ERAB, *Report of the Cold Fusion Panel to the Energy Research Advisory Board*. 1989: Washington, DC.

A copy of the ERAB report has been prepared by the National Capital Area Skeptics (NCAS) organization (www.ncas.org). It is available here in HTML format: http://www.ncas.org/erab/. It is converted to Acrobat format in this document, below.

This organization has not posted any other papers about cold fusion.

Cold fusion researchers consider the ERAB report highly prejudiced for many reasons. It was concluded in a rush long before there was time to perform and publish serious replications. The authors dismissed experimental evidence by pointing to theory, which is a violation of the scientific method. And they selectively ignored positive data. For example, ERAB report authors visited Dr. Melvin Miles at the China Lake Naval Weapons Laboratory when he had just begun experiments in cold fusion. He told them he had not observed excess heat or other evidence of fusion. Months later, he did observe significant heat. He contacted the authors. He informed them of his results and invited them to return. They ignored him and reported only his initial, negative results. [1] [2]

The ERAB report begins:

"The recent interest in cold fusion was stimulated by reports from Utah scientists in March 1989 that fusion had occurred in experiments on the electrolysis of heavy water (D_2O). Dr. Stanley Pons and Dr. Martin Fleischmann at the University of Utah claimed to measure a production of heat that could only be explained by a nuclear process. Dr. Steven Jones at Brigham Young University did not observe heat but claimed to observe neutron emission that would also indicate a nuclear process. The claims were particularly astounding given the simplicity of the equipment, just a pair of electrodes connected to a battery and immersed in a jar of D_2O--equipment easily available in many laboratories."

. . . and goes downhill from there. This is a mischaracterization of the findings and the nature of the experiment. There is nothing "simple" about a cold fusion experiment. Most experiments take weeks or months to prepare. Cathodes must be carefully selected and prepared. Many things can go wrong. For example, heavy water found is sometimes so contaminated it will prevent a reaction from occurring. Common contaminants include light water, surfactants, [3] heavy metals and a species of bacteria that has been discovered living in most heavy water supplies in Europe and North America. [4] No published paper describes the use of a "jar." Laboratory grade Teflon glassware or steel cells must be used, after careful preparation.

- Jed Rothwell

1. Miles, M. and K.B. Johnson, *Anomalous Effects in Deuterated Systems, Final Report.* 1996. http://www.lenr-canr.org/acrobat/MilesManomalousea.pdf

2. Storms, E., *A critical evaluation of the Pons-Fleischmann effect: Part 1*. Infinite Energy, 2000. **6**(31): p. 10. http://www.lenr-canr.org/acrobat/StormsEacriticale.pdf
3. Fleischmann, M. and S. Pons, *Reply to the critique by Morrison entitled 'Comments on claims of excess enthalpy by Fleischmann and Pons using simple cells made to boil.* Phys. Letters A, 1994. **187**: p. 276.
4. Celani, F., et al. *High Hydrogen Loading into Thin Palladium Wires through Precipitate of Alkaline-Earth Carbonate on the Surface of Cathode: Evidence of New Phases in the Pd-H System and Unexpected Problems Due to Bacteria Contamination in the Heavy-Water*. in *ICCF8, Eighth International Conference on Cold Fusion.* 2000. Lerici (La Spezia), Italy: Italian Physical Society, Bologna, Italy.

Cold Fusion Research

November 1989

A Report of the Energy Research Advisory Board to the United States Department of Energy

Washington, DC 20585

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[1999]

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Energy Research Advisory Board
to the
United States Department of Energy
1000 Independence Avenue. S.W.
Washington, D.C. 20585
(202)586-5444

November 26, 1989

The Honorable James D. Watkins
Secretary of Energy
Washington, DC 20585

Dear Mr. Secretary:

It is my privilege to forward to you the enclosed final report of the Cold Fusion Panel of the Energy Research Advisory Board. This report reflects the diligence and care with which the members of the Panel addressed the charge you gave to the Board last April. It also reflects their broad and germane experience and their strict observance of professional standards.

On November 8, the full Board reviewed the conclusions and recommendations drafted by the Panel and, after making only minor revisions, approved the report unanimously.

All members of the Panel deserve praise for the excellence of their work and thanks for the considerable time and energy they put into this study. As you well know, this time and energy had to be extracted from busy schedules and demanding jobs.

Special recognition is in order for the Co-Chairmen of the Panel, Drs. John R. Huizenga and Norman F. Ramsey, who not only organized and directed the complex effort required to evaluate the results of the cold-fusion experiments conducted to date, but also contributed significantly to the writing of the report itself.

The Energy Research Advisory Board believes that the Panel's findings comprise a valuable base for future Department of Energy decisions on cold fusion.

Sincerely,
John. W. Landis, Chairman

[Signature]

Energy Research Advisory Board

JWL:bg

UNIVERSITY
OF

ROCHESTER

COLLEGE OF ARTS AND SCIENCE

DEPARTMENT OF CHEMISTRY

John R. Huizenga
Tracy H. Harris Professor

November 8, 1989

Mr. John W. Landis, Chairman
Energy Research Advisory Board
U.S. Department of Energy
Washington, D.C. 20585

Dear John,

I am pleased to forward to you the Final Report of the Cold Fusion Panel. This report reviews the current status of cold fusion and includes major chapters on Calorimetry and Excess Heat, Fusion Products and Materials Characterization. In addition. the report makes a number of conclusions and recommendations, as required by the Secretary of Energy.

The Panel or subgroups thereof have participated in the Workshop on Cold Fusion in Santa Fe, have visited several laboratories, have examined many published articles and preprints, studied numerous communications and privately distributed reports, and have participated in many discussions. In addition, the Panel held five public meetings where its findings were discussed and drafts of both the Interim and Final Reports were formulated.

I wish to thank the members of the Panel and its staff for their cooperation and their diligent work during the last six months. I hope the Department finds this report useful in formulating funding policy.

Sincerely,
John R. Huizenga

[Signature]

Co-Chairman, Panel on Cold Fusion

JRH:dsm

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NOVEMBER 1989

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[[i]]

ENERGY RESEARCH ADVISORY BOARD COLD FUSION PANEL

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***ERAB Members**

EXECUTIVE SUMMARY

As a result of the startling announcements in March 1989 by Utah scientists claiming the attainment of cold fusion, the Secretary of Energy requested (see Appendix 1.A) that the Energy Research Advisory Board (ERAB) convene a panel to assess the possibility of cold fusion. Since early May 1989, the Panel or subgroups thereof have participated in the Workshop on Cold Fusion in Santa Fe, have visited several laboratories, have studied the open literature and numerous privately distributed reports, and have participated in many discussions. The Panel meetings and schedule of laboratory visits are summarized in Appendix 1.B.

Since the above announcement, many laboratories worldwide have initiated research in cold fusion. In the United States, a major effort has been undertaken to search for cold fusion by a large number of research groups at university and national and industrial laboratories. Some laboratories support the Utah claims of excess heat production, usually for intermittent periods, but most report negative results. Those who claim excess heat do not find commensurate quantities of fusion products, such as neutrons or tritium, that should be by far the most sensitive signatures of fusion. Some laboratories have reported excess tritium. However, in these cases, no secondary or other primary nuclear particles are found, ruling out the known D+D reaction as the source of tritium.

The Panel concludes that the experimental results on excess heat from calorimetric cells reported to date do not present convincing evidence that useful sources of energy will result from the phenomena attributed to cold fusion. In addition, the Panel concludes that experiments reported to date do not present convincing evidence to associate the reported anomalous heat with a nuclear process.

Neutrons near background levels have been reported in some D_2O electrolysis and pressurized D_2 gas experiments, but at levels 10^{12} below the amounts required to explain the experiments claiming excess heat. Although these experiments have no apparent application to the production of useful energy, they would be of scientific interest if confirmed. Recent experiments, some employing more sophisticated counter arrangements and improved backgrounds, found no fusion products and placed upper limits on the fusion probability for these experiments, at levels well below the initial positive results. Hence, the Panel concludes that the present evidence for the discovery of a new nuclear process termed cold fusion is not persuasive.

The Panel also concludes that some observations attributed to cold fusion are not yet invalidated.

The Panel recommends against the establishment of special programs or research centers to develop cold fusion. However, there remain unresolved issues which may have interesting implications. The Panel is, therefore, sympathetic toward modest support for carefully focused and cooperative experiments within the present funding system.

Following an introductory chapter, calorimetry, fusion products and materials are assessed in the next three chapters. Conclusions and recommendations are summarized in the final chapter.

[[1]]

CONCLUSIONS AND RECOMMENDATIONS

A. PREAMBLE

Ordinarily, new scientific discoveries are claimed to be consistent and reproducible; as a result, if the experiments are not complicated, the discovery can usually be confirmed or disproved in a few months. The claims of cold fusion, however, are unusual in that even the strongest proponents of cold fusion assert that the experiments, for unknown reasons, are not consistent and reproducible at the present time.

However, even a single short but valid cold fusion period would be revolutionary. As a result, it is difficult convincingly to resolve all cold fusion claims since, for example, any good experiment that fails to find cold fusion can be discounted as merely not working for unknown reasons. Likewise the failure of a theory to account for cold fusion can be discounted on the grounds that the correct explanation and theory has not been provided. Consequently, with the many contradictory existing claims it is not possible at this time to state categorically that all the claims for cold fusion have been convincingly either proved or disproved. Nonetheless, on balance, the Panel has reached the following conclusions and recommendations.

B. CONCLUSIONS

1. Based on the examination of published reports, reprints, numerous communications to the Panel and several site visits, the Panel concludes that the

experimental results of excess heat from calorimetric cells reported to date do not present convincing evidence that useful sources of energy will result from the phenomena attributed to cold fusion.

2. A major fraction of experimenters making calorimetric measurements, either with open or closed cells, using Pd cathodes and D_2O, report neither excess heat nor fusion products. Others, however, report excess heat production and either no fusion products or fusion products at a level well below that implied by reported heat production. Internal inconsistencies and lack of predictability and reproducibility remain serious concerns.

   In no case is the yield of fusion products commensurate with the claimed excess heat. In cases where tritium is reported, no secondary or primary nuclear particles are observed, ruling out the known D+D reaction as the source of tritium. The Panel concludes that the experiments reported to date do not present convincing evidence to associate the reported anomalous heat with a nuclear process.

3. The early claims of fusion products (neutrons) at very low levels near background from D_O electrolysis and D_2 gas experiments have no apparent application to the production of useful energy. if confirmed, these results would be of scientific interest. Recent experiments, some employing more sophisticated counter arrangements and improved backgrounds, found no fusion products and placed upper limits on the fusion probability for these experiments at levels well below the initial positive results. Based on these many

   [[2]]

   negative results and the marginal statistical significance of reported positive results the Panel concludes that the present evidence for the discovery of a new nuclear process termed cold fusion is not persuasive.

4. Current understanding of the very extensive literature of experimental and theoretical results for hydrogen in solids gives no support for the occurrence of cold fusion in solids. Specifically, no theoretical or experimental evidence suggests the existence of D-D distances shorter than that in the molecule D_2 or the achievement of "confinement" pressure above relatively modest levels. The known behavior of deuterium in solids does not give any support for the supposition that the fusion probability is enhanced by the presence of the palladium, titanium, or other elements.

5. Nuclear fusion at room temperature, of the type discussed in this report, would be contrary to all understanding gained of nuclear reactions in the last half century; it would require the invention of an entirely new nuclear process.

RECOMMENDATIONS

1. The Panel recommends against any special funding for the investigation of phenomena attributed to cold fusion. Hence, we recommend against the establishment of special programs or research centers to develop cold fusion.

2. The Panel is sympathetic toward modest support for carefully focused and cooperative experiments within the present funding system.

3. The Panel recommends that the cold fusion research efforts in the area of heat production focus primarily on confirming or disproving reports of excess heat. Emphasis should be placed on calorimetry with closed systems and total gas recombination, use of alternative calorimetric methods, use of reasonably well characterized materials, exchange of materials between groups, and careful estimation of systematic and random errors. Cooperative experiments are encouraged to resolve some of the claims and counterclaims in calorimetry.

4. A shortcoming of most experiments reporting excess heat is that they are not accompanied in the same cell by simultaneous monitoring for the production of fusion products. If the excess heat is to be attributed to fusion, such a claim should be supported by measurements of fusion products at commensurate levels.

5. Investigations designed to check the reported observations of excess tritium in electrolytic cells are desirable.

[[3]]

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6. Experiments reporting fusion products (e.g., neutrons) at a very low level, if confirmed, are of scientific interest but have no apparent current application to the production of useful energy. In view of the difficulty of these experiments, collaborative efforts are encouraged to maximize the detection efficiencies and to minimize the background.

[[4]]

I. INTRODUCTION

The recent interest in cold fusion was stimulated by reports from Utah scientists in March 1989 that fusion had occurred in experiments on the electrolysis of heavy water (D_2O). Dr. Stanley Pons and Dr. Martin Fleischmann at the University of Utah claimed to measure a production of heat that could only be explained by a nuclear process. Dr. Steven Jones at Brigham Young University did not observe heat but claimed to observe neutron emission that would also indicate a nuclear process. The claims were particularly astounding given the simplicity of the equipment, just a pair of electrodes connected to a battery and immersed in a jar of D_2O--equipment easily available in many laboratories.

This was not the first time fusion had been claimed to occur in electrolysis experiments, the earliest dating to the late 1920's in experiments that were later retracted, as discussed below. Nonetheless the implications of the Utah claims, if they were correct, and the ready availability of the required equipment, led scientists around the world to attempt to repeat the experiments within hours of the announcement. The Panel estimates that several tens of millions of dollars have been spent in the United States on cold fusion experiments. These experiments are discussed in the following sections.

To understand the initial excitement, and also the profound skepticism, that has surrounded cold fusion experiments, it is helpful to review the nature of the fusion process.

The excitement stems mainly from the claims of heat production by nuclear fusion in these experiments, and the implications of these claims on future energy supply. The attribution of heat production to fusion arises from the presence of deuterium, D, an isotope of hydrogen widely abundant in nature. The known fusion reactions in hydrogen isotopes are shown in Table 1.1.

TABLE 1.1

KNOWN FUSION REACTIONS OF HYDROGEN ISOTOPES

REACTION	**Energy Release (MeV)**	**Reaction/sec per 1 W Output**
D + D --> 3He + n	3.27	1.90x10l2
D + D --> T + p	4.03	1.54xl012
D + D --> 4He + gamma	23.85	2.61xl011
D + T --> 4He + n	17.59	3.53x1011
p + D --> 3He + gamma	5.49	1.13xl012
p + T --> 4He + gamma	19.81	3.14x1011

[[5]]

All of these nuclear reactions produce millions of times more energy per reaction than do chemical reactions. A simple way to harness this energy would be an extremely important discovery.

Then why the skepticism?

First, while some researchers claim to confirm excess heat production, many report only negative results. The claims of excess heat are based upon rather difficult calorimetric measurements. Many laboratories do not find any heat production beyond that expected from normal water electrolysis, and the overall evidence in favor of excess heat production is not convincing (Section II).

The second reason for skepticism is the discrepancy between the claims of heat production and the failure to observe commensurate levels of fusion products, which should be by far the most sensitive signatures of fusion. Again referring to Table 1.1, we see that the only possible outcome of fusing two deuterium nuclei (each having 1 proton, 1 neutron) is the production of either tritium (T: 1 proton, 2 neutrons) or helium (2 protons, and either 1 neutron in He^3 or 2 neutrons in He^4). Moreover, the amount of heat produced and the amount of tritium or helium produced are strictly correlated by any of the currently understood fusion processes.

As is shown in Table 1.1, if 1 watt of heat production is observed (the maximum order of magnitude reported), then either tritium or helium must be produced at the same time at a rate of about 10^{12} atoms/second. In addition to tritium or helium, fusion in deuterium by the known reactions should also produce observable radiation in the form of a neutron, an energetic proton, or a gamma ray (see Table 1.1). These additional fusion products carry away most of the energy--millions of electron volts (MeV) of energy per particle. At such energies, the neutrons or gammas should escape and should be more readily observable than the heat. The proton should also be detectable directly or by its production of gamma rays.

The initial announcement by Pons and Fleischmann in March 1989 exhibited the discrepancy between heat and fusion products in sharp terms. Namely, the level of neutrons they claimed to observe was 10^9 times less than that required if their stated heat output were due to fusion.

The persistence of this major discrepancy in all subsequent experiments has led to various explanations as to how the observation of fusion products might be obscured. For example, some have suggested that in a solid the fusion energy is released directly as vibrations of the metal lattice, so that no hard radiations would be observed. In any case, this would not explain the absence of helium or tritium. Helium should be produced in about 50% of all reactions (see Table 1.1). Several electrodes from cold fusion experiments have been examined for helium, but at this writing, none has been reported. The amount of tritium directly observed in some experiments is much too small to account for observable heat. These data and their implications are discussed in Section III.

A third reason for skepticism is that cold fusion should not be possible based on established theory. Nuclear fusion reactions have been studied for many years and their potential as a vast source of energy was well understood from the outset. It was also understood that net energy production from fusion should

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be possible at extremely high temperatures such as occur at the center of stars--millions of degrees centigrade. That fusion does occur under such conditions was firmly established with the successful development of thermonuclear weapons. As early as 1929, several years before fusion reactions were first observed in the laboratory, Atkinson and Houtermans proposed the now well accepted explanation that fusion is the source of energy for the sun.

The importance of high temperature arises as follows. For fusion to occur, two deuterium nuclei must come very close together. Because of their positive charge, nuclei repel each other, whereby they normally are separated by about 0.1 nanometer, much too far apart for fusion to occur. However, at very high temperatures, the atoms move with enough speed to overcome the mutual repulsion of their nuclei and therefore they do undergo close collisions. They approach more closely the higher the temperature until finally, at millions of degrees centigrade, fusion reactions begin to occur at a rapid rate.

While it is possible to observe fusion reactions in the laboratory by accelerating deuterium nuclei to equivalent speeds in a particle accelerator, this cannot produce net power because the accelerated nuclei will preferentially slow down by colliding in cold matter rather than undergoing fusion. Thus, it has been thought that the way to create useful fusion energy is to recreate on earth the high temperatures found in stars. A major effort toward this goal has been underway for three decades.

The idea that palladium or titanium might catalyze fusion stems from the special ability of these metals to absorb large quantities of hydrogen (or deuterium), the hope being that deuterium atoms would be close enough together to induce fusion at ordinary temperatures. The special ability of palladium to absorb hydrogen was recognized in the nineteenth century. In the late nineteen twenties, two German scientists, F. Paneth and K. Peters, reported the transformation of hydrogen into helium by spontaneous nuclear catalysis when hydrogen is absorbed by finely divided palladium at room temperature. These authors later acknowledged that the helium they measured was due to background from the air.

