Cold Fusion Overview

and Executive Summary

by

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National Cold Fusion Institute
University of Utah
Salt Lake City, Utah

1-1
Table of Contents

I. Status of Cold Fusion 1-3
   1. Political and Financial Status in the United States 1-3
   2. Climate of Cold Fusion Abroad 1-4
   3. Technical Status of Cold Fusion 1-5
      a. Excess Heat 1-9
      b. Nuclear By-Products 1-10
      c. Excess Heat and Nuclear By-Products 1-13
      d. Theoretical Aspects 1-15
      e. Conclusions 1-16
      f. References 1-17
      g. Cold Fusion Review Articles 1-19

II. Executive Summary of National Cold Fusion Institute Work 1-20

III. Conclusions 1-28

IV. Cold Fusion Bibliography 1-29
I. Status of Cold Fusion

1. Political and Financial Climate in the United States

Recent strong findings in support of the reality of cold fusion, obtained at several Navy laboratories, Los Alamos National Laboratory, and the National Cold Fusion Institute, are giving rise to the hope that the perception of cold fusion in the scientific community and the public will be improving.

Presently, however, in spite of very encouraging scientific results obtained in cold fusion work, both in the United States and abroad, the political and financial climate in the U.S. remains generally negative. In public interview with the media in February, an official of the U.S. Department of Energy continued to express a negative attitude towards cold fusion, making it very difficult to obtain funding of cold fusion work from the Department of Energy until more significant positive evidence for cold fusion may change this environment. Other U.S. government agencies that had funded cold fusion work one year ago, have terminated or decreased their level of funding. However, the Electric Power Research Institute continues funding cold fusion work in the United States, and it is estimated that this Institute has appropriated approximately 1.5 million dollars in 1991 in support of cold fusion studies.

Several government laboratories are continuing their work on cold fusion, among them most notably are Los Alamos National Laboratories, The Naval Research Laboratory, The Naval Underwater Systems Command and The Naval Weapons Center. Significant positive results have been obtained in each of these laboratories. It is estimated that the rate of spending in these laboratories amounts to approximately $500,000 annually. At Universities, cold fusion efforts are continuing at Brigham Young University, Texas A&M University, Idaho State University, Colorado School of Mines, Arizona State University, The University of Tennessee, Massachusetts Institute of Technology, the University of Hawaii and a few others.

At the National Cold Fusion Institute, the University of Utah, the cold fusion effort in fiscal year 1991 has continued with about 15 technical personnel at an annual rate of expenditure of approximately $800,000.

All combined, it is estimated that the current rate of expenditures for cold fusion efforts nationally amounts to approximately four million dollars annually.
Corporate laboratories appear to be mostly in a holding pattern with respect to cold fusion work and are carefully monitoring advances made in cold fusion elsewhere.

Based upon the good progress achieved in cold fusion work in the U.S. and abroad, it is predicted that cold fusion work in the U.S. will be expanded slowly and cautiously within the next year. It will be unavoidable that the weight of convincing scientific results will have a positive impact on the willingness of government funding agencies and corporations to invest more money in cold fusion work.

2. Climate of Cold Fusion Work Abroad

Japan continues its diverse involvement in cold fusion with what is most likely the largest effort anywhere. Reportedly, Japan now devotes 2% of its fusion budget to cold fusion studies. This would indicate that the number of groups and researchers involved in cold fusion work last year has increased. Last year, an estimated 200 researchers were involved in cold fusion studies in approximately 40 groups, mostly at universities.

Probably the second largest effort in cold fusion overseas is in Russia. The Soviet Academy of Science has given cold fusion a priority designation and work in over 20 institutions is now reportedly financed with $15 million Rubels for four years. The recent first Soviet National Conference on cold fusion that took place in Dubna, from March 22-26, 1991, bears witness to the increasing interest in cold fusion in Russia. The meeting was attended by over 100 scientists, and 60 papers were presented dealing exclusively with nuclear effects in deuterium-loaded solids.

