reports indicated that the heat generation in the Pons-Fleischmann type experiments has been observed in light water.

The energy mechanism responsible for crack initiation and propagation and, thus, the excess heat will be discussed in Part II to this report.

The Author

Ali F. AbuTaha is a consultant with extensive background in engineering and management. He is recognized for his analysis of the extensive reports of the Challenger accident and for his important findings for safe spaceflight. During the period 1970-1975, Mr. AbuTaha was responsible for material testing and selection for aerospace applications for the Spacecraft Laboratory at COMSAT Labs. During this, and other, periods, he conducted extensive study of hydrogen embrittlement phenomenon to identify materials for use in concentrated hydrogen environments, e.g., $Ni-H_2$ fuel cells. Mr. AbuTaha is an engineering graduate from George Washington University and had successfully completed many specialized courses. He lectured on varied subjects in the U.S. and abroad. He is a member of AIAA, AAAS, BIS, and other technical groups, Member of the Year (1988) of the Challenger Society, and a Distinguished Life Member of AFCEA.

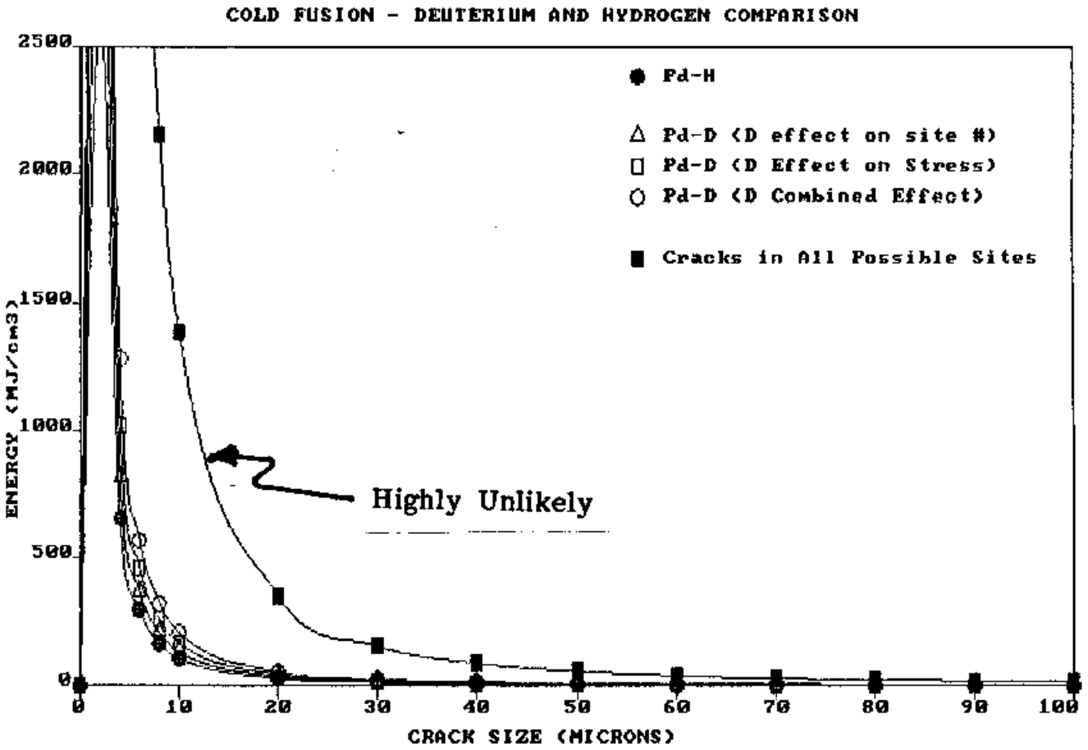
References

Tables

Figures

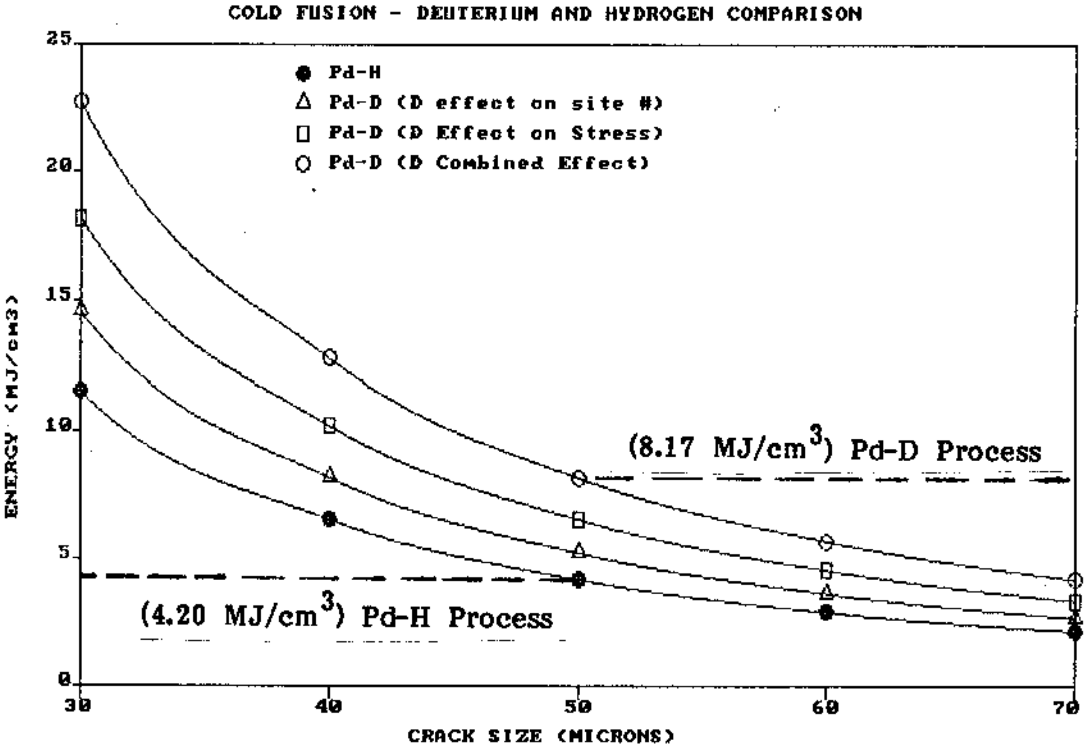
Appendices

Peer review



Highly Unlikely

Figure 5. Heat Liberated by Work-of-Fracture



(8.17 MJ/cm^3) Pd-D Process

(4.20 MJ/cm^3) Pd-H Process

Figure 6. Enthalpy of Different Crack Lengths in Pd-H and Pd-D Processes