In 1927, Swedish scientist J. Tandberg claimed that he had fused hydrogen into helium in an electrolytic cell with palladium electrodes. On the basis of his work he applied for a Swedish patent for "a method to produce helium and useful reaction energy". After deuterium was discovered in 1932, Tandberg continued his experiments with D_2O. Due to Paneth and Peters' retraction, Tandberg's patent application was denied eventually [PAN].

In fact, even though palladium can store large amounts of deuterium, the deuterium atoms are still much too far apart for fusion to occur in normal theories. Actually, deuterium atoms are closer together in D_2 gas molecules, which do not exhibit fusion. The closest deuterium-deuterium distance between deuterons in palladium is approximately 1.7×10^{-1} nanometers. This distance is large compared to the bond distance in D_2 gas molecules of 0.74×10^{-1} nanometers (Section IV).

The discrepancy between actual atomic spacings versus what is required for fusion to occur is not a small matter. The spacing requirement is mitigated by the quantum mechanical phenomenon of tunneling whereby nuclei at greater nominal separation may sometimes exist at very small separations, albeit very rarely. Even so, theoretical calculations indicate that a separation distance 1/10 normal

[[7]]

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atomic spacings would be required to obtain a measurable fusion rate for palladium saturated with deuterium at a density roughly like that of the solid palladium. However, as ordinary experience shows, compressing solid matter 10-fold in length--a 1000-fold reduction in volume--would require enormous pressures. The effective "pressure" binding atoms in metals is orders of magnitude weaker (see Section IV).

These theoretical considerations apply both to the claims of excess heat and also to the more modest claims, first from Brigham Young University, that neutrons near background levels had been observed in D_2O electrolysis experiments, and later in pressurized D_2 gas experiments. These latter claims concerning neutrons correspond to only 0.1 neutron per second, 10^{12} times less than would be needed to explain measurable heat. On the other hand, even such a slow rate of neutron production is at least 10^{40} times theoretical expectations (see Section III).

Finally, we note that the Panel has not considered the well established and reproducible process of muon catalysis, itself sometimes called cold fusion. The muon, first discovered in cosmic rays in the 1940's, is an elementary particle with a mass 207 times that of an electron. In muon catalysis, the heavy, negatively-charged muon acts like a heavy electron in binding deuteron pairs at close enough spacing for fusion to occur. As presently understood, muon catalysis will not produce net energy in competition with the power required to produce the muons (too few reactions before the muon sticks to a helium nucleus made in the process).

The calorimetric measurements of heat are discussed in Section II. The claims of observations of fusion products are discussed in Section III. Materials properties relevant to palladium and other metals used in cold fusion experiments are discussed in Section IV. Conclusions and recommendations are given in Section V.

[[8]]

II. CALORIMETRY AND EXCESS HEAT

The claim for electrochemically charged palladium cells as prospective energy sources rests on reports by several groups of "excess heat" (or, more precisely, excess power) that cannot be accounted for in the thermal balance normally applied to water electrolysis. A number of other groups that have carried out calorimetric experiments In similar cells under a wide variety of conditions have found no excess heat.

The early chronology of reports on calorimetry in these electrochemical cells is outlined in Appendix 2.A. A summary of the results in published papers and manuscripts submitted or in press available to the Panel, is contained in Table 2.1. We also received a number of internal reports and private communications that were useful in assessing the question of excess heat. These varied widely with respect to number of trials, quality of data, number of control experiments, and types of cells and calorimeters (see Appendix 2.B). Many were considered by their contributors to be preliminary or interim reports, and in several, the results were ambiguous or inconclusive. These are listed in Table 2.2. Because it was difficult in most of these cases to examine the experimental procedures and results in detail, the quantitative results are not included in Table 2.2. The written reports from the national laboratories and others made available to the Panel are on file.

Among the issues the Panel addressed in examining published reports, assessing private communications, and in site visits were whether the power levels themselves are being accurately measured and whether the reactions being considered in these cells are, in fact, satisfying the chemical assumptions made. These heat measurements have been done with calorimetry that varied as to the technique and to the levels of precision and accuracy. In most cases calorimetric effects attributable to excess heat are small. The calorimetric measurements are difficult to make and may be subject to subtle errors arising from various experimental problems [SHE].

For the purposes of this report, the calorimetry is usefully differentiated as to whether the D_2 and O_2 gases are allowed to exit the cell completely unreacted (open cells) or are intentionally catalytically recombined to regenerate D_2O and to recover the corresponding heat (closed cells).

In the case of open cells, where the gases are assumed to be vented without reaction, any output power (as heat) greater than the electrical input power minus the power equivalent of the D_2O formation enthalpy [1.527 V (volts) x I (cell current)] is considered excess, a result reported by several groups. In closed cells with total recombination (and with a deuterium-charged Pd electrode), the total electrical power in and total heat power out would normally balance (as for Pt and Pd electrodes in light water). At present, most experimenters who have performed calorimetry with closed cells under strict recombination conditions have reported no excess heat. Another important point is that most of the reported excess heat measurements are actually power measurements, and the data in most experiments have not conclusively demonstrated that the total amount of energy produced (as heat and chemical energy) integrated over the whole period of tell operation exceeds the total electrical energy input.

Since the claimed excess heats have, in most cases, been of a magnitude significantly less than the 1.527 V x I factor itself, issues of calibration, reliability, and support of the assumptions of zero recombination in open cells are especially critical. The Panel's site visits have identified experimental

[[9]]

uncertainties, e.g., nonlinearities of the calibration in power output vs. temperature, time dependence of calibration, and doubtful accuracy of data acquisition relative to the magnitude of the effects asserted (Appendix 2.C). Even in laboratories that report excess heat, this effect, under apparently identical conditions, is not always reproducible. Moreover, in most cases where groups reporting excess heat have supplied complete cells or materials to other laboratories, excess heat effects have not been confirmed. In none of our visits to the different sites did we see an operating cell that was claimed to be producing excess heat at that time.

It is difficult to account for the widely divergent findings of excess heat. The failure to observe excess heat has been attributed by proponents to differences in materials (especially the Pd and D_2O), size of electrodes, insufficient time of electrolysis and too small current densities, as well as to unknown effects of adventitious impurities or special, still unknown electrode surface conditions. However, examination of the results of those reporting positive effects (Table 2.1.A) shows that a wide variety of Pd from different sources has been used. There is a similar variation in the number of sources and batches of D_2O. Current densities as low as 8 to 64 mA/cm2 have been reported to produce excess heat, and much higher current densities than these have been used in cells yielding negative results (Table 2.1.B). While very long electrolysis times have been required to produce excess heat effects in some laboratories, several have reported excess heat effects with electrodes of similar size that begin after a few hours of electrolysis. At this time we cannot find clear differences in materials, cells, or operating conditions that can account for the widely irreproducible behavior.

After assessing the reports from the different laboratories, considering the experimental difficulties and calibration problems, as well as a lack of consistency and reproducibility in observation of the excess heat phenomenon, we do not feel that the steady production of excess heat has been convincingly demonstrated.

However, there are reports of sporadic temperature "excursions" or "bursts" that apparently represent power outputs significantly larger than the input power. These events cannot be attributed to problems with accuracy or calibration alone and are presently not understood (see Appendix 2.D).

[[10]]

Table 2.1.A

SUMMARY OF CALORIMETRIC RESULTS:[a] GROUPS OBSERVING EXCESS HEAT

(Published reports, manuscripts submitted or in press)

	Research Group	**Calorimeter, Cell**[b]	**Pd type, source**[c]	**Current Density, Voltage**	**Excess Heat**	**Controls**[d]	**Comments, References**
1.	Univ. of Utah Fleischmann, Pons et al.	ISO A, open	JM, rod, sheet, cube	8, 64, 512 mA/cm^2, 3-10 V	5-111% (9 cells)	none	n,t [FLE]
2.	Texas A&M Univ. Appleby, Srinivasan et. al.	ISO-C (Tronac) Open	Alfa, Wire	0.3, 0.6, 1.0 A/cm^2, 3.4-5.6 V	6-30%	H_2O, Pt	[APP]
3.	Stanford Univ. Huggins, Gur et al.	ISO A, Open	Disks (arc melted)	10-1000 mA, 3-15 V	10-30%	H_2O	[BEL]
4.	Texas A&M Univ. Bockris et al.	ISO A	H&S, Rods (Ni anode)	100-500 mA/cm^2	5-25% (3 of 10 cells)	Pt	[KAI]
5.	U. Minnesota, Oriani et al.	ISO-C, Open	Jm[e], Rod	0.6-1.6 A/cm^2	2-21% (2 of 3 cells)	H_2O	[ORI]

[[11]]

Table 2.1.B

SUMMARY OF CALORIMETRIC RESULTS:[a] GROUPS NOT OBSERVING EXCESS HEAT

(Published reports, manuscripts submitted or in press)

***NCAS EDITOR'S NOTE:** This table was originally spread over two pages. In the interest of readability, the page break has been omitted.*

	Research Group	**Calorimeter, Cell**[b]	**Pd type, source**[c]	**Current Density, Voltage**	**Excess Heat**	**Controls**[d]	**Comments, References**
1.	U. British Columbia, Hayden et al.	Flow, Closed	Englehard, Bars	to 2.2 A/cm^2	none (10 d)	Pt	[HAY]
2.	M.I.T., Wrighton et al.	ISO B, Open	JM/Aesar, Rods	69 mA/cm^2, 2.9V	none (> 200 h)	H_2O	no t, n [ALBA]
3.	Cal Tech, Lewis et al.	ISO B, ISO C (Tronac), open	Several Rods	72-140 mA/cm^2	none (5 cells)	H_2O	no t, n, He [LEW]
4.	Naval Weapons Ctr. Miles et al.	ISO, Open	JM/Wesgo, Rods	100-200 mA/cm^2, 3.5 V	none (1-10 d)	Pt, H_2O	no n, gammas [MIL]
5.	Sandia N.L. Roth et al.	ISO A, Open	Rod & Pd/Li alloy	320 mA/cm^2	none (17d, 36d)		no n, t [ROT]
6.	AT&T Bell Labs, Fleming, Law et al.	ISO C (Setaram), closed&open	Several wire, rod	16-512 mA/cm^2, 2-10 V	none (1-40 d)	Pt, H_2O	[FLEM]
7.	Argonne N.L. Redey et al.	ISO B, ISO C, Open	JM, Rod	15-500 mA/cm^2	none (460 h)	H_2O	[RED-1]
8.	Free U. Berlin, Kreysa et al.	ISO A, Open	Rod, sheet	1.2 A, 9 V	none (circa 10 cells)	H_2O	no n, t, gammas, [KRE]

9.	EG&G Idaho, Longhurst et al.	ISO A, ISO C, Open	Foil, wire	0.1ma-5.7A, 3.3-5.1 V	none (> 20 cells) (120 h)	H_2O	no n,t, gammas [LON-1]
10.	Iowa St. U. Hill et al.	open	Rod	0.7-1 A/cm^2	none		no n, gammas [HIL]
11.	U. Newcastle-upon-Tyne, Armstrong et al.	flow, open	Sheet, Cube	100 mA/cm^2, 15-20 V	none (8 d, 2 cells)	Pt(H_2O)	[ARM]
12.	Harwell Lab. Williams et al.	ISO A, ISO C-type, Open	JM, Rod, cast, Beads. Ribbons	20-530 mA/cm^2, 3-15 V	none (11 cells, to 33 d)	H_2O, Pt (14 cells)	no n, t, gammas [WIL]
13.	Chalk River Nuclear Labs, D.R. McCracken et al.	Flow, closed	JM, Rod	150-300 mA/cm^2	none (2 cells) (18d, 47 d)		no n, t [MCC]

FOOTNOTES (Tables 2.1.A and 2.1.B):

a

Solutions were LiOD (usually 0.1 - 0.2 *M*) in D_2O. Anodes were generally Pt.

Open cells: excess heat = measured heat + 1.53 I - power in.

Closed cells: excess heat = measured heat - power in.

% excess heat = (excess heat/power in) x 100

Sometimes % excess heat = excess heat/(power in - 1.53) 100 is used.

b

See Appendix 2B

c

JM, Johnson-Matthey; H&S, Hoover & Strong.

The Pd was obtained from manufacturer in various forms (drawn, cast. cold worked...) and subject to no further pretreatment, vacuum degassed, vacuum annealed, arc melted, preanodized, or recast, in both experiments finding excess heat and those yielding negative results.

d

H_2O indicates substitution of H2O for D2O and usually LiOH for LiOD in cell . Pt indicates substitution Pt for Pd.

e

Electrolyte was 0.1 M LiOD reacted with excess D2SO4.

One Pd sample was a 0.1 cm rod obtained from Texas A&M University.

[[12]] [[13]]

Table 2.2

Internal and Unpublished Reports and Private Communications on Calorimetric Results

(Experimental conditions generally the same as those in Table 2.1.)

A. Groups Observing Excess Heat or Bursts in Some Cells

1. U. Landau - Case-Western Reserve University
2. E. Yeager, B. Cahan, R. Adzic - Case-Western Reserve University
3. D. Hutchinson - Oak Ridge National Laboratory
4. C. Scott - Oak Ridge National Lab.
5. A. Schoessow - University of Florida
6. B. Liebert - University of Hawaii
7. T. Droege - Batavia, Illinois
8. G. Balding - Nytone Electronics
9. H. T. Hall, Jr. - Novatek
10. M. Wadsorth - University of Utah
11. M. McKubre - Stanford Research Institute

B. Groups Reporting No Excess Heat

1. C. Martin, B. Gannom, K. Marsh et al. - Texas A&M University
2. S. Gottesfeld - Los Alamos National Laboratory
3. S. Little et al. - Austin, TX
4. 0. Bennion - Brigham Young University
5. W. Ayers - Electron Transfer Technologies

6. R.P. Allen, J.R. Morrey et al. - Battelle Northwest DOE Laboratory
7. T. R. Jow, E. Plichta et al. - U.S. Army ETDL
8. H. W. Randolph - Westinghouse Savannah River 'kite
9. H. Weissman - Brookhaven National Laboratory
10. P. Ross - Lawrence Berkeley Laboratory
11. F. Wagner - General Motors Corp.
12. J. C. Farmer - Lawrence Livermore National Laboratory
13. E.L. Fuller, Jr. et al. - Oak Ridge National Laboratory

[[14]]

III. FUSION PRODUCTS

A. INTRODUCTION

The nuclear fusion of deuterium has been studied intensively for over 40 years. The reaction between two low energy deuterium nuclei has been observed to proceed in three ways:

(a) D + D -->^{3}He (0.82 MeV) + n (2.45 MeV)

(b) D + D -->T (1.01 MeV) + p (3.02 MeV)

(c) D + D -->^{4}He + gamma (23.85 MeV)

The reactions (a) and (b) have been studied down to deuteron energies of a few keV and the cross sections (production rates) found to be equal to within 10%. In the interaction of deuteron beams with heavy ice or metal deuteride targets, almost one 2.45 MeV neutron is produced (with an accompanying ^{3}He for every triton (with an accompanying proton). This near-equality of neutron and proton branches (production rates) of the D+D reaction, shown in Figure 3.1, is a reflection of the basic symmetry of nuclear forces between proton and neutron, disturbed only slightly at the MeV energies of the emerging particles by the Coulomb interaction, which is not symmetrical between proton and neutron. The cross section (production rate) for reaction (c) is on the order of 10^7 lower than the first two reactions.

All nuclear reactions at low energies between two deuterons are retarded by Coulomb repulsion between the positively charged nuclei--the penetration of the repulsive Coulomb barrier changes rapidly with bombarding energy: for instance the measured cross section for reaction (b) changes from 0.2 microbarns at 2.7 keV to 35 millibarns at 100 keV. But the ratios for the three reactions appear to be constant below 100 keV.

Any fusion between deuterium nuclei must lead to detectable fusion products. For reaction (a) neutrons are the most easily detected product, by direct counting. For (b) the protons or tritons can be detected by direct counting, and the accumulated tritium could also be identified by its radioactivity, albeit with lower sensitivity for few-hour or few-day experiments, in view of the 12-year half life of T. Neutron counting is perhaps again the most useful technique, since neutrons must be produced by the energetic tritons interacting with deuterons in the material at the expected rate of 1 neutron for every 10,000 to 50,000 tritons. Reaction (c) leads to readily detectable high energy gamma rays and ^{4}He; the latter may be identified by mass spectroscopic measurements, whose sensitivity is low--though the 10^{11} levels implied by 1 watt of heat should be readily observable.

In the following we summarize the experimental evidence on these fusion products. First we discuss the plausibility of reactions at room temperature and the issue of whether the constancy of the three reaction modes is a reasonable extrapolation to such low energies. Then the data on neutrons, charged particles, gamma rays and tritium are summarized. Finally, some comments are included on unconventional explanations, and geochemical evidence is summarized on proposed cold fusion in the interior of the earth.

We have used published material, where available, or material prepared For publication and presented at formal meetings or as preprints distributed without restriction as to citation. We have also benefited from data submissions in response to Panel questions and from reports from the national laboratories, all of which are available to the public in the DOE reading room. It is important to include not only positive results, that claim the detection of fusion products, but also the negative ones, that have attempted to replicate the experimental procedure of the former and failed to detect anything above background, at a level of sensitivity substantially better than the positive results.

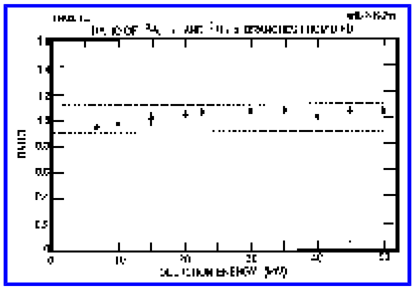

Figure 3.1: Neutron & Proton Branches of the D+D Reaction

Click on thumbnail to see full-size image.

[[16]]

B. THE REACTION PROCESS

Fusion reactions can occur only if during a nuclear collision, the Coulomb barrier is surmounted or, at low energies, penetrated so that the nuclei approach each other within about 10^{-5} nanometers. This distance is some 10,000 times smaller than the typical separations of atoms in ordinary matter. The penetration of the barrier at low energies takes place through a well-understood quantum mechanical phenomenon called tunneling that allows fusion to occur in collisions far less violent than might be required otherwise.

In the thermonuclear fusion that occurs in stars and in laboratory "hot fusion" experiments, high temperatures, (tens of millions of degrees or more) provide 'he violent collisions required to produce fusion. However, in the cold fusion interpretation of the experiments, it is claimed that the penetration of the barrier through quantum mechanical tunneling has become so effective as to allow fusion to occur even at room temperatures. Further, some experimenters claim that the nuclear process is changed by an unspecified mechanism so as to alter dramatically the nature of the reaction products. Each of these claims must be understood as separate and equally surprising.