An increasing number of groups appears to work on cold fusion in China. This involves at least 10 groups at different universities and at the Chinese Atomic Energy Center. Various Chinese cold fusion researchers have been participating in cold fusion conferences, such as the Provo-Utah Conference in October 1990. Also, Chinese scientists are performing cold fusion work on a Visiting Scientists basis at several universities in the U.S.

Cold fusion work is also continuing at the Bombay Atomic Research Center in India, although at a somewhat reduced level. Last year, approximately 40 researchers
were involved in cold fusion work in India, most of them at the Atomic Research Center in Bombay.

In Europe, it appears that Italy continues to have the largest cold fusion effort. Work is carried out at a number of universities across the country. The forthcoming Second International Cold Fusion Conference, a continuation of the First Cold Fusion Conference held in Salt Lake City in March 1990, will take place in Como, Italy from June 29 - July 4, 1991. This conference is expected to be attended by over 300 scientists with over 70 papers scheduled for presentation.

Work on a smaller scale continues in several other countries, among them, Argentina, Australia, Bulgaria, Canada, Germany, Isreal, Spain, Sweden and Taiwan.

3. Technical Status of Cold Fusion

Significant progress has been achieved in cold fusion, particularly in the area of nuclear phenomena. This is evident from the large number of papers published in the literature and from the fact that the two last major conferences on cold fusion, those in Provo, Utah and Dubna, Russia, have almost exclusively addressed nuclear phenomena rather than excess heat findings. Nevertheless, important excess heat findings have also been reported by several groups within the last year. Several of these new results were on excess heat, coupled with the generation of nuclear by-products.

An updated compilation of the groups that have reported to have found various manifestations of cold fusion is presented in Table 1. Over 100 groups from more than 12 countries have now reported on various types of evidence for the occurrence of nuclear reactions in deuterium-loaded metals or compounds. This includes evidence for excess heat, tritium, neutrons, x-rays or gamma rays, helium or charged particles. Results of this work have been presented in over 500 publications. A bibliography is given at the end of this Overview and Executive Summary.

Several review articles have also been published in the past year and are listed separately after the references of the Technical Status of Cold Fusion. In view of the existence of these review articles, only the highlight results obtained in cold fusion work will be addressed in the present overview.
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TOTAL NUMBER OF GROUPS: 130
NUMBER OF COUNTRIES: 14

* Key: 1 = Refereed Journal Publication
        2 = Conference Proceedings
        3 = Non-refereed Report
        4 = Conference Presentation
        5 = Newspaper Article
        6 = Personal Communication
        7 = Submitted to Journal
        8 = Patent/Patent Application
Highlight results presented in this overview will be grouped into three major categories: a) Excess heat. b) Nuclear by-products. c) Excess heat coupled with nuclear by-products. d) Theoretical Aspects. e) Conclusions.

a. Excess Heat

Fleischmann and Pons continue reporting excess heat findings, measured by isoperibolic calorimetry, carried out in double-walled, evacuated glass cells. In a paper published in July 1990 [1], they reported on continuous excess heat generation of 10 to 35% corresponding to more than 100 W/cm³Pd. They also reported on rare heat bursts of up to 4000% excess power. The energy generated in these heat bursts is equivalent to between 5 and 50 megajoules/cm³Pd. More recently, they have said to have identified a parameter that is the key to the reproducible generation of excess heat [2]. Reportedly, the generation of large excess heat events occurs after 9 to 10 days of electrolysis [3].

At the Provo-Utah meeting in October 1990, Liaw and Liebert [4] reported on the achievement of excess heat values up to 1500% in a molten salt eutectic, containing molten LiD at 380°C. Excess energy values of up to 5 megajoules were obtained in a 190 hour time span. No excess heat was observed in a LiH control cell.

McKubre [5] at Stanford Research International, sponsored by the Electric Power Research Institute, reports finding up to 10% excess heat which can be switched on and off on demand by raising and lowering the current into the electrochemical cell. Apparently, the heat-producing palladium electrodes had been preselected on the basis of whether high loading with deuterium had been achieved in electrochemical cells outside of the calorimeter. In spite of the fact that the excess heat attained is only 10%, the result is regarded as very significant due to its reproducibility and the high accuracy of the calorimetric technique employed. Furthermore, no excess heat is generated in light water control cells.