Some simple calculations illustrate how remarkable is the claim of fusion at room temperatures. The fusion rate for the two deuterium nuclei in a deuterium molecule (where their separation distance is even closer than when embedded in a metal) results in one fusion per year in a solar mass of deuterium. Further, the fusion of protons and deuterons is calculated to be 10^9 times faster than the D&@nbsp;+ D reaction (although it is still extraordinarily slow). No mechanism is known by which these rates could be enhanced by the 40-50 orders of magnitude required to agree with the reported observations.

One mechanism invoked for enhancing cold fusion rates is screening the electrostatic repulsion by "heavy" electrons. Endowing the electrons with a hypothetical mass would indeed enhance fusion rates sufficiently to agree with most cold fusion claims [KOO]. It is also true that there are "heavy fermion" materials whose thermodynamic properties at very low temperatures are characteristic of quasiparticles with masses many times those of a free electron. However, this phenomenon is understood as involving long-wavelength Extcitations in which strong correlations modify the electron wave function near the Fermi surface. As such, heavy fermions extend over many lattice sites. Because the tunnelling in nuclear fusion occurs at distances smaller than one lattice site, only the short-wavelength "bare" electron excitations are relevant for screening, and cannot enhance the fusion rate significantly.

[[17]]

B.1. The D + D Branching Ratios

The relative rates of reactions (a), (b), and (c) are called the branching ratios and are a crucial issue in the discussion of some cold fusion claims. These reactions have been studied in laboratory experiments using accelerators for deuteron energies above a few keV [KRA]; the smallness of both the reactions (a) and (b) cross sections prevents reliable measurements at lower energies. The ratio between these two rates exhibits a weak energy dependence and is near 1.0 at the lowest energies, as seen in Figure 3.1. Data from muon-catalyzed D + D fusion [BAL], which probes an even lower energy range, is still consistent with nearly equal rates.

A change in the known branching ratios of more than one million, in favor of reaction (b) over reaction (a), would be required to explain experiments that claim to observe high fusion rates (either through heat or tritium production) without a corresponding high neutron flux. As cold fusion is thought to occur at energies on the order of a few electron volts (eV), this is not directly ruled out by the data discussed above. However, no mechanism is known for inducing such a rapid energy-dependence in the branching ratio. The Oppenheimer-Phillips process involving the Coulomb break-up of the deuteron has sometimes been invoked in this regard. However, this process is not effective at low energies in the D + D system.

B.2. The Gamma Branch.

Some researchers have hypothesized that the D + D --> ^{4}He + gamma (23.85 MeV) reaction, which is ordinarily some 10^{7}times weaker [BARN] than reactions (a) and (b) in which two fragments are produced, somehow dominates in cold fusion situations. To be consistent with the lack of neutrons, a very large enhancement of the gamma branch by a factor somewhere in excess of 10^{13} would be required. We know of no way whereby the atomic or chemical environment can effect such an enhancement, as this ratio is set by nuclear phenomena and is on a length scale some 10^{4} times smaller than the atomic scale.

If there were such an enhancement, high-energy electromagnetic radiation (photons, positrons, or fast electrons) would be observed. While direct coupling to the lattice through unspecified mechanisms has been invoked to suppress such radiation, any such coupling must occur through the electromagnetic field and would result in some observable high-energy radiation.

B.3. Anticipated Secondary Yields from Fusion Products.

i. **Neutrons from tritium**. The tritons produced in reaction (b) have an energy of 1.01 MeV. This energy must be lost in the immediately surrounding material, which in an electrolytic cell is either the Pd electrode saturated with deuterium, or heavy water. The tritons have insufficient energy to cause nuclear reactions with Pd.

However, they will also bombard the deuterium in the surrounding material. The T + D reaction is a rich source of 14-MeV neutrons, with a cross section that reaches 5 barns (i.e., 5x10^{14}cm^{2}) at 0.12 MeV, then falls to about 0.7 barns at 0.5 MeV, and reaches slightly below 0.3 barns at 1 MeV. For the 1.01 MeV tritons from the D + D reaction an average cross section is about 1.2 barns. For tritons that are stopped in PdD this translates into a neutron yield between 1.5 and 2x10^{-5} neutron per triton; for tritons stopping in heavy water there are about $9x10^{-5}$ neutron per triton.

ii. **Coulomb excitation of Pd by protons.** The even Pd isotopes (104, 106. 108, 110) with abundances of 11, 27, 26, 12% have first-excited 2-states at 555, 512, 434, 374 keV and cross sections between 0.5 and 0.8 barns. The cross sections for Coulomb excitation are in the vicinity if 20 to 50 millibarns and thus the yields of gamma rays expected are 2 to $5x10^{-6}$ per proton. In palladium the half thickness for absorption oF these gamma rays is about 4 mm, in water it is several cm.

In terms of power, there must be about 10^8/sec secondary (14 MeV) neutrons per watt of fusion, even if direct neutron production (reaction a) is completely suppressed and all the reaction goes into tritium production (reaction b). Under these conditions there must also be slightly under 10^7 secondary gamma rays per second, of well defined energies, in the 500 keV range.

B.4. The p + D Reaction

It has been suggested that an alternative fusion process could be the reaction

$p + D \to {}^3He$ + gamma (5.49 MeV)

for which the gamma ray production (observability) factors are still overwhelmingly small at room temperature, but somewhat less so than for the D + D process [KOO]. This reaction produces a readily observable gamma ray and if it is to account for 1 watt of heat, then it should also produce ${}^3He$ in observable concentrations.

C. NEUTRONS

C.1. Detection.

Neutrons are a major product of D + D fusion. Neutrons are convenient particles to detect, since they interact only with the nuclei of atoms and so can emerge from reaction vessels of substantial size unscathed and without having lost energy. Similarly, large counters can be used without the problem of thin entrance windows, since neutrons enter into the volume of the counter without difficulty. Some simple facts about neutron detection are summarized in Appendix 3.A.

[[19]]

C.2. Initial Claims

The University of Utah (UU) group in its initial publication (FLE] claimed the detection of neutrons from D + D by virtue of the gamma ray emitted by the capture of the moderated neutron in the water bath surrounding the electrolytic cells. A narrow peak in the pulse-height spectrum from the NaI scintillator was published, narrower than is possible with this type of detector, and with internal inconsistencies in the energy scale as pointed out by a group at MIT [PET]. The photopeak at 2.2 MeV obtained at MIT from ^{252}Cf spontaneous fission neutrons moderated in water and radiatively captured on protons is accompanied by other peaks from natural background that enable one to calibrate the energy. Successive interchange between UU and MIT groups in the scientific literature has demonstrated that the claimed detection of neutrons by the proton capture gamma ray at UU was an artifact of the experimental apparatus.

The original publication from Brigham Young University (BYU) [JON-1] presented the detection of neutrons as experimental evidence for the existence of cold nuclear fusion. The neutrons were detected in a two-stage neutron counter--first by the proton recoil in organic scintillator, followed within a few tens of microseconds by a signal from the capture of the moderated neutron on boron viewed by the same photomultipliers. This double detection of a single neutron serves substantially to reduce the ambient background due to gamma rays, although there remains background in the experiment due to gamma rays and to real neutrons from cosmic rays and other sources.

BYU has been working in collaboration with other groups, notably at Los Alamos National Laboratory (ME4], and also with a group at Yale University. The original claim of neutron detection five standard deviations above the background is somewhat reduced in statistical strength if one considers the degrees of freedom that are fixed by the presentation of a peak in one of a number of experiments and at a particular energy, and also the possible fluctuation in the cosmic-ray neutron background. Ordinarily, however, such a result can be improved through improved shielding or by moving to an underground site. Another group at BYU [PIT] electrolyzed 3 M LiOD on Pd cathodes and detected about 2.1x10^{-3} counts per second as compared to 1.2x10^{-3} for light water cells.

Typical of the experiments with greater sensitivity is work by the group at Sandia National Laboratory [SCH], in which a site was found with substantially less background and results presented for a limit on neutrons produced in electrolytic fusion. Similar results from the Frejus tunnel in France were also presented in Santa Fe [DEC]. However, in a BYU collaboration at the Grand Sasso Laboratory deep underground [BER] involving "electrolytic infusion of deuterons into titanium" cathodes, the detection of 350±51 counts of 2.5 Mev neutrons

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*Care is needed as the rate of cosmic ray neutrons can fluctuate by 20% or more with variations in barometric pressure or with solar activity.

indicates consistency with their initial results, though unfortunately their background is 100-1000 times higher than previous measurements of the neutron level in the Grand Sasso Laboratory [ALEK] so that the excess neutron yield reported is still comparable to the background and the advantages of the underground site are not fully realized.

At the Santa Fe workshop, Moshe Gai of Yale presented results obtained in collaboration with Brookhaven National Laboratory, in which no neutrons were detected from electrolytic cells above the detection limit of 10^{-25} n per D-D pair/sec [GAI]. In a recent @preprint Salamon et al. from the University of Utah [SAL] report measurements of neutrons in the Pons Laboratory over 67 hours with several electrolytic cells operating. They observed no neutrons above background and quote a limit of 1 neutron per second emitted by any of the cells, comparable to the limits in Table 3.1.

Many claims have been made for the production and detection of neutrons produced in electrochemical cells, but these claims have mostly been withdrawn or moderated by the discovery of difficulties with the counter--particularly with the BF counters used. Some counters are sensitive to humidity; others to microphonic noise (vibration), or to other afflictions. Some results on reported neutron fluxes, compared to the flux reported by the BYU group, are summarized in Table 3.1.

C.3 Dry Fusion.

Results presented in April 1989 by a group at Frascati (DEN] opened a different area of investigation for the study of D + D cold nuclear fusion. In this work, deuterium gas at 60 atmospheres pressure was allowed to contact titanium lathe turnings in a stainless steel reaction vessel, and the temperature of the sample was varied either by heating or by cooling. No neutrons were observed from the hydriding reaction, at room temperature or at elevated temperature, when viewed by a nearby BF counter. However, after cycling to liquid nitrogen temperature (77°K) bursts of counts were observed--typically on the order of 20 counts per burst over a period of 60 microseconds. One set of counts, obtained by cycling to nitrogen temperature, shows neutrons mainly in these bursts.

A different type of neutron emission was also claimed by the Frascati group [DEN] following warming from nitrogen temperature over one weekend. The observed count rate follows a bell-shaped curve, rising to a peak of 300 neutrons per 10-minute counting interval, over some 5 hours. These important experimental results provoked great effort toward verification, both at Frascati and elsewhere. A recent personal communication from M. Martone at Frascati indicates that neither the burst results nor the continuous neutron emissions from the D-Ti system or from any other dry fusion activity at Frascati have been confirmed. In addition, electrochemical cells produced no observable neutrons, and their operation was terminated in July.

A group at LANL [MEN] has conducted dry fusion work with Ti and Pd, and has presented results both at the Santa Fe meeting and in a preprint. This group at LANL uses high-efficiency systems that moderate any fast neutrons emitted from experimental cells, detecting the moderated thermal neutrons in ^{3}He gas counters. Some bursts of neutron counts are observed 3000-5000 seconds after the sample

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is removed from liquid nitrogen, at sample temperatures of about -30°C. These bursts, of up to 100 neutrons, are seen in about 30% of the samples tested. An attempt to reproduce this effect at Sandia National Laboratory yielded negative results [BUT].

In a very recent report, a Yale-BYU-BNL collaboration using a different detection scheme, with multiple liquid scintillation counters with an overall efficiency essentially the same as that of the Los Alamos group, and incorporating counters to monitor cosmic ray showers, has examined four cells with conditions reproducing those af the Los Alamos experiment [RUG]. They see no bursts larger than five neutrons in 103 hours of temperature cycling with these cells. Two bursts of five were seen in background runs, and two more in the runs with the pressurized Ti-O cells, all of them coincident with cosmic ray events.

Finally, a conference report [IYE] from the Bhabha Atomic Research Center [BARC] in India provides text and tabulated results from several groups at BARC. Fig. 1 of the BARC report shows counts from neutron detectors observing a large electrolytic cell, with an estimated 2×10^7 neutrons in the 5 minutes following an overpower trip of the electrolyzer. Tritium and neutrons are observed at BARC from cathodes fabricated of PdAg alloy as well as from pure Pd.

Figure 2 of the BARC report shows dry fusion ^{3}He neutron-counter output during a gradual increase of temperature of 20 g of Ti while deuterium gas was being pumped off. It is also commented that samples could be loaded with deuterium gas at 1 atmosphere and 900°C, and that "one such disc shaped button loaded on Friday 16th June began emitting neutrons on its own, almost 50 hours after loading. It produced (about) 10^6 neutrons over an 85-minute active phase. The background neutron counter did not show any increase in counts over this time."

C.4. Fracto-Fusion.

In 1986 a group at the Institute of Physical Chemistry in Moscow reported that when a single crystal of LiD was Fractured by a device powered by an air gun, a few neutrons appeared to be produced [KLU]. These were attributed to internal fields associated with fractures in the material. Recently the same group reported that when titanium chips were agitated in a drum with heavy water and deuterated polypropylene, using steel balls and vibration at 50 Hz, neutrons were observed for a few minutes at a rate of 0.31 ± 0.13 counts/sec [DER]. After a few minutes no neutrons were seen.

Neutron emission during plastic deformation of deuterium-containing solids under pressure is reported by Yaroslavskii [YAR] from "rheological explosions" induced by rotating the anvils of a press on a rock sample to which grains of beryllium bronze and D_2O have been added. Typically, 1000 pulses are detected in a burst, interpreted by the experimenter as arising from 10^6 neutrons.

These effects are not fully understood at present, the experiments are difficult and need to be repeated by others. If confirmed, a quantitative understanding of such effects could lead to interesting physics. The scale of energy in internal field experiments is still orders of magnitude higher than the one relevant to cold fusion.

[[22]]

C.5. Secondary Neutron Yields

There are problems of consistency between the numbers of tritium atoms detected in some of the experiments discussed above and the number of neutrons. The BARC abstract reads, "The total quantity of tritium generated corresponds to about 10^{16} atoms suggesting a neutron to tritium branching ratio less than 10^{-8} in cold fusion." But, as discussed above there should be at least one neutron per 10,000 tritons, if the observed tritium were originating from fusion. Hence the neutron yield is 1000 times less than expected.

C.6. Summary

All the experimental measurements of neutrons associated with cold fusion give upper limits that are much smaller than that consistent with the reported excesses of heat production if resulting from D + D fusion.

D. DIRECT DETECTION OF CHARGED PARTICLES AND GAMMAS

D.1. Charged Particle Searches

A few experiments [POR, PRI, REH, SUN] to measure the 3 MeV protons and/or the 1 MeV tritons produced in the reaction, D + D -- T +p, have been reported; they are summarized in Table 3.2. A variety of different methods has been used, but the lowest limit on charged-particle production appears to be that set by Price using plastic track detectors. Their setup was designed so that the light water control cell matched the heavy water cell as closely as possible. Electrolysis was performed for 13 days, and the cathode stoichiometry was determined to be H(D)/Pd = 0.8.

Both cells showed track production rates that were consistent with the alpha-particle emission rate for native Pd foils due to trace (ppm) impurities of the natural ^{238}U and ^{232}Th decay chains; however, no tracks due to protons with energies between 0.2 and 3 MeV or tritons with energies between 0.2 and I MeV were found. From these data Price [PRI] set limits on the fusion rate of less than 0.002 per cm^3 per second. This value results in an upper limit of 8.3x10^{26} fusions per D-D pair per second. This is about an order of magnitude lower than the limits obtained using Si surface barrier (SSB) techniques.

A limit on the fusion rate of 0.028 per cm^3 per second or 1.2x10^{-24} fusions per D-D pair per second was obtained by Ziegler [ZIE] using a SSB technique. Porter [POR] used a SSB detector to view the back of a 76 micron thick Pd foil cathode in a heavy water electrolysis cell. They obtained an upper limit of 6x10^{-25} protons per D-D pair per sec at the 2 sigma level; chemical analysis of their electrolytes showed no evidence for anomalous increases in tritium concentrations.

Sundqvist et al. [SUN] also used a SSB technique to detect protons. The detector was placed close to Pd foil cathodes that were thin enough to allow all the protons produced to escape from the foil. All of their runs gave a null result within the statistical errors, resulting in a fusion rate of -2.1 (±2.2)x10^{24}, if a bulk process is assumed.

[[23]]

Recently, Rehm [REH] has reported using a proportional Counter to search for charged particles from electrolytic cells with Pd and Pt electrodes in 0.1 M LiOD in D_2O. They obtained an upper limit of 4x10^{-23} fusions per D-D pair per second, not as low as the limits using the other methods.

In summary, a variety of experimental techniques has been used in searches for charged particles; all of them set very low limits on fusion occurring via the D + D --> T + p reaction. Most of these results set limits that are considerably less than Jones' [JON-1] maximum value of 1±0.2 x 10^{-23} fusions per D-D pair per second for the D + D --> ^{3}He + n channel obtained from neutron measurements.

The upper limit of Price [PRI] Of 8x10^{-26}fusions per DD pair per second is below the average rate inferred from the neutron measurements of Jones or even of Menlove [MEN]. The low limits which the searches for charged particles (either protons or tritons) place on their production is thus inconsistent with the reported production of either neutrons or tritium via the cold fusion reaction.

D.2. Gamma-Ray Searches

A rare branch of the D+D reaction proceeds through capture, in which a 23.85-MeV gamma ray is emitted. Similarly, the p+D reaction is associated with a 5.49 MeV gamma ray. In several published searches no gamma rays that would be associated with the D+D or p+D capture reactions were seen. They include a report by Henderson [HEN] who cites limits around 10^{-23}/sec 24-MeV gamma rays emitted per deuteron in various cells. Porter [POR] reports no 5.5 MeV gamma rays--though no absolute limit is quoted. They also comment on the absence of K X-ray production from Pd. Greenwood [GRE] reports limits of 10^{-23} for gamma rays above 1.9 MeV.

Other negative results are quoted in the Santa Fe abstracts without quantitative detail. From the data of Lewis et al., [LEW] it can be calculated that fewer than 4×10^{-25} 5.5-MeV gammas are emitted per second per deuteron in a Pd cathode, and fewer than 2×10^{-23} 24-MeV gammas are emitted per second per deuteron. Negative results from measurements of gamma rays were also reported recently from Utah on electrolytic cells in the Pons Laboratory over 831.5 hours during which several cells were operating [SAL].

D.3. Cluster Ion Fusion.

Another effect reported recently is that of Beuhler et al. [BEU] who accelerated singly charged clusters of D_2O, on the order of 100 molecules, to voltages up to 325 keV onto a deuterated Ti target. They obtained evidence of the D + D --> p + T reaction, and more recently of the n+^{3}He branch, at a rate of about 1 per 10^{11} clusters.

These effects are not fully understood at present, the experiments are difficult and need to be repeated by others. If confirmed, a quantitative understanding of such effects could lead to interesting physics. The scale of energy in cluster ions experiments is still orders of magnitude higher than the one relevant to cold fusion.

[[24]]

E. SEARCH FOR ACCUMULATION OF TRITIUM AND HELIUM

As has already been noted, all D+D fusion reactions produce either tritium or helium. Besides the direct detection of tritium or helium nuclei when they are produced, as discussed above, searches have also been made for the accumulation of tritium or helium gas in some of the palladium cathodes claimed to produce excess heat. These searches for accumulation of tritium or helium are discussed below.

In such experiments it is important to determine the initial tritium content of the heavy water and recognize that the electrolysis of the heavy water will enrich the naturally occurring tritium in the heavy water. Also, it should be noted that the detection of accumulated tritium or helium is generally less sensitive than direct detection. For example, the detection of tritium by measurement of its beta decay is inherently a less sensitive probe of the D+D reaction than the direct measurement of neutron or charged particle production. About 10^7 tritium atoms give 1 decay by beta emission per minute. The tritium content of normal water is about 10^{-18} relative to hydrogen but, as discussed in Appendix 3.B, the normal manufacturing of heavy water also enriches tritium. Heavy water currently being sold gives between 120 and 180 disintegrations per minute per milliliter (dpm/ml) from tritium decay. Thus it is important to determine the initial tritium content of the heavy water and to account for the electrolytic enrichment.

E.1. Null Experiments with no Excess Tritium.

Most reports to date of excess tritium in electrolytic cells can be accounted for by the electrolytic enrichment process. This includes experiments at ANL [3RE, RED-2], BNL [DAV, MCB, WIE], Cal Tech [LEW], CRNL [SCO], INEL [LON-2], LLNL [ALD], NRL [ERI], ORNL [FUL, SCO], Sandia [NAR], SRL [RAN], Texas A & M [MAR], and Utah [WAD, WIL]. The levels of tritium reported by Fleischmann and Pons are also consistent with this interpretation.

E.2. Tritium Bursts.

A few experimenters report occasional irreproducible amounts of excess tritium in D_2O samples from their electrolytic cells after days of operation. This includes observations by Storms [STO] at Los Alamos, and Fuller [FUL] and Scott [SCO] at Oak Ridge National Laboratory (ORNL). The ORNL experiments show single cases of excess tritium of short duration, after which a cell returns to background level. Storms reports excess tritium, 100 times background, in two cells out of 70.

E.3. Closed Cells - Correlation with Excess Heat.

Four groups [MCB, MCC, SCO, MAR] have looked for tritium production in closed electrolytic cells. The initial tritium in the cell is that contained in the heavy water, and any contained in the electrodes. These experiments detect the excess tritium generated from the electrolytic process except for that which may be contained in the Pd cathode. In general, the deuterium inventory in the cathode is negligible compared with the D_2O. Only that tritium formed within the cathode and which remains there because of slow diffusion is unaccounted for. In these experiments the total excess tritium formed in the D_2O is less than

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10^4 T atoms/sec. If this tritium is produced by the D+D reaction, then the maximum excess power (cold fusion power) is 10 milliwatts. In one experiment [WAD] in an open cell there was a heat burst reported of 35 watts for 90 minutes (187,000 joules). No excess tritium above the electrolytic enrichment was measured after the burst. Clearly the heat burst does not come from the D+D reaction.

E.4. High Levels of Tritium.

Two groups [PAC, IYE] find tritium at levels of 10^{12} to 10^{14} T atoms/ml D_2O after periods if electrolysis of the order of hours. This amount of tritium cannot be produced by electrochemical enrichment with the D_2O volume reductions reported. The results of the Bockris [PAC] group at Texas A&M for cells in which excess tritium was found are given in Table 1 of their paper. Excess tritium is not found in all of their cells. A listing of cells in which no excess tritium was found is given in their Table 4. The Bockris cells are 0.1 M in LiOD and have nickel anodes. They precipitate nickel oxide during the electrolysis; some nickel is also electroplated out on the palladium cathode. In one experiment, A8, the specific activity of the D_2 gas produced by the electrolysis was measured. It is 100 times that of the electrolyte.

Wolf et al [WOL-1] at Texas A&M looked for neutron production in Bockris type cells. An upper limit to the production rate is 1 neutron/second, which is 10^{-10} less that of the tritium production rates reported with similar cells by the Bockris group [PAC]. This large discrepancy from the equal production rates for neutrons and tritons required by the branching ratio in the fusion reaction, discussed in section II.B., is inconsistent by a factor of 10,000 to 100,000, even with the secondary neutrons that must accompany the tritons produced from nuclear fusion.

The most extensive and systematic search for tritium in the electrolysis of D_2O with Pd cathodes has been carried out by Martin [MAR] at Texas A&M. He has used both open and closed cells. His cathodes come from either Johnson & Mathey, a major supplier, or Hoover and Strong, who supplied the cathodes to the Bockris [PAC] group. He has operated cells with Pt, Ni wire and Ni gauze (obtained from Bockris) anodes. In a recent communication Martin has reported that, in a recent cell, tritium has been found at a level approximately 50 times the initial specific activity of the heavy water (cell M-1, Table 1) [WOL-2]. This amount of excess tritium is larger than what can be expected from electrolytic enrichment. Wolf [WOL-2] now concurs with the analysis of this Panel that none of the tritium found in any of the Texas A&M experiments is produced by the known D+D reaction.

The BARC [IYE] group have found amounts of tritium comparable to the Bockris group in the D_2 electrolyte from cells in which electrolysis was carried out for a few days with currents varying between 1 to 100 amperes. There is again a factor of 1000 internal inconsistency between the measured neutron yields and the secondary neutrons that have to be there if this tritium was produced by fusion--even if one assumes a drastic modification of the branching ratio in the D+D reaction.

E.5. Summary of Tritium Results.

Some experiments have reported the production of tritium with electrolytic cells. The experiments in which excess tritium is reported have not been reproducible by other groups. These measurements are also inconsistent with the measured neutrons on the same sample. Most of the experiments to date report no production of excess tritium. Additional investigations are desirable to clarify the origin of the excess tritium that is occasionally observed.

E.6. Searches for Helium.

One branch of the D+D reaction produces ^{3}He and a neutron, while another, more rarely, produces ^{4}He and a gamma ray.

Thus far, there are no reports of accumulated helium, either ^{3}He or ^{4}He. Early reports of helium by Pons and Fleischmann were latter retracted. The Panel has been informed that new measurements of helium have been carried out on palladium cathodes (0.38 gm) provided by Professor Pons to several laboratories. The University of Utah arranged with Battelle Northwest to have five of their Pd electrodes examined for helium. Battelle distributed a portion of each Pd electrode to seven different laboratories. These results, although available, have not yet been released.

Other reported searches for helium have yielded only negative results. These searches involve sensitive mass spectroscopy, for instance by Lewis [LEW]. Both the gaseous products of electrolysis and the Pd electrode were examined. Helium is expected to be trapped in the palladium lattice, so the Pd electrodes were melted after being used in the electrolysis of heavy water and the evolved gases analyzed: no helium was found above a limit of $8x10^{11}$ He atoms per cm^3 of Pd. A similar limit was set by the Harwell (U.K.) group [WIL]. Although such limits are not as stringent as the ones set by direct counting of particles, the levels of helium corresponding to the background are still several thousand times below that corresponding to 1 watt of D+D fusion for one hour.

Searches for helium were made at Lawrence Livermore National Laboratory on palladium cathodes provided by the Texas A&M group (0.017 gm and 0.018 gm). These small wire cathodes were claimed to produce excess heat generation of 40 mW. To the level of $3x10^5$ ^{3}He atoms and $5x10^8$ ^{4}He atoms in the sample, there was no helium generation in the wires. This is many orders of magnitude below the level required with 43 mW of fusion power for 100 hours as claimed [HOL, THO].

F. UNCONVENTIONAL EXPLANATIONS

F.1. D + D Reactions

The data on fusion products, even where positive results are reported, give rates far below those that would be expected from the levels of heat reported in some electrolysis experiments. Some proposals invoke mechanisms where the reaction heat from the D + D --> ^{4}He process would go entirely into lattice heat, rather than a photon [WAL, HAGE]. Analogies have been made with the internal conversion process, and with the Mossbauer effect. Neither of these analogies is applicable to ^{4}He, as discussed in the next two paragraphs.

Internal conversion allows an atomic electron of an excited nucleus to carry off the reaction energy instead of a photon. This process is understood quantitatively--it is dominant in heavy atoms with tightly bound inner electrons and for low energy (less than 1 MeV) photons. In helium the atomic electrons are loosely bound and the photon is 23.85 MeV--there cannot be any appreciable coupling between the photon and the atomic electrons, and internal conversion or any related process cannot take place at anywhere near the rate that would be required. The proposal of Walling and Simons invokes enhancement of internal conversion by electrons of high effective mass appropriate to the solid; as we have discussed above, such band structure effects cannot play the role of real high-mass electrons either in screening at sub-atomic distances or in the internal conversion process at MeV energies. Furthermore, although Walling initially reported ^{4}He in an appropriate amount to explain claims of excess heat, this result was due to atmospheric contamination.

In the Mossbauer effect the momentum of a very low energy (below 100 keV) photon, but not its energy, is taken up by the entire lattice in a coherent mode. The process cannot be relevant to the present process.

More generally, there are numerous reactions analogous to the D+D or p+D fusion process in which gamma rays of comparable energy are emitted from low energy nuclear reactions (thermal-neutron capture gamma rays). The cross sections for capture have been studied carefully and quantitatively; they are essential to the operation of fission reactors. If there were any anomalous processes in which a capture gamma ray were totally suppressed in favor of direct conversion into lattice heat, this would have almost certainly been noticed as a discrepancy in cross sections with major implications for the operation of reactors. After four decades of extensive study of the processes relevant to the operation of fission reactors the possibility is remote that an entirely new process, that could dominate these nuclear reactions, would have remained hidden.

F.2. Other Fusion Reactions

In addition to the D+D and p+D reactions discussed thus far, there are several other nuclear reactions that would be substantially exothermic if they could take place at a reasonable rate at low energy. Among these are deuterons fusing with ^{6}Li, ^{7}Li, ^{16}O, as well as various Pd isotopes. The reaction rates for these processes are again governed by the Coulomb barrier and for fusion at low temperatures this becomes even more overwhelming than for D+D. The process on Li isotopes, where the nuclear charge is three, is relatively the most favorable, but even these would give fusion rates that are enormously suppressed even in comparison with that for the D+D reaction; the rates are some forty orders of magnitude slower. The D + ^{6}Li and p + ^{7}Li reactions would not produce neutrons or direct gamma rays--all the energy would be in alpha particles (^{4}He nuclei), but these in turn would cause Coulomb excitation of the Pd. No such gammas have been seen.

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G. SEARCH FOR PRODUCTS OF COLD FUSION IN THE EARTH

Products of low-level cold fusion have been inferred to be produced by natural geologic processes [JON-1, JON-2]. The ^{3}He:^{4}He ratio is anomalously high in volatile emissions from deep-source volcanoes such as those in Hawaii, Iceland, and Yellowstone [LUP, KUR, MAM]; anomalous T is also suggested by fragmentary data [OST, JON-3], and production of other radiogenic products such as ^{36}Cl have been predicted [KYL]. Although the high ^{3}He values have previously been considered relics from early earth processes, presence of anomalous T or anomalous ^{36}Cl (beyond that due to bomb tests) would be definitive evidence of natural cold fusion deep within the earth. Implications would be major for geophysical problems such as heat-flow modelling, element-distribution with depth, and composition of the Earth's core.

Some isotope geochemists see no evidence for naturally occurring cold fusion [CRA]. However, several government and university labs are searching for evidence of such fusion processes as recorded by volcanic volatile emmissions [JON-3, KYL, GOF, LOC, QUI], independently of laboratory fusion experiments. Such geologic studies could add to understanding the behavior of volcanic emissions. No rigorous results are yet available, but experiments proposed or underway at Brigham Young, Los Alamos, Lawrence Livermore, New Mexico Tech, and the U.S. Geological Survey (Denver) should yield data within 6 months to 1 year.

H. SUMMARY

Careful experiments have been carried out to search for the expected products of cold fusion. The measured products are many orders of magnitude lower than what would be expected from the heat production reported in electrolysis. In many experiments, no products are detected. Some experiments report neutrons or tritium at a much lower level--however, the rates of these two fusion products (measured in the same experiments) are inconsistent with each other, again by large factors. In particular, reported tritium production is accompanied neither by the one 2.45-MeV neutron per T observed in all other low-energy D+D fusion, nor by the 10^{-5} 14-MeV neutron per T that would be produced by the 1.01-Mev T itself in the D-rich environment.

The neutron bursts reported in some experiments are not reproducible by other experimenters, or even by those who report them. While some mechanism might produce small bursts of hot fusion (e.g. high voltage internal fields associated with fracture of the material at certain temperatures), the present experimental evidence is not readily reproducible, and the phenomenon does not appear to be related to cold fusion as postulated in the heat production experiments.

If there were such process as room temperature fusion it would require:

a. a major enhancement of quantum mechanical barrier penetration, which has been extensively tested against measurements (such as the systematics of spontaneous fission and alpha radioactivity lifetimes and those of nuclear cross sections);

2. drastic modifications of branching ratios in the D+D reaction; and

3. if all fusion proceeded to ^{4}He and lattice heat a hitherto undiscovered nuclear process.

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TABLE 3.1

SOME COLD FUSION NEUTRON RATES

AUTHORS	Reference	Neutrons per DD pair per sec[a]	Yield Normalized to Jones et al. [JON-1] neutrons[b]

Jones et al.	[JON-1]	1x10^{-23} [c]	1
Mizuno et al.	[MIZ]	5x10-23	5
Williams et al.	[WIL]		<0.5
Alber et al.	[ALBE]	<4x10-24	<0.4
Broer et al.	[BRO]	<2x10-24	<0.2
Lewis et al.	[LEW]	<2x10-24	<0.2
Schriber et al.	[SCH]		<0.2
Kashy et al.	[KAS]	<1x10-244	<0.1
Gai et al.	[GAI]	<2x10-25	<0.2
De Clais et al.	[DEC]		<0.1

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[a] Assuming that neutrons are produced throughout the volume of Pd or Ti.

[b] For comparison one watt of heat production by D + D fusion would correspond to 0.9x10^{12} in these normalized neutron yield units.

[c] This fusion rate is reported by Jones et al. [JON-1] for run 6. The average fusion rate for all runs [JON-1] is a factor of 6 less.

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TABLE 3.2

SOME COLD FUSION FAST CHARGED PARTICLE RATES

AUTHORS	**Reference**	**Protons per**	**Yield Normalized to Jones**

		DD pair per sec[a]	**et al. [JON-1] neutrons[b]**
Rehm et al.	[REH]	<4.0x10^{-23}	<4.0
Schrieder et al.	[SCH]	<3.1x10^{-24}	<0.31[c]
Sundqvist et al.	[SUN]	<2.0x10^{-24}	<0.2
Ziegler et al.	[ZIEI	<1.2x10^{-24}	<0.12[c]
Porter et al.	[POR]	<6.7x10^{-25}	<0.07
Price et al.	[PRI]	<8.3x10^{-26}	<0.008

[a] assuming that particles are produced throughout the volume of Pd.

[b] For comparison one watt of heat production by D + D fusion would correspond to O.9x10^{12} in these units.

[c] Rehm et al. comment that the choice of the low-energy cutoff (e.g. 1 MeV) [ZIE] "restricts the emission angle of the protons with respect to the foil to a small cone representing only a few of the total solid angle." [sic] This effect seems to have been neglected in the efficiency calculations for the limits quoted by these authors.

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IV. MATERIALS CHARACTERIZATION

A. INTRODUCTION

Relatively little emphasis has been placed on the role of material properties in cold fusion experiments. Characterization of the anode and cathode compositions, microstructures, homogeneity, etc. generally has not been carried out and has not played a significant role in the discussions directed towards understanding cold fusion. These materials parameters have, however, been involved in discussions directed towards explaining difficulties associated with reproducibility in these experiments. Most experimental protocols have utilized Pd cathodes for the electrolytic charging, and Ti (or Ti alloys) for gas charging experiments, following the examples of the initial experiments by Fleischmann and Pons [FLE], and Jones [JON-1]. In addition, most electrolytic charging experiments have utilized Pt anodes, with the important exception being those at Texas A&M for which tritium (T) generation has been reported and which utilize Ni anodes [PAC].

B. STOICHIOMETRY ATTAINED

It has become increasingly common for the D/Pd ratio attained to be reported in the electrolysis experiments. Measurements of the D concentration are often based on the weight gain of the cathode during electrolysis. Values of D/Pd in the range 0.7 to 1.1 have been reported for experiments which report both positive and negative cold fusion results. The gravimetric method of measurement is often employed and is generally reliable for D/Pd values in the range of 0.6 to 1, as long as the loss of D is minimized between the period of charging and the weighing. Most investigators do not report the details of their procedures. Precautions taken to avoid loss of D, such as the storage of specimens at low temperature, are not discussed. Consequently, in the absence of other difficulties, the reported D/Pd values are lower limits to the values in the operating cells. An additional difficulty in the electrolytic charging experiments is that deposits on the cathode or "diffusion" of Li into the cathode must be accounted for properly before the gravimetric results can be considered accurate. In the majority of the reported results, it has not been shown that suitable procedures have been carried out.

C. CATHODE CHEMICAL ANALYSIS

In a few cases the cathodes have been analyzed for T, He^3, and He^4 after electrolysis, with negative results [WIL, HOL, THO, LEW]. In most experiments these analyses have not been carried out despite the importance of these fusion products in establishing the presence or absence of cold fusion. Reports of diffusion of Li into the cathodes have been made [PAC] but the basis for these reports has generally not been specified. In one case [WIL], the presence of Li up to several micrometers into the Pd cathode was detected by Secondary Ion Mass Spectrometry (SIMS) but the authors suggest that this was the result of surface cracking and contamination of the crack surfaces by the electrolyte. They also detected other components of the electrolyte on the cathode surface.

Even less materials characterization has been carried out for the gas charging experiments. Often mixtures of metals have been used and they have been characterized as "turnings", "sintered powder", "mossy solids" etc.; which have very limited meaning with respect to the material's character. The D/Pd ratios have generally not been determined nor has sufficient information been given to allow an estimate to be made. In some cases, the pressure of the D_2 gas above the material has been measured and shown to decrease during period when the material was to have absorbed D. In other experiments, D absorption has not been demonstrated and there is no evidence that the experiments have been carried out on metals which contain D. It is important to determine the D/metal ratio in these experiments as absorption of D in Ti and its alloys is a very surface sensitive process. Exposure to D_2 gas does not assure that significant absorption of D occurs.

D. "RELEVANT" MATERIALS PARAMETERS

As discussions of the success or failure of cold fusion experiments have often been ascribed to properties of the cathode materials, it is useful to consider the various materials parameters suggested to be significant. In the following, these will be considered in light of what is known of the behavior of D(H) in Pd and Ti.

1. Deuterium - Deuterium Distance

> The suggestion has been made that as a result of the high fugacity, confinement of D in Pd during electrolysis results in a very small D-D distance. Both the alpha and beta phases of the Pd-H(D) system are solid solutions. As discussed in

Appendix IV.A, of all the configurations considered, the smallest distance between interstitial sites occupied by D in Pd is 0.17 nm; which is large compared to the D-D distance in the D_2 molecule, 0.074 nm. Significant dual occupancy of interstitial sites by D is not in accord with the linearity of the lattice expansion measured by X-rays [PEI) or with theoretical treatments of the Pd-D system [NOR, RIC]. Furthermore, multiple occupancy of vacancy sites [BES] leads to an increased D-D spacing. Thus even under the high D/Pd values attained by electrolytic charging, the D-D spacing remains much too large for any fusion reaction.

2. Confinement Pressure

The possibility of a successful electrolytic cold fusion experiment has been ascribed to the very high deuterium "confinement pressures" achieved at the cathode at the electrolytic overpotentials applied. Fleischmann and Pons [FLE) discuss equivalent D_2 pressures of about $8x10^{26}$ atm. corresponding to their overpotential of 0.8 V. As discussed in Appendix IV.A, the overpotentials do result in a high deuterium fugacity, i.e. a high chemical potential of hydrogen relative to the standard state at one atmosphere, at the Pd surface. However, the non-ideality of D_2 gas and the loss of deuterium by D_2 bubble formation at the surface results in a much decreased equivalent D_2 pressure. The relation between fugacity and

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equivalent pressure is not easily obtained as it depends sensitively on the surface structure and impurity concentration. However, at steady state, i.e. after long charging times, the D in the specimen is at the same chemical potential as that at the surface. Hence the H(D)/Pd values obtained by cathodic charging may be compared to those obtained by gas charging [BARO]. Upon making this comparison (Appendix IV.A), it is seen that the compositions attained by cathodic charging correspond to a very moderate D_2 pressure of $15x1O^3$ atmospheres. While high fugacities are produced by the overpotentials used in cathodic charging, confinement pressures of the order discussed by Fleischmann are not present.

3. Charging Times

The suggestion has been made that successful experiments require very long charging times. Assuming that this is related to materials issues, diffusion is the important materials parameter to consider. As discussed in Appendix IV.A, the diffusivity of D in Pd is sufficiently large at 300°K so that equilibrium can be attained in a 1 cm thick sheet of Pd in times of the order of 7 days. In the 1 mm thick cathodes often used, the time to attain equilibrium at 300°K is of the order of 2 hrs. Longer time may be required as a consequence of surface impedances to diffusion which result from impurities plated out from the electrolyte (Pd) or from surface oxides (Ti). These times are very much shorter than the very long times which, it is often claimed, are required for successful cold fusion experiments.

4. Microstructure

The suggestion [PON] that a particular form of the cathode material, e.g. cast material, must be used for successful cold fusion experiments is not in accord with the known behavior of Pd. Annealing the material to minimize the dislocation concentration should not be necessary. The very large inhomogeneous deformations which accompany cathodic charging of Pd, under the conditions used, result in high dislocation densities even in a well annealed material [HO]. Furthermore, the suggestion that vacuum annealing is necessary to remove the interstitial impurities [HUG) does not seem to be in accord with the conditions under which cold fusion is claimed. At the high D/Pd values, the presence of a few interstitial or dislocation trapping sites is insignificant compared to the high D concentrations.

5. Surface Contamination

Deposition of various materials from the anode and from the electrolyte (leached from the container) onto the cathode has clearly occurred in many of the experiments. Analysis [WIL] has revealed Pt (probably from the anode), Si (probably leached from the glass container), Cu, Zn, Fe, Pb, and other trace elements. Surface contamination of the cathode may affect the rates of reactions and therefore the effective fugacity. In general, surface poisons increase the fugacity by decreasing the rate of D_2 gas formation. This is indicated by the high D/Pd values attained and by the observation, reported in several experiments, that the loss of D from the cathode after electrolysis was slow. Thus surface contamination probably had the effect of increasing the D/Pd values and the fugacities attained.

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6. Surface Morphology

"Dendritic" growths were reported on the surfaces of the cathodes in the Texas A&M experiments which utilized Ni anodes [PAC). This has led to the suggestion that these dendrites are of significance for the formation of tritium during electrolysis, possibly "due to increased electric fields at the dendrite tips" [BOC, PAC]. Other experiments which reported these "dendrites" have not reported generation of tritium [WIL]. It is difficult to understand the importance of these "dendrites" in cold fusion. (These dendritic growths are not uncommon in plating experiments.) The field at the "dendrite tip" is the voltage across the double layer divided by the thickness of the layer. Since the total voltage across the double layer at the cathode is of the order of several volts, high fields can be attained if the double layer thickness is small. However, acceleration of D^+ ions across this double layer will only result in energies of several eV (the energy determined by the voltage drop at the cathode), hardly enough to cause fusion.

7. Fracture Phenomena

The conditions of the gas charging experiments are likely to result in hydride formation in the Ti-D system and formation of the beta phase in the Pd-D system. The process of gas charging is well understood, as is the process of discharging of D into the gas phase from hydrides. Anomalous behavior which may lead to fusion and the formation of fusion products is not expected in these processes. Fracture of the brittle hydride phases is likely and has been well studied [SHI-1] . These fracture processes are of low energy and occur at a fraction of the speed of sound in the hydride. While acceleration of charged particles has been suggested to occur during fracture, this phenomenon remains speculative. Palladium deuteride and titanium deuteride are metallic conductors and hence large fields are unlikely to form during fracture. An alternative view has been expressed [MAY].

E. CONCLUSIONS

The behavior of H(D) in Pd and Ti is sufficiently well understood both experimentally and theoretically to answer many of the speculations about the properties of H(D) interstitials under the conditions for which cold fusion has been reported. None of the known behavior is consistent with the possibility of overcoming the coulombic repulsion between the D ion cores. The confinement pressures and energies of D in Pd and Ti are far from the regimes which are required for a reasonable possibility of cold fusion based on our present understanding. No aspect of the known behavior of D in Pd or Ti is compatible with formation of energetic neutrons, tritium or helium.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. PREAMBLE

Ordinarily, new scientific discoveries are claimed to be consistent and reproducible; as a result, if the experiments are not complicated, the discovery can usually be confirmed or disproved in a few months. The claims of cold fusion, however, are unusual in that even the strongest proponents of cold fusion assert that the experiments, for unknown reasons, are not consistent and reproducible at the present time. However, even a single short but valid cold fusion period would be revolutionary. As a result, it is difficult convincingly to resolve all cold fusion claims since, for example, any good experiment that fails to find cold fusion can be discounted as merely not working for unknown reasons. Likewise the failure of a theory to account for cold fusion can be discounted on the grounds that the correct explanation and theory has not been provided. Consequently, with the many contradictory existing claims it is not possible at this time to state categorically that all the claims for cold fusion have been convincingly either proved or disproved. Nonetheless, on balance, the Panel has reached the following conclusions and recommendations.

B. CONCLUSIONS

1. Based on the examination of published reports, reprints, numerous communications to the Panel and several site visits, the Panel concludes that the experimental results of excess heat from calorimetric cells reported to date do not present convincing evidence that useful sources of energy will result from the phenomena attributed to cold fusion.

2. A major fraction of experimenters making calorimetric measurements, either with open or closed cells, using Pd cathodes and D_2O, report neither excess heat nor fusion products. Others, however, report excess heat production and either no fusion products or fusion products at a level well below that implied by reported heat production. Internal inconsistencies and lack of predictability and reproducibility remain serious concerns. In no case is the yield of fusion products commensurate with the claimed excess heat. In cases where tritium is reported, no secondary or primary nuclear particles are observed, ruling out the known D+D reaction as the source of tritium. The Panel concludes that the experiments

reported to date do not present convincing evidence to associate the reported anomalous heat with a nuclear process.

3. The early claims of fusion products (neutrons) at very low levels near background, from D_20 electrolysis and D_2 gas experiments, have no apparent application to the productinn of useful energy. If confirmed, these results would be of scientific interest. Recent experiments, some employing more sophisticated counter arrangements and improved backgrounds, found no fusion products and placed upper limits on the fusion probability for these experiments, at levels well below the initial positive results. Based on these many negative results and the marginal statistical significance of reported positive results, the Panel concludes that the present evidence for the discovery of a new nuclear process termed cold fusion is not persuasive.

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4. Current understanding of the very extensive literature of experimental and theoretical results for hydrogen in solids gives no support for the occurrence of cold fusion in solids. Specifically, no theoretical or experimental evidence suggests the existence of D-D distances shorter than that in the molecule D_2 or the achievement of "confinement" pressure above relatively modest levels. The known behavior of deuterium in solids does not give any support for the supposition that the fusion probability is enhanced by the presence of the palladium, titanium, or other elements.

5. Nuclear fusion at room temperature, of the type discussed in this report, would be contrary to all understanding gained of nuclear reactions in the last half century; it would require the invention of an entirely new nuclear process.

C. RECOMMENDATIONS

1. The Panel recommends against any special funding for the investigation of phenomena attributed to cold fusion. Hence, we recommend against the establishment of special programs or research centers to develop cold fusion.

2. The Panel is sympathetic toward modest support for carefully focused and cooperative experiments within the present funding system.

3. The Panel recommends that the cold fusion research efforts in the area of heat

production focus primarily on confirming or disproving reports of excess heat. Emphasis should be placed on calorimetry with closed systems and total gas recombination, use of alternative calorimetric methods, use of reasonably well characterized materials, exchange of materials between groups, and careful estimation of systematic and random errors. Cooperative experiments are encouraged to resolve some of the claims and counterclaims in calorimetry.

4. A shortcoming of most experiments reporting excess heat is that they are not accompanied in the same cell by simultaneous monitoring for the production of fusion products. If the excess heat is to be attributed to fusion, such a claim should be supported by measurements of fusion products at commensurate levels.
5. Investigations designed to check the reported observations of excess tritium in electrolytic cells are desirable.

6. Experiments reporting fusion products (e.g., neutrons) at a very low level, if confirmed, are of scientific interest but have no apparent current application to the production of useful energy. In view of the difficulty of these experiments, collaborative efforts are encouraged to maximize the detection efficiencies and to minimize the background.

APPENDIX 1.A

The Secretary of Energy
Washington. DC 20585

April 24, 1989

Mr. John H. Schoettler
Chairman
Energy Research Advisory Board
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dear Mr. Schoettler:

In recent weeks, there has been a great deal of interest in the prospects for "cold fusion" based on experiments at universities in Utah and subsequent experiments performed elsewhere. At present, the apparent observations of cold fusion and significant quantities of energy from this phenomena are being investigated extensively. Because of the potential benefits from practical fusion energy, I request that the Energy Research Advisory Board (ERAB) assess this new area of research. Specifically, I would like the Board to:

1. Review the experiments and theory of the recent work on cold fusion.

2. Identify research that should be undertaken to determine, if possible, what physical, chemical, or other processes may be involved.

3. Finally, identify what R&D direction the DOE should pursue to fully understand these phenomena and develop the information that could lead to their practical application. I request that the Board provide an interim report on the first

item by July 31 and a final report on all items by November 15, 1989.

Sincerely,

[Signature]

James D. Watkins
Admiral, U.S. Navy
(Retired)

APPENDIX 1.B

PANEL MEETINGS AND SCHEDULE OF LABORATORY VISITS

PANEL MEETINGS

Washington, DC	June 22, 1989
Washington, DC	July 11-12, 1989
Chicago, IL	October 13, 1989
Washington, DC	October 30-31, 1989

SCHEDULE OF LABORATORY VISITS

University of Utah	June 2, 1989
Brigham Young University	June 13, 1989
Texas A&M Univeristy	June 19, 1989
California Institute of Technology	June 20, 1989
Stanford University	July 6, 1989
SRI International (at EPRI)	July 9, 1989

OTHER

Workshop on Cold Fusion, Santa Fe, NM	May 23-25, 1989

APPENDIX 2.A

EARLY CHRONOLOGY OF HEAT PRODUCTION

March 23-28, 1989. A press release from the University of Utah announced that "A Simple Experiment Results in Sustained Nuclear Fusion..." Statements in the release included that "the discovery will be relatively easy to make into a usable technology for generating heat and power," that "this generation of heat continues over long periods and is so large that it can only be attributed to a nuclear process."

Follow-up news stories quoted Fleischmann and Pons that they had "achieved nuclear fusion in a test cell simple enough to be built in a small chemistry laboratory," and that "the experiment generated a great deal of heat as well as neutron radiation." (*New York Times*, 3-24). It was also reported that "they have run the device for periods as long as 100 hours, and continue to produce more energy than it took to run the experiment." (*Dallas Times-Herald*, 3-24) and that "a palladium wire only a quarter-inch in diameter and an inch long reached the boiling point of water within a few minutes."

"He (Pons) said the wire produced about 26 watts of energy per cubic centimeter of wire, 'about 4 and one half times what we put into it'." "He (Pons) said that in an early stage of the experiments the apparatus suddenly heated up to an estimated 5000 degrees, destroying a laboratory hood and burning a four-inch-deep hole in the concrete floor." (Wall Street Journal, 3-27). "Evidence that fusion was taking place was the fact that in addition to heat they detected the production of neutrons, tritium, and helium - the expected by-products of fusion reactions." (*Wall Street Journal* 3-24).

James Brophy, Vice President for research at the University of Utah, said that "the experiment is easy to carry out once you know how. They [F & P] have reproduced it a dozen times." (*Austin American-Statesman*, 3-28). "The process, he [Pons] said, is extremely slow, especially if a large cathode is used. Using a cathode consisting of palladium wire, the process required 10 hours before fusion was observed." (*New York Times*, 3-28).

April 10, 1989. A paper by M. Fleischmann, S. Pons, and M. Hawkins appears (*J. Electroanal. Chem.*, 261, 301 (1989)). Some details of the calorimetric measurements are given (e.g., open cell, isothermal calorimeter). Excess heat production of 5 to 111% reported for current densities of 8, 64, and 512 mA/cm^2. "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."

April 11. 1989. A group at Texas A & M University (C. R. Martin, B. E. Gammon, and K. N. Marsh) announce confirmation of the excess heat results from isothermal heat leak calorimeter measurements with an open cell. Excess energies of 20 to 80% are reported (*New York Times*, 4-11; *Austin American Statesman,* 4-11). (These results were retracted by the group during a visit of panel members to Texas A & M University on 6-19-89).

April 12-30, 1989. Several other calorimetric experiments announcing excess heat appear (Appleby, Srinivasan, Texas A&M, *Austin American Statesman,* 4-22; Huggins et al, Stanford, *Nature*, 4-27) while other groups report no excess heat.

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May 1, 1989. A paper presented at the American Physical Society meeting in Baltimore report no excess heat in calorimetric measurements with an open cell at current densities of 72 to 140 mA/cm^2 (e.g., N. Lewis et al, Caltech).

May 9, 1989. Several papers at the Electrochemical Society Meeting in Los Angeles report calorimetry confirming excess heat (Srinivasan, Huggins, Landau) and the first announcement of an energy "burst" that generated 4.2 MJ over a 2-day run (50 times the electrical energy put into the cell). (*Science*, 5-12).

May 23-25, 1989. A number of papers on calorimetry are presented at a Workshop on Cold Fusion in Santa Fe under the sponsorship of Los Alamos National Laboratory. Both positive excess heat results (Texas A&M, Stanford) and negative results (Caltech, MIT, Argonne National Laboratory, Naval Weapons Center, EG&G Idaho, University of British Columbia, Chalk River Nuclear Laboratories) are described. (These results, as well as some which have appeared later, are summarized in Table 2.1). No lectures discuss energy "bursts". The first meeting of the Cold Fusion Panel takes place.

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APPENDIX 2.B

TYPES OF CALORIMETERS EMPLOYED IN STUDIES

1. **Isothermal (isoperibolic or heat leak).** The cell is immersed in a constant temperature bath (at T_b) sometimes separated from it by a vacuum jacket or other material to control the rate of heat conduction from the cell to the bath. The temperature of the the cell, T_c, which is always at a higher temperature than the bath, is monitored.

   ISO A. The heat flow from the cell to the bath is determined from the temperature difference, $T_c - T_b$ and the heat transfer coefficient, determined by periodically calibrating the cell with an internal heater in the cell, by Newton's law of cooling. In this type of cell, T_C varies and increases as the power output of the cell increases.

   ISO B. The cell is maintained at a constant temperature by varying the power to the heater (heat substitution method). The cell is first brought to a given steady state temperature, T_c by the heater operating at a given power, P_h. The electrolysis cell is then turned on and the heater power decreased to a level, P_{hc}, to maintain the cell temperature at T_c. The power generated by the electrolysis is calculated as $P_c = P_h - P_{hc}$.

2. **Isothermal, heat flow (ISO C).** Power that flows between the cell and the external constant temperature bath is detected by a multitude of thermocouples connected in series and completely surrounding the cell chamber. The system is calibrated at different power levels by a heater in the cell chamber.

3. **Flow Calorimeter.** The cell is surrounded by a chamber cooled by a constant flow of water or other fluid. The inlet temperature of the fluid, T_{in}, and the outlet temperature, T_{out}, are monitored and the power evolved in the cell calculated from the difference in temperatures, the flow rate, and the heat capacity of the fluid.

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APPENDIX 2.C

EXPERIMENTAL PROBLEMS IN THE EVALUATION OF HEAT EFFECTS

Tables 2.1 and 2.2 summarize many experimental efforts aimed at verification of the excess heats originally reported by Pons and Fleischmann. The Panel is aware of other efforts that have remained unreported in any formal way. It was not possible to visit all of the active laboratories, but the Panel did send representatives to the Pons-Fleischmann laboratory and the Wadsworth laboratory at the University of Utah, the Huggins laboratory at Stanford University, the Lewis laboratory at Caltech, the Appleby, Martin, and Bockris laboratories at Texas A&M, and to McKubre of SRI at EPRI. In addition, detailed queries were made of other investigators by telephone or by conversation at meetings. It is not practical here to provide a detailed analysis of each group's work. Instead, we will provide a summary of the kinds of experimental problems that we identified in the calorimetric measurements.

One of the important ideas advanced in this field is that large amounts of heat arise from a previously unrecognized source, hence it was the one of the Panel's chief responsibilities to evaluate experimental work from the positive claimants with great care. The experimental shortcomings discussed here were widely encountered. No single study was compromised by all of them, but no positive report that we were able to study in detail was free of such problems.

1. Fundamental Considerations

The experimental schemes used in most laboratories reporting positive heat effects normally have many elements in common. A cell containing a Pd cathode and a Pt anode immersed in D_2O (or H_2O) containing LiOD (or LiOH) is allowed to pass a steady current for a long period of time. For those which have followed the Fleischmann-Pons method (ISO A), the cell body is immersed in a heat sink (usually a water bath), and precise measurements are made of the temperature difference between the interior of the cell and the heat sink. Thermocouples and microvoltmeters are usually used for the temperature measurements, but sometimes thermistors are employed. The evolved heat power is usually calculated from the temperature differential by a heat transfer coefficient, which is obtained by calibration via the input of additional heat power at a resistor immersed in the working solution. The variant of this scheme to make it more truly isothermal (ISO B), and avoid possible temperature dependence of the heat transfer coefficient by standard heat substitution, combines calibration and measurement.

An increasing number of laboratories are now reporting results with calorimeters that measure heat flux directly (ISO C) but calibrations with power dissipated through standard resistors in the cell compartment are still required. This is also true for flow calorimeters.

The claims of excess heat rest upon a comparison between the measured heat power evolved from the cell and the electrical power input. The latter quantity is determinable as the product of the current through the cell and the voltage across it. Comparisons normally involve a correction of this quantity by subtraction of 1.527 V times the cell current, to account for the enthalpy leaving the cell as vented D_2 and O_2. The underlying assumption is that 100% of the current goes to produce D_2 and O_2, which is vented perfectly. It is possible to operate the cell in a closed fashion by including a catalytic recombiner capable of regenerating deuterium oxide from D_2 and O_2. Very rarely has excess heat been reported from such a cell.

In most cases, the current through the cell is held constant, and the voltage is allowed to fluctuate according to variations in mass transfer rates and electrode surface exposure in the cell. (These occur largely because of the intense gas evolution normally taking place in the cells.) In other experiments, the total applied voltage is controlled, and the current fluctuates. The controlled parameter is usually defined by four significant figures, but the measured one typically varies instantaneously over a range of several percent.

When current is passed through an electrolytic system, the heat power output can be considered as the product of the cell current, I, times the sum of a series of voltages equivalent to the recombination enthalpy (e.g. for $D_2 + 1/2\ O_2$ to D_2O) and the Joule heating terms. The latter include the recombination entropy and the current-dependent overpotentials at the two electrodes (the voltages necessary to drive the electrode kinetics at the rate defined by the current), plus the IR drop in the electrolyte (external IR effects ignored). In a gas evolving system, a further term related to the heat of evaporation may be relevant.

With respect to considerations of experimental error in determining whether there is an additional component in the heat balance equation due to an unknown source of heat (e.g. cold fusion), two comments on these voltage equivalents may be made.

First, the enthalpy term depends on whether the cell is open (gases vented, no recombination enthalpy) or closed (total recombination and fully recovered enthalpy). Since most experiments quoting positive effects in steady state measurements have cited a voltage equivalent to the excess heat power less than, or only slightly greater than, the figure of 1.527 V corresponding to full recombination, the degree to which the cell is open or closed is critical . For example, in the original Fleischmann--Pons paper [FLE], only two of nine cells showed more than 1.527 x I in excess heat power, and then only slightly.

Second, the cells listed for both positive heat effects in Table 2.1 typically have voltages in the range of 5-20 V. The larger contributions to this magnitude are the overpotentials and the IR drop. Since these Joule components cause both heating (temperature increment) and power input (voltage increment), they obscure the observation of any experimental difference assignable to an excess heat with a voltage equivalent smaller than or on the order of 1.527 V. Thus their existence effectively multiplies the expected error in the output heat excess determination by factors of ca. (cell voltage - heat excess voltage)/(heat excess voltage), where the denominator is the excess heat expressed as its voltage equivalent.

This factor can obviously be very large and places an increasing burden on the quality of the measurements as the current density rises (implying larger overpotentials and I^2R heat). Even an overall precision of 1% of input power at 20 V implies a corresponding relative error for excess heat (even of a magnitude equivalent to 1.5 V) of greater than 10%. With the high rate of gas evolution of cells operating at 500 mA/cm^2, instantaneous variation of cell voltages due to both changing overpotentials (actual unblocked surface areas of electrodes vary) and IR drops (fluctuating electrolytic resistive path) can be several percent or more. Such analysis only serves to point out the rather severe requirements of this type of calorimetry attempted in the high current density regimes which have been applied in typical cold fusion experiments.

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2. Intrinsic Problems with Calibration

The calibration method used by most groups reporting positive results is based on the temporary addition of a power increment delta-P via a resistive element in the cell. This delta-P causes a change in the steady-state temperature by an amount T, then a differential heat transfer coefficient k_D = delta-P/delta-T is calculated. This measurement can be carried out as the cell is running. The resistive power increment is added on top of that from the electrolytic process, thus maintaining similar stirring conditions for power dissipation. Once k_D is determined, the heat power evolved from the electrochemical action is calculated as the product of k_D and the difference in temperature between the operating cell (with the calibration heater off) and the external sink. This temperature differential sometimes reaches 30° C or more, but this could develop either from excess heat or from high input current densities leading to large resistive power dissipations in the solution.

In principle and in practice, the differential coefficient k_D depends on the magnitude of the difference in temperature between bath and cell. In using the value of k_D at the operating point to calculate the evolved heat power, investigators often assume that k_D remains constant over the range of cell temperatures from the value of the bath to the operating point. The real need is for the integral heat transfer coefficient k_I at the operating temperature T_c, which is truly related to the evolved heat power P as $k_I(T_c-T_b)$, where T_b is the bath temperature. The differential value k_D, is related to k_I, as:

$$k_I = \frac{\int_{T_b}^{T_c} k_D \, dT}{\int_{T_b}^{T_c} dT}$$

Some groups use small added heats, relative to the electrolytic power, and a single point calibration. Others use values 20-100 times as large as the reported excess heat. In these latter cases, the calibration is approximately a measurement of the integral heat transfer coefficient for a wide span of power above the operating point. This value is then assumed to be equal to the integral heat transfer coefficient below the operating point.

In all its variants, this calibration method is intrinsically prone to overestimate the evolved heat power, because the temperature differential is typically a nonlinear function of heat power in such a manner as to produce a positive error in the estimated k_I, (taken as measured k_D). An error of a few percent in the assumption that $k_I=k_D$ would invalidate nearly all reports of excess heat.

The methodology is, in principle, capable of defining the evolved heat accurately. Calibration needs to be done frequently enough over the operating range to be able to calculate k_I directly; however the panel saw no instance in which calibrations were made in sufficient detail to allow the calculation of a true k_I. If there are changes in the structure of this system (e.g., the electrolyte level in the cell), the heat transfer coefficient becomes time dependent. Repeated recalibration is then required.

[[46]]

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3. Lack of Estimates of Precision

A surprising aspect of the calorimetry related to cold fusion is the lack of attention that has been given so generally in reports of excess heat, to the statistical assessment of errors. It is evident on the face of the data in some reports that a group's claim of excess heat is not supported with results of sufficient precision to allow such a conclusion. More usually, it is not possible to assess precision from reported results, because the result is reported from a single run and no error bars are provided for the measured parameters. Conclusions in this arena simply cannot be accepted without a thorough assessment of the measurement errors. In its visits and conversations, the members of the Panel were struck repeatedly by the absence of critical assessments of this kind. Several different kinds of problems were common:

a. ***Lack of sufficient controls.*** In no case of a positive report have we seen investigations of comparable numbers of test and control cells. In this context, the "test" cells would involve deuterated Pd electrodes operating in D_2O solutions, while the "control" cells would feature either Pt cathodes in D_2O solutions or Pd cathodes in H_2O solutions. Even the most ardent proponents of excess heat readily admit that the effect is erratic, often being seen only occasionally in one or a few test cells of many. In this circumstance, it is not acceptable to compare results from many test cells against the behavior of one, or only a few, control cells. Statistically meaningful results require comparisons of like numbers of cells of both types.

b. ***Failure to assess errors in primary measurements.*** There are few reports in which adequate attention is given to the evaluation of measurement precision in the chief experimental quantities. Often, the uncertainly is estimated by the precision of simply reading a voltmeter, for example, when the true precision is determined by fluctuations of cell voltage or by disconnection and reconnection of terminals or other small experimental matters. In hardly any case has the measurement precision been assessed by repeated measurement. Normally, it is only estimated from concepts of optimal performance, if the issue has been addressed at all.

   Moreover, errors in calculated results are typically not developed systematically from the measurables via arguments based on propagation of error. Sometimes linear relationships yielding a critical slope or intercept are used in calibration or in the final evaluation of excess heat effects, yet the lower limit of standard deviation of the slope or intercept is not assessed even from the evident scatter in the data.

c. ***Significant figures***. In a surprising number of instances, there are important violations of simple significant figure rules. One sees, for example, subtractions of input electrical power from evolved heat power, wherein both power quantities are tabulated to significant figures far beyond three, even when the measurements are clearly valid to no more than two or three figures. In fact, many investigators simply do not say in public reports exactly how the measurements are made; only by visiting the laboratories does it become evident that tabulations of quantities with so many figures is wholly unjustified. This practice is insidious in the absence of real assessments of precision, and it could explain why some groups see positive heat effects only erratically.

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4. Possible Electrical Artifacts

In some of the laboratories examined, the electrolytic cells were operated at constant voltage, not constant current. Since the conductivity of solutions of LiOD is only about half that of corresponding solutions of LiOH, and since the cells were operated in a regime where the applied voltage appeared as a drop across the solution resistance, cells operated with H_2O electrolyzed more moles per second than equivalent cells containing D_2O. In some representations of data (e.g. temperature differential vs. applied power for cells in the two different solvents), this effect can show apparent excess heat for the cells evolving deuterium, simply because less power is carried out of the cell in the enthalpy of vaporization of water carried by the vented products.

A careful consideration of measurements with thermocouples clearly illustrates the difficulty of precise measurements of evolved heat power. The excess heats reported by several groups normally correspond to about one half degree in temperature differential. The sensitivity of the thermocouples is typically about 40 microvolts per degree, hence the effect is represented by a dc signal on the order of 20 microvolts, readable with a meter precision of about 2 microvolts per reading, or about 3 microvolts for the difference of two readings. The scatter of data points in various studies suggests that the actual precision is no better than about half to one-third of the differential ascribed to excess heat. Precise measurement of the differential is, of course, only half the story. One also needs *accurate* measurements of dc voltages at these low levels. If there were an experimental bias inducing even a few microvolts at the thermocouple in the cell, one could see an apparent excess heat. Since the thermocouple is operated in the electric field caused by the resistance losses in solution, such an induced signal is a very real possibility. This problem could also manifest itself at thermistors. One additional source of error is the improper choice of cold junctions in thermocouple measurements.

A thermocouple is normally encased in a glass or ceramic tube containing a heat transfer medium (sometimes water). It is assumed to be electrically isolated from the solution, but a few microvolts of pickup are not beyond the realm of possibility. Since the electric fields are typically larger in D_2O solutions than in H_2O solutions, this effect could be relevant to the differences between cells operated in D_2O vs. H_2O. It would also explain why the excess heat power sometimes seems to be nearly linear with applied electrolytic power.

Corrosion of the thermocouple in the heat transfer fluid could also produce dc offsets large enough to yield an apparent excess heat, especially if the heat transfer fluid were a polar liquid such as water.

The precise, accurate measurement of temperature differentials via thermocouples at the level of quality required to confirm typically reported excess heats is an experimental challenge of a high order.

A completely different problem is with the assumption that the input electrical power is simply the product of a time-averaged current and a time-averaged voltage. If an alternating component is present, there can be an error arising from the fact that the time-averaged power is generally not the same as this product. In effect, the measurements, as usually practiced, are blind to the ac component of power dissipation, so that the electrical input power is underestimated and an "excess heat" can be expected in the calorimetry. The fluctuations in mass transfer and surface coverage discussed above produce some ac component in nearly all cells. In addition, there are reports that the current or cell voltage can undergo oscillatory behavior with large amplitudes for brief periods [MOL] upon changing the operating conditions, such as the current density. Such effects would lead to sizable transitory discrepancies between the apparent (dc) and true (ac + dc) electrical input power, hence they might be the basis of some of the bursts that are reported by various groups.

5. Recombination of D_2 and O_2

An assumption in most cases for which positive heat effects are reported is that the gaseous products D_2 and O_2, are vented without recombination. It is widely recognized that any recombination of these products to regenerate deuterium oxide within the cell will produce heat that will appear as an excess, simply because of the correction for the enthalpy of the products. Many groups have guarded against this error by measuring the volumes of gases produced and comparing them with the expectations based on the charge passed through the cell. On the other hand, these measurements are sometimes not made at all, and in other cases they are not made with sufficient precision and accuracy to assure the absence of recombination at a level that could account for the thermal excess. In a surprising number of instances, the cells were operated with Pt or Pd surfaces exposed in the headspace above the solution. These are efficient catalytic surfaces and could be expected to produce a breakdown of the assumption of no recombination.

A related, but different, issue concerns the current efficiencies at the anode and cathode. In open cells, the application of the enthalpic correction implies that 100% of the electron flow at the cathode is devoted to the production of D_2 and that the same perfect efficiency applies to the generation of O_2 at the anode. If D_2 reaches to the anode, it will be oxidized there in competition with the D_2O and will invalidate this assumption. The same reduction in efficiency will be seen at the cathode if O_2 reaches its surface. The net effect is a kind of "electrochemical recombination" within the cell, and to the extent that it occurs, one cannot validly correct the input power for the enthalpy of vented products in the usual manner. In virtually all cells, the anode and cathode operate without a diaphragm separating them, so some reduction in current efficiency is inevitable. The effect was actually evaluated quantitatively [SHE, CUN].

It is not of concern in a closed cell.

[[49]]

APPENDIX 2.D

LARGE HEAT BURSTS

Some reports of excess heat have described abrupt changes in cell temperature which appear sporadically, often after a change in operating conditions (e.g. current density), and last for an indefinite period. These frequently occur only in a single run or with a single specimen. In most cases, the heat bursts represent fluctuations in heat power balance on the order of 1.527 V x I or less [ORI, APP, KAI, BEL]. These "small" bursts are subject to the same experimental problems discussed in Appendix 2.C and can be evaluated according to considerations set forth there. Therefore, they will not be considered further here. There have also been reports of "large" heat bursts of claimed integrated energy magnitudes amounting to megajoules. The temperature changes are so distinct (tens of degrees, even to boiling of the electrolyte) that they seem far out of the range of reasonable calibration errors.

In our Interim Report, the Panel indicated its intention to offer a fuller analysis here of these events. To date, we have been informed of them only through oral presentations, press reports, or private communications. No description has been made in writing, therefore we still have no adequate documentation from which to analyze the significance, and we can provide no references. In fact, the Panel has learned of very few, if any, fresh reports of large bursts since the time when our Interim Report was prepared in July. One laboratory that had previously reported large bursts in open cells has seen no further events since switching to closed cells and better instrumentation. Given the very limited and unpredictable appearance of these large heat bursts, they remain mysterious and perplexing.

APPENDIX 3.A

NEUTRON DETECTION

Neutrons from DD fusion can be detected either at their initial energy in the MeV range as "fast" neutrons, or after their energy has been "moderated" by sharing it in successive collisions with light material -- particularly hydrogen. Fast neutrons can be detected by photomultiplier tubes viewing the proton recoil in plastic or liquid scintillation material. Slow neutrons (those that have lost almost all their kinetic energy and are in thermal equilibrium at room temperature) are conventionally detected by the charged particles produced when the neutron is captured with high probability in the nucleus of an atom of ^{10}B (producing an alpha particle), or in a ^{3}He nucleus, producing a recoil proton. A noble gas, ^{3}He is used in the form of a proportional counter, while boron can be used either in the form of BF_3 proportional counters or in the solid form, with the boron immersed in plastic or inorganic scintillator viewed by a photomultiplier.

Additionally, neutrons can be detected after moderation by their capture in some material of very high capture cross section (such as cadmium Cd), which produce several gamma rays that may, in turn, be detected by a photomultiplier viewing a scintillation detector. Similarly, neutrons moderated in water are almost entirely captured on the protons ("radiative capture"), giving rise to a deuteron plus a gamma ray with an energy of 2.2 MeV.

Finally, moderated neutrons may be captured in a trace element in the moderator (silver is a detector of choice) to produce a radioactive material that can be transported away from the experimental apparatus and counted separately with high efficiency at low background. The emitted radiation is typically a beta ray (negative electron), or a characteristic gamma ray following the beta decay. Of course, the world has enormous experience since the 1930's in detecting neutrons and detecting neutrons from the D+D fusion reaction.

APPENDIX 3.B

CONSIDERATIONS IN TRITIUM CONCENTRATIONS

Tritium is produced in the atmosphere by cosmic ray bombardment. Most of such tritium ends up in the oceans and in rivers. The "natural" abundance of tritium varies widely and was greatly increased by atmospheric testing of thermonuclear weapons in the '50s and in the early '60s. The order of magnitude of tritium in ordinary water is T/H - 10^{-18} (1 TU). Sources vary from 1 to 200 TU. The production of heavy water from ordinary water is even more efficient in the enrichment of tritium than deuterium from the feed material. Most of the heavy water currently available is produced by the H_2S - H_2O dual temperature exchange process (GS process). The tritium content of fresh heavy water produced by the GS process is 68 dpm/ml D_2O/TU feed. Processes that are more efficient than the GS process in heavy isotope enrichment will have a minimum tritium specific activity of 50 dpm/ml D_2O/TU feed. Heavy water currently being sold on the open market has a specific activity in the range 120 - 180 dpm/ml D_2O. There are sources of D_2O with specific activity as high as 10^4 dpm/ml.

Most of the work done to date on the search for tritium produced in the electrolysis of D_2O in cells with palladium cathodes has been done in open cells. The measurements are frequently limited to assays of the specific activities of the starting D_2O and the electrolyte after electrolysis. In general, there have been periodic additions of D_2O to replace the D_2O decomposed to form Pd-D and D_2(gas). To determine how much tritium, if any, has been produced requires a complete inventory of the tritium at the beginning and end of the experiment. From the data on the current and on the duration of the electrolysis it is possible to estimate the amount of D_2O which has been electrolyzed. Electrolysis will enrich the tritium in the D_2O of an electrolytic cell. The amount of enrichment is primarily a function of the amount of water electrolyzed fur a given type of cathode. It can reach a factor of 5 when 95% of the initial charge of water is electrolyzed. Thus a careful analysis of an electrolytic experiment must be carried out if one is to interpret specific activities of tritium after electrolysis, below 1000 dpm/ml of D_2O, as anything other than electrolytic enrichment [BIG].

[[52]]

APPENDIX 4

MATERIALS FOR COLD FUSION

Cold fusion experiments have utilized two types of cathode materials; palladium and titanium (including several titanium alloys). These two metals have significantly different behaviors in the presence of hydrogen and its isotopes. Their response to exposure to hydrogen isotopes has been extensively studied and well documented [ALEF, MEU], particularly in the case of palladium. In the following, we shall highlight some of the behavior of the Pd-H and the Ti-H systems, selecting those aspects that are most pertinent to the issues raised by the suggested cold fusion experiments. Much of what is known derives from experiments using the mass one isotope, H. The isotopic dependence is sufficiently well understood to allow the behavior of deuterium, D, to be deduced from the measurements on H where data on D are not available. Many aspects of the behavior of hydrogen isotopes in body centered cubic (bcc) (beta phase Ti alloys) and face centered cubic (fcc) (Pd) metals result from their behavior as quantized particles; other properties can be understood using classical concepts. Behavior as quantized particles has not been established for hydrogen isotopes in the hexagonal close packed (hcp) crystal structure (titanium, alpha phase Ti alloys) but such behavior may be expected.

A. The Palladium - Hydrogen (Deuterium) System

Palladium has a fcc close packed crystal structure and as hydrogen is added this structure is maintained across the phase diagram [WIC]. Palladium can absorb large quantities of H(D), with concentrations as high as H/Pd = 1.1 being attainable. Both the alpha and beta phases of the Pd-H(D) system are solid solutions and, at temperatures near 300°K, no ordered structures are known. The H(D) occupies predominantly octahedral interstitial sites, which if they were all filled would result in a H(D)/Pd ratio of 1. Hydrogen can also be accommodated in tetrahedral interstitial sites at a somewhat higher energy and it is believed that the sites may be partially occupied at the higher H(D)/Pd ratios. The spacing of H(D) occupying these sites is not particularly small as shown by Table 4.A below. Both the octahedral and tetrahedral sites have cubic site symmetry. Since H(D) appears to have random distribution in the occupied sites, the maintenance of the cubic crystal structure on adding H(D) is consistent with the high H(D)/Pd values attained. Further evidence for the random occupancy of sites and the cubic distortion of the lattice is provided by X-ray studies of the Pd-H(D) system [PEI], which also indicate that the behavior of D is closely similar to that of H.

Recent theoretical treatments [RIC, NOR] show that H(D) does not attain exceptionally close nearest neighbor distances, even under dynamic conditions. Molecular dynamic simulations [RIC] at concentrations up to D/Pd = 1.1 found no D-D distances shorter than 0.07 nm compared to the molecular D-D distance of 0.074 nm. Interactions of D with lattice defects have been studied both experimentally and theoretically. Significant attractive interaction energies are found [BES] with those defects, such as vacancies, which have a decreased electron density. Palladium has such an attractive interaction between H(D) and vacancies, but it is particularly weak. Each vacancy can accommodate up to 6 D interstitials with the D solutes occupying sites displaced towards the octahedral interstitial sites adjacent to the vacancy. The D-D distance adjacent to the vacancy is 0.18 m.

[[53]]

Table 4.A

DEUTERIUM - DEUTERIUM DISTANCES

SITES OCCUPIED	**DISTANCE IN NANOMETERS**
Nearest neighbor octahedral sites	0.28
Nearest neighbor tetrahedral sites	0.19
Nearest neighbor octahedral-tetrahedral sites	0.17
D-D distance in a multiply occupied vacancy [BES]	0.19
Intramolecular D-D distance in deuterium gas	0.074
Intramolecular D-D distance in liquid deuterium	0.074

Intermolecular D-D distance in liquid deuterium	0.27
Intramolecular D-D distance in water	0.15

The phase diagram of the Pd-H(D) system [ALEF, MEU] is typical of many of the bcc and fcc hydride forming systems and is shown in Figure 4.1. The dominant feature is a miscibility gap, i.e. a phase region in which the alpha and beta phases are in equilibrium, with a critical temperature of about 549°K and a critical composition of H(D)/Pd = 0.27.

At about 300°K the initial alpha phase has a solubility of about H/Pd = 0.03 and the two phase region extends to about H/Pd = 0.6 at which point the beta phase is formed. Both the alpha and beta phases have fcc structures. Phase relations in the Pd-H system depend on the isotope of hydrogen used, but the isotopic dependence is not very large. Important differences do exist in the P-C-T data [ALEF, MEU], which characterize the equilibrium of gaseous hydrogen isotopes with Pd. These differences are consistent with the differences in the isotopic masses. Many of the thermodynamic properties of the Pd-H(D) system are consistent with theoretical calculations based on mean field theory [WAG] based on a repulsive nearest neighbor interaction between H solutes. This repulsive interaction has been measured using a variety of methods [WAG, VOL, PIC, OAT].

While the alpha and beta phases are solid solutions of H(D) in the Pd interstitial sites, formation of long range ordered structures does occur at high concentrations and low temperatures [ELL]. These structures form by ordering of the H(D) interstitials on subsets of the interstitial sites and are consistent with nearest neighbor deuterium repulsive interactions. At H(D)/Pd = 1 the structure is of course ordered if the H(D) occupies octahedral interstitial sites. No hydrides are known to form at temperatures of the order of 300°K in the high concentration region of the phase diagram. Ordered hydrides do form at temperatures of a about 77°K [ELL]. Few careful investigations have been carried out in this region. Lattice parameter measurements [PEI], which extend into this composition region, indicate a linear lattice expansion in the alpha and in the beta phases up to H/Pd = 1.0. The lattice expansions due to H and to D are very similar.

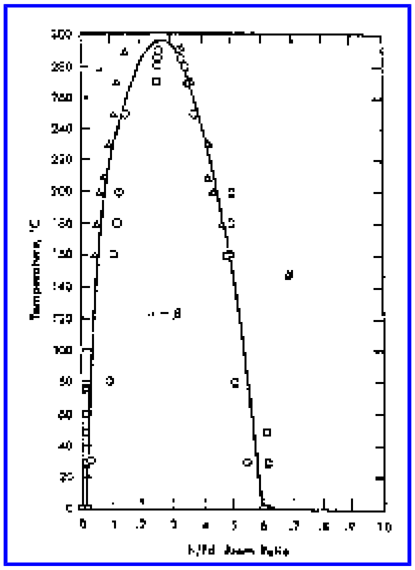

Figure 4.1: Phase Diagram of the Palladium - Hydrogen System

Click on thumbnail to see full-size image.

[[55]]

Hydrogen and its isotopes diffuse very rapidly in the Pd lattice [VOL] as shown in Figure 4.2. At 300°K, the diffusivity of H in the alpha phase is about $4x10^{-11}$ m^2s^{-1}. Hydrogen diffusivity in the beta phase is somewhat slower but is still very high. The effect of isotopic mass on diffusivity is very nonclassical in Pd with $D_D > D_W > D_T$ at 300°K, a clear indication of the quantum mechanical tunneling process which dominates the diffusion of H(D) in the Pd lattice. H(D) interacts with solutes and lattice defects, both of which can act as "traps" or low energy sites. The presence of these traps decreases the

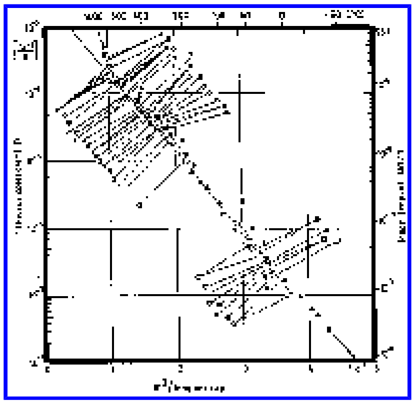

Figure 4.2: Hydrogen Diffusivity in Palladium

Click on thumbnail to see full-size image.

[[56]]

effective diffusivity of H(D) when they are unsaturated, i.e. at low H(D) concentrations. Under cathodic charging conditions, which correspond to high H(D) concentrations, the defect or solute traps are saturated and the diffusivity is little affected by their presence. With respect to the cold fusion experiments, an important point is that the known diffusivities of D in Pd allow equilibrium in times considerably shorter than those stated as necessary for attainment of cold fusion. For example, a time of the order of 7 days is required to achieve equilibrium during the charging of a 1 cm thick sheet specimen and a time of the order of 2 hrs is required for a 1 mm thick sheet.

Hydrogen charging of Pd can be carried out in several ways. Electrolytic charging with the Pd as a cathode has been carried out in a number of different electrolytes. In general, the Pd surface is highly active towards the dissociation of the H_2 (D_2) molecule. Little H_2 (D_2) gas is evolved until relatively high H(D)/Pd ratios are obtained. Additions of "poisons", such as arsenic ions, to the electrolyte increase the fugacity of the H (D) at the surface by decreasing the formation rate of H_2 (D_2). A higher H(D)/Pd value can then be obtained with the same overvoltage. Since the fugacity of hydrogen, i.e., the variation of the chemical potential of hydrogen from the standard state at one atmosphere, depends on the overvoltage, as well as on the surface conditions, it is difficult to obtain a direct relation between the cathodic charging conditions and the H(D)/Pd values obtained. Although the units of fugacity are identical to those of pressure, the non-ideality of H_2 (D_2) results in the equivalent pressure at high fugacity being many orders of magnitude less than the fugacity. A calibration of the equivalent pressure can be obtained by equilibrating the Pd alternatively with both an electrolytic potential and a high pressure H_2 (D_2) gas at the same H(D)/Pd value.

Gaseous charging of hydrogen is also commonly carried out [BARC]. High H(D)/Pd ratios can be obtained for relatively moderate pressures as shown in Figure 4.3. The data for the Pd-D system is not expected to differ greatly as the isotope effect on solubility is classical. Solution of H(D) in Pd follows Sievert's Law at low pressures and then shows significant deviations from ideal solution behavior, probably as a result of H(D)-H(D) interactions in the Pd. In the region of Sievert's Law behavior, the proportionality of the H(D)/Pd to the square root of the gas pressure is further evidence for solution of H(D) in Pd in the atomic form rather than as a molecule.

Concentrations of D/Pd = 1 are sometimes claimed in cold fusion experiments, and are often quoted as a necessary condition. It has also been suggested [FLE] that the very high confinement pressures produced by electrolytic charging are necessary for cold fusion. Comparison of the D/Pd values attained by gaseous charging with electrolytic charging allows an estimate of these "confinement pressures" to be made. A concentration of about H/Pd = 1 requires a gas pressure of about 150k bars (about 15,000 atm.) at 300°K [BARO] as deduced from Figure 4.3. Thus the effective pressure corresponding to the high fugacities calculated from the overvoltage during cathodic charging to the assumed D/Pd = 1 is equivalent to the very moderate gas pressures required to attain the same H(D)/Pd value.

[[57]]

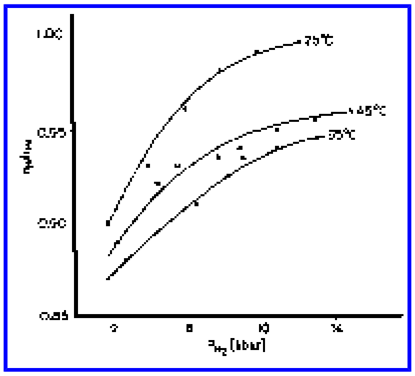

Figure 4.3: Concentration of Hydrogen in Solid Solution vs Gas Pressure

Click on thumbnail to see full-size image.

Palladium is an "exothermic occluder" of H(D), i.e. the heat of solution, relative to the gas phase as a standard state, is negative. The heat of solution is relatively small having a value of -19 kJ/mole H_2 in the alpha phase [MEU, WIC] a value of about -46 kJ/mole H_2 in the beta phase. The heats of formation of the hydrides in the Pd-H(D) system have not been measured. Hydride heats of formation of many other systems have been measured, are generally exothermic, and lie in the range -58 to - 209 kJ/mole H_2 [MEU]. There is only a small effect of isotopic mass on these values. The significance of the values is that the molal enthalpy change on forming the deuteride from a solid solution of the same concentration would be the (heat of formation of the hydride) -

(the heat of solution). This value is about -150 kJ/mole or less and represents the upper limit of the heat released from the specimen due to an ordering reaction at high concentrations of D.

Formation of the beta phase from the alpha phase during charging causes a large amount of lattice strain and deformation [HO] as a result of the large increase in volume. Since the molar volume of the beta phase is larger than that of the alpha, the beta phase is in compression during charging and plastic deformation occurs in the alpha phase. On removing the H(D) the decrease of volume that accompanies the beta to alpha phase change causes very high tensile stresses and surface cracking.

[[58]]

B. The Titanium - Hydrogen (Deuterium) System

While considerably less is known about the Ti-H(D) system than about Pd-H(D), our knowledge is sufficient to answer many of the questions of interest for the cold fusion experiments. Hexagonal close-packed (hcp) titanium absorbs H(D) in the alpha solid solution up to concentrations of about H(D)/Ti = 0.05 at 300°K. Low temperature measurements are not very accurate due to surface oxides which impede the absorption of H(D) from the gas phase. Above this concentration a two phase equilibrium exists between the hcp alpha solid solution and the gamma hydride. This hydride exists over the composition range $TiH(D)_{1.9}$ to $TiH(D)_2$. The hydride has a fluorite face centered cubic (fcc) structure at the lower compositions and a face centered tetragonal structure as the H(D) concentration is increased. At temperatures above about 570°K the alpha phase H(D) solubility is about H(D)/Ti = 0.1 and the solid solution is in equilibrium with the body centered cubic (bcc) beta phase as shown in the phase diagram displayed in Figure 4.4. The beta phase has a very high solubility for H(D) of the order of H(D)/Ti = 1. Above this composition the beta phase is in equilibrium with the dihydride, $TiH(D)_2$.

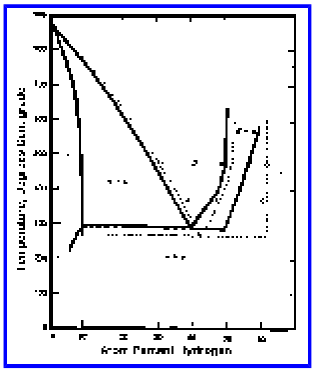

Figure 4.4: Titanium - Hydrogen Phase Diagram

Click on thumbnail to see full-size image.

[[59]]

Since the beta phase of Ti can be stabilized to below 300°K by solute additions, it is possible to absorb large quantities of H(D) into the beta stabilized alloys at temperatures near 300°K without forming hydrides. The extent of this low temperature H(D) solubility in the beta stabilized Ti alloys has not been established [SHI-2]. Gas phase cold fusion experiments have utilized Ti alloys as well as unalloyed Ti. In some cases these alloys have been specified to be Ti-6A1-6V-2Sn [MEN] which is an alpha-beta alloy, i.e. it was a two phase alloy mixture of the hcp and bcc phases. These two phase alloys have been studied in H atmospheres without noting unusual behavior with respect to the properties of H.

Site location studies have been carried out for some of the Ti - H(D) structures. Random occupancy of tetrahedral sites in the non-stoichiometric gamma hydrides was deduced from NMR measurements [STA-1]. The nearest neighbor D-D distances in the gamma hydride phase [SID] are shown in Table 4.B below. If we assume tetrahedral site occupancy in the hcp alpha phase and both octahedral and tetrahedral site occupancy in the beta phase, the nearest neighbor distances given in Table 4.B below can be calculated. As can be seen, these are larger than the D-D distances in the molecule and much larger than the distances required for fusion.

Table 4.B

DEUTERIUM - DEUTERIUM DISTANCES IN TITANIUM

	D-D Distance in nm
Alpha Phase (Hexatherman Close-Packed)	
Nearest neighbor tetrahedral sites	0.23
Gamma Phase (Face Centered Cubic)	
Nearest neighbor sites	0.22

Beta Phase (Body Centered Cubic)	
Nearest neighbor octahedral sites	0.17
Nearest neighbor octahedral-tetrahedral sites	0.083

The thermodynamics of the Ti - H(D) system has been extensively studied. Heats of solution for H(D) in the alpha and the beta phases are exothermic as is the formation of the gamma hydride. The isotopic mass dependence is very small. These enthalpies are given in Table 4.C below [STA-2, STA-3, MCQ, HAGG, MOR]. Since the heats of solution are negative (exothermic), Ti and its alloys absorb D as they are cooled in D_2 gaseous atmospheres and desorb D on heating.

[[60]]

While diffusion of H(D) in Ti has not been measured, the diffusivity at 300°K can be deduced from permeation experiments to be about 1×10^{-10} m^2s^{-1}. This diffusivity would allow equilibration of a 1 mm thick sheet with the H(D) gas atmosphere in about 0.7 hrs. Equilibration of Ti with gaseous H_2 at low temperatures is slow due to surface oxides which inhibit the entry processes. Even under cathodic charging conditions, entry of H(D) is inhibited unless the surface oxide is minimized and "electrolytic" poisons are used to minimize the recombination reaction which leads to H_2 formation at the surface. As a consequence, equilibration in a gaseous atmosphere or under cathodic charging is dominated by surface reactions.

Table 4.C

ENTHALPIES OF SOLUTION AND FORMATION

(kJ/mole H)

	DEUTERIUM	HYDROGEN
Solution in alpha phase	-90.4	-94.6

Solution in beta phase	-116.4	
Formation of gamma phase	-138	-121

Titanium hydrides are brittle and undergo cleavage when stressed. Hydride formation in alpha phase alloys causes embrittlement [SHI-1]. The beta phase alloys are much less susceptible to embrittlement, and can absorb large quantities of H(D) without fracturing. The tendency to fracture during absorption and desorption of H(D) is clearly associated with the hydride (deuteride) formation and the large volume changes which accompany these phase changes. It is not surprising that the gas charging cold fusion experiments report fracturing of Ti specimens used as the D is absorbed and desorbed. This fracturing is most likely to occur during the heating of specimens which have absorbed large quantities of D. During the cooling cycle the Ti absorbs D from the gas phase and the D composition gradient (and its accompanying molar volume gradient) causes a compressive stress at the outer portion of the specimen. During the heating portion of the cycle the loss of D causes tensile stresses at the outer parts of the material and these cause the fracture to occur.

[[61]]

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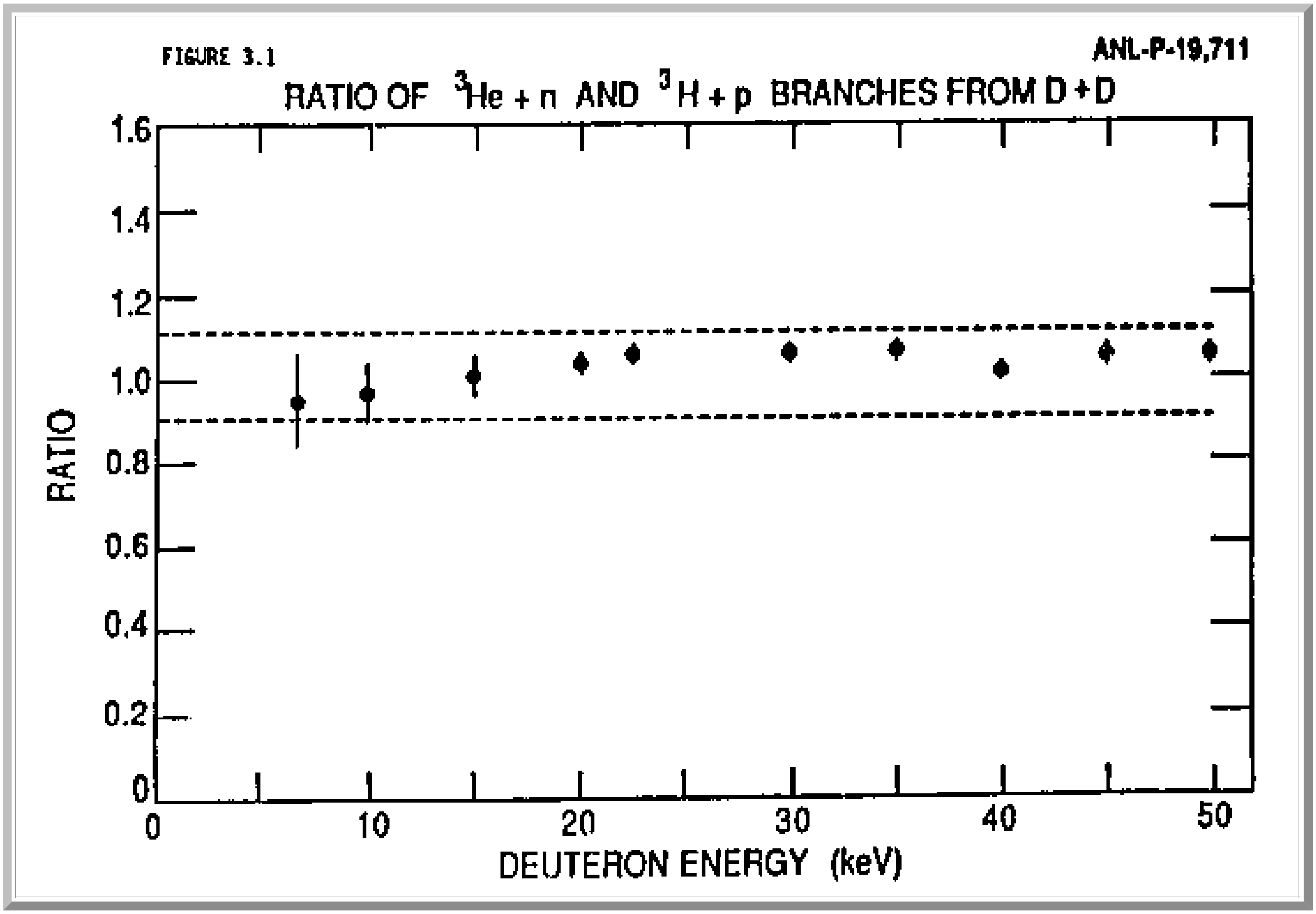

Figure 3.1: Neutron & Proton Branches of the D+D Reaction

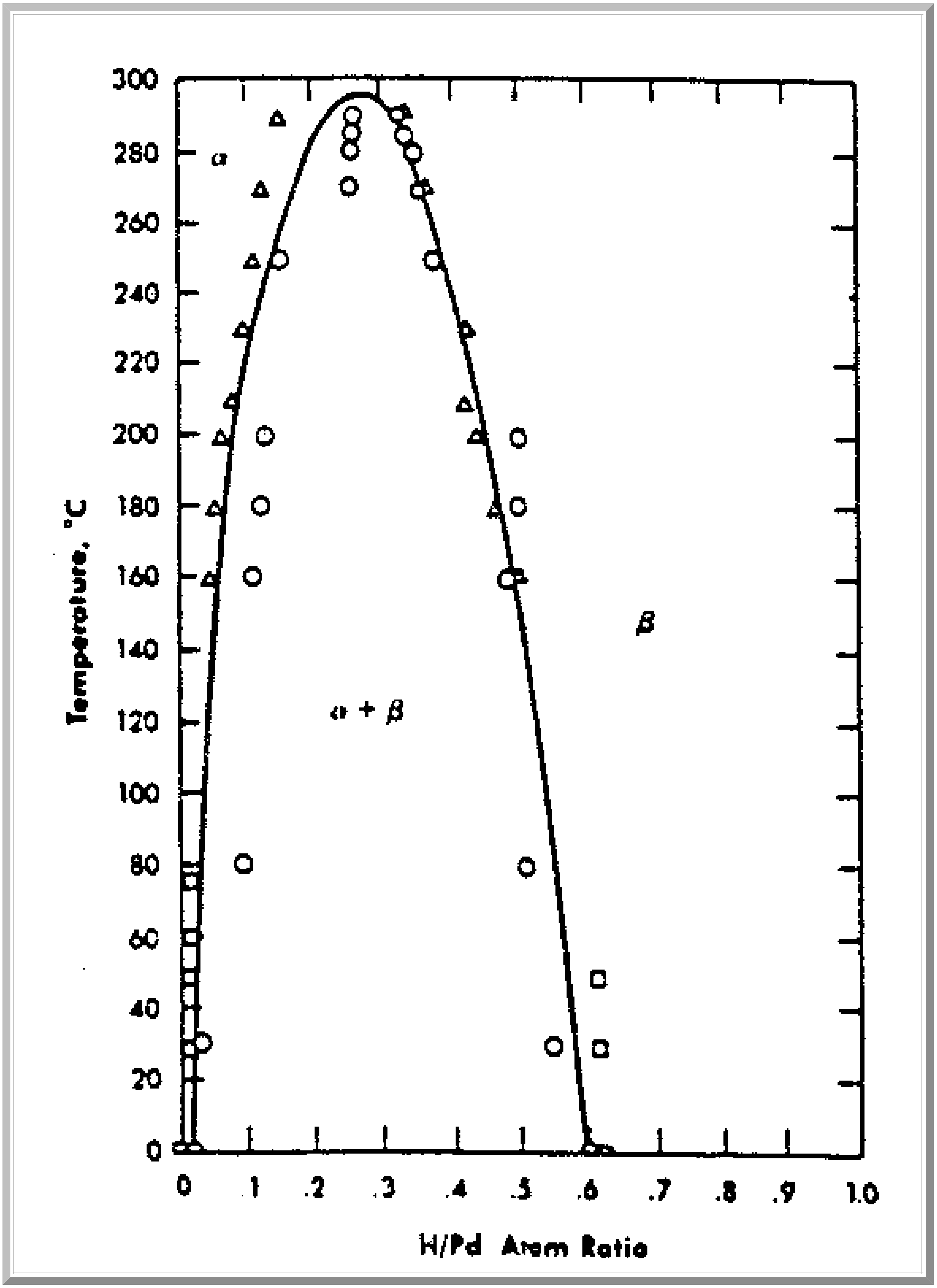

Figure 4.1: Phase Diagram of the Palladium - Hydrogen System [MEU]. The beta phase extends to H/Pd values greater than 1.0.

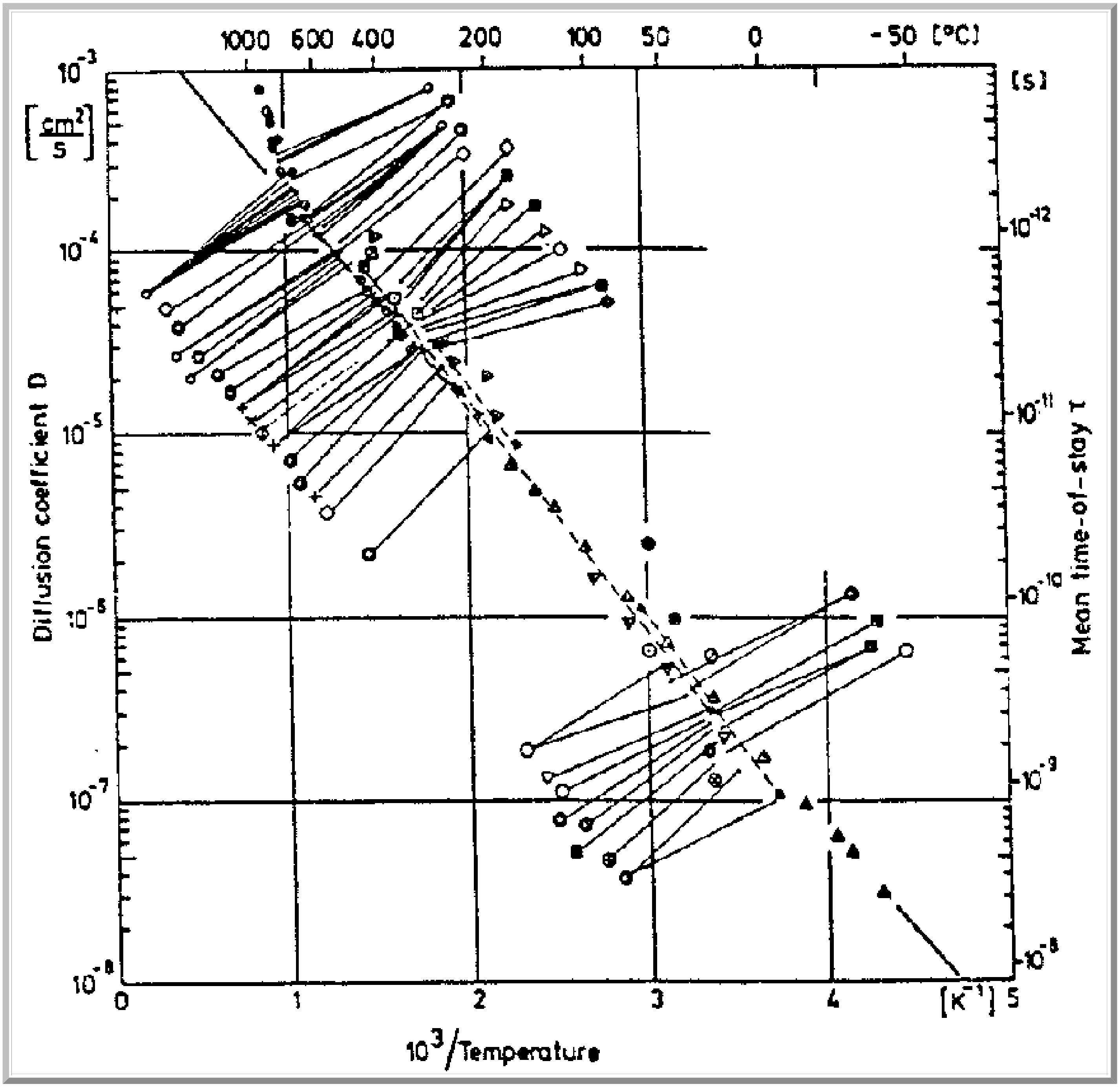

Figure 4.2: Hydrogen Diffusivity in Palladium [VOL]

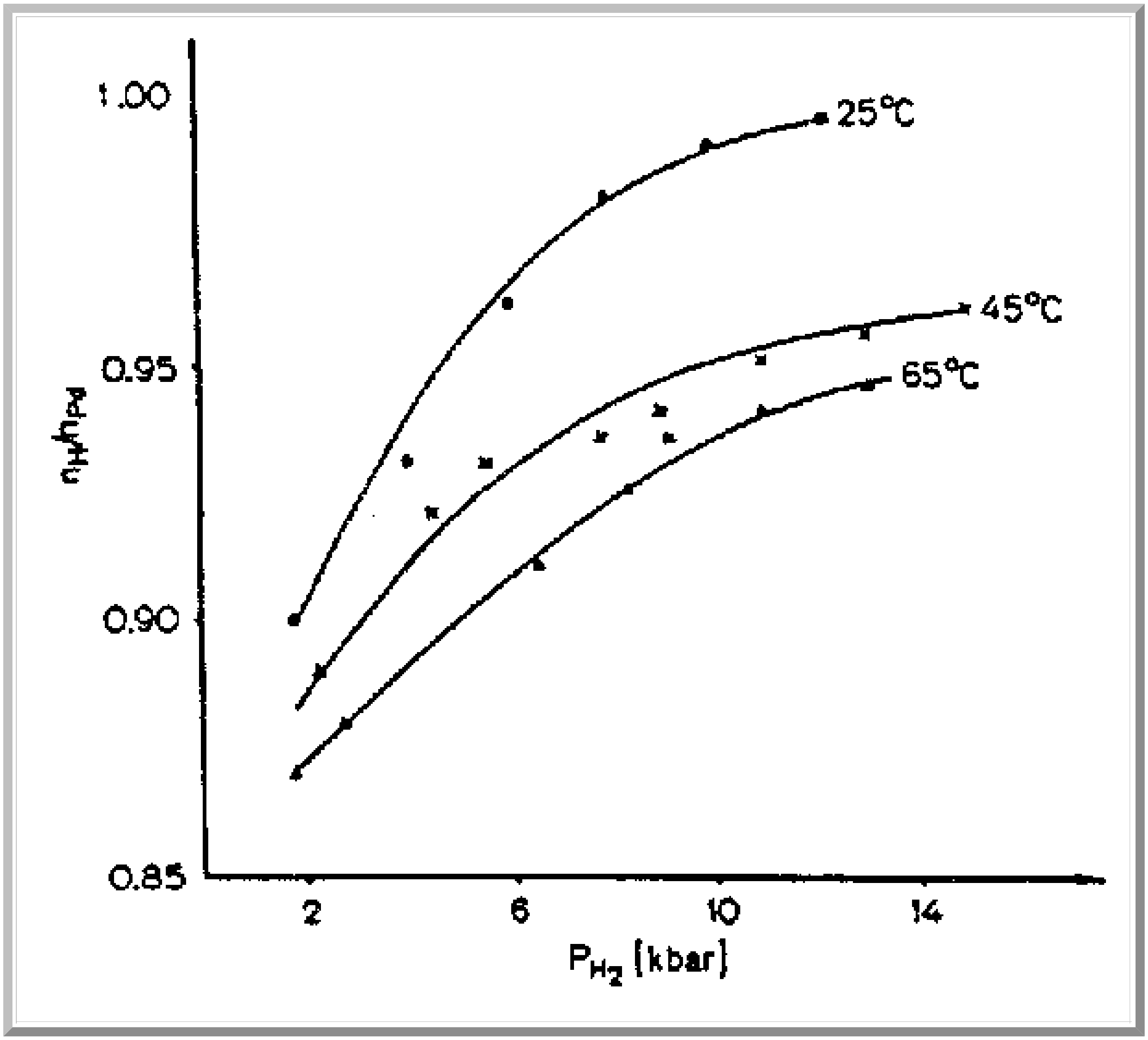

Figure 4.3 Concentration of Hydrogen in Solid Solution vs Gas Pressure [BARO]

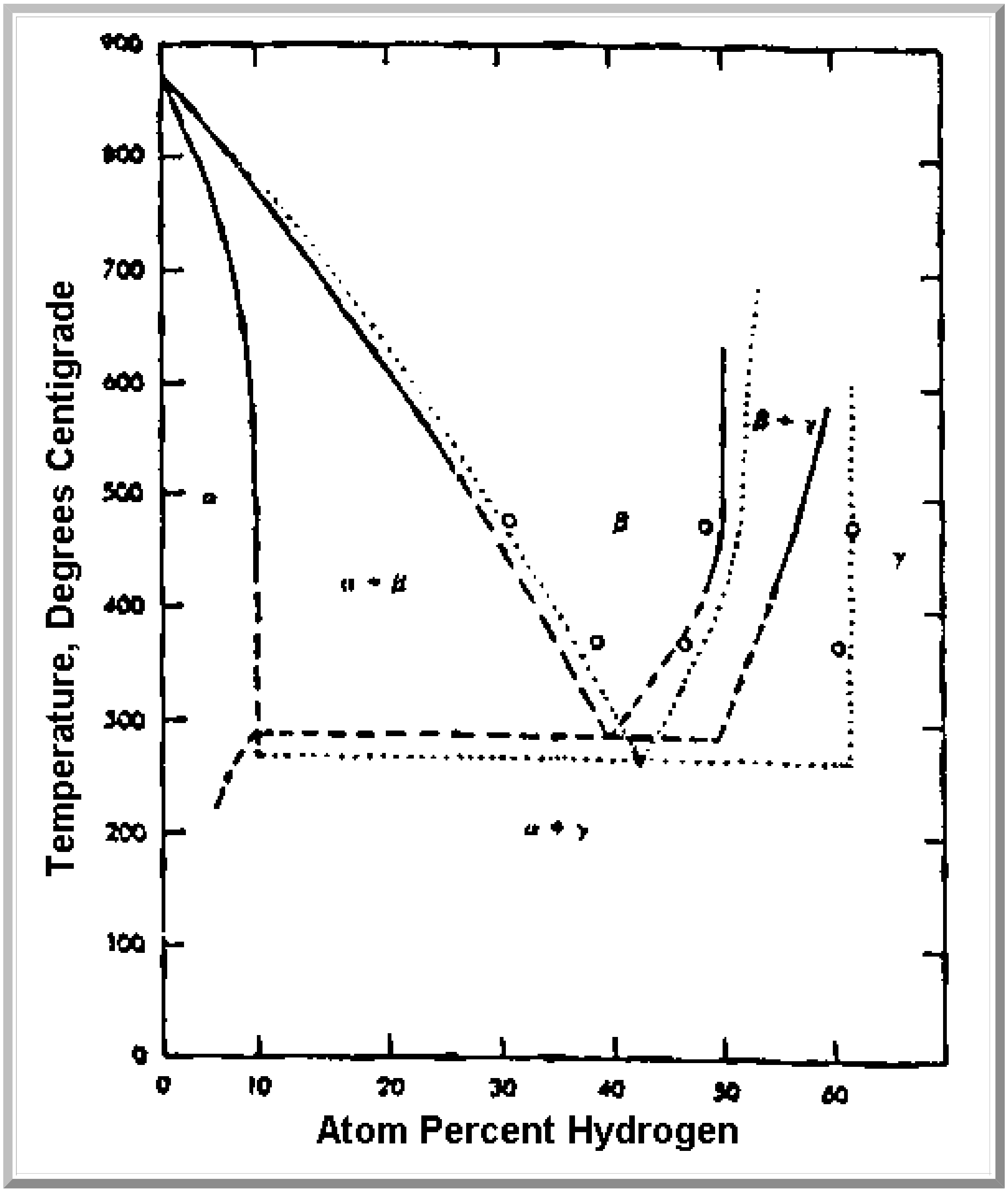

Figure 4.4: Titanium - Hydrogen Phase Diagram [MEU].

(The concentration is shown in atom percent; H/Ti = 1 corresponds to 50 atom percent)