In an international patent application published in February 1991, Schoessow [6] claims up to 63% excess heat generation in electrochemical cells employing palladium, titanium and zirconium cathodes. Light water controls did not exhibit any excess heat, and heavy water cells that originally produced excess heat ceased to generate excess heat when large amounts of light water were added.
b. Nuclear By-Products

A significant number of results has been obtained during the last year on the generation of nuclear by-products, in particular, neutrons and tritium, and to a lesser extent charged particles, helium and gamma radiation.

Neutrons

Jones [7] was the first to determine the energy of neutrons emitted during deuterium loading of palladium and titanium cathodes in electrolytic cells. He employed a fast neutron spectrometer to measure an energy of 2.5 MeV, showing the occurrence of deuterium fusion at room temperature. Shortly thereafter, DeNinno et al [8] detected neutron bursts up to 5,000 per second on titanium in deuterium gas. Since then, considerable refinement in instrumental techniques has occurred. This has led to significantly higher counting efficiencies and much reduced background.

Menlove [9] at Los Alamos National Laboratory conducted experiments on titanium filings in deuterium gas in an underground laboratory, employing 51 $^3$He tubes, arranged in two concentric rings. This resulted in a counting efficiency of 44%. When performing the experiments in an underground laboratory, the coincidence neutron count background was only 0.03 counts per hour. Neutron events were counted in a time gate of 128 $\mu$sec. When temperature-cycling the titanium between -190 and 25°C, neutron bursts of 200 - 300 neutrons in the 128 $\mu$sec time gate were observed. The most intense bursts occurred at -30°C. Superimposed on the neutron bursts was a rather continuous low-level neutron activity, amounting to three counts per minute.

Menlove's findings substantiated the earlier neutron results of DeNinno on deuterium-loaded titanium. A large number of other groups have in the meantime also confirmed these findings.

Takahashi [10] at the University of Osaka, Japan, measured the energy spectrum of neutrons emitted during heavy water electrolysis, using palladium cathodes. The energy spectrum of the neutrons showed a peak at 2.5 MeV and a second broader peak at about 4.5 MeV. The neutron intensities were fairly low, amounting to 1.5 to 2 x above background. But, significantly, the neutron emissions were found to be time-related to the electrolysis conditions: The neutron intensity
increased when the current density was increased and vice versa. The energy maximum at 2.5 MeV is expected for d-d fusion. However, the maximum at 4.5 MeV cannot be readily reconciled with that reaction. Takahashi postulated a 3-body reaction namely, d-d-d. In quantum mechanical calculations, Takahashi was able to show that the probability for this reaction in a palladium lattice is about as high as for the d-d reaction. Other investigations have in the meantime substantiated the finding of a neutron energy maximum around 5 MeV.

Tritium

Storms and Talcott [11] made an extensive study of tritium production on Pd in heavy water electrolysis. They found tritium enhancement in 11 out of 53 cells at levels of 1.5 to 80 times the original concentration. The accumulation of tritium in the electrolyte with time of electrolysis was also determined. Tritium production was found to start within two to several days of starting the electrolysis and on cathodes having a D/Pd ratio as low as 0.7. However, the D/Pd ratios were determined by weighing and are likely to be too small, owing to D loss, especially at high loading ratios. Only one light water control cell was run which did not show any tritium enhancement.

In another extensive study of tritium generation during heavy water electrolysis involving titanium, palladium and palladium-silver alloys, researchers at the Bombay Atomic Research Center (BARC) have consistently found significant tritium enhancement in the electrolyte [12, 13]. In 11 separate electrolytic experiments, they found cumulative tritium generation, in experiments run between 12 hours and 190 days, from $1 \times 10^{10}$ to $1.7 \times 10^{14}$ tritium atoms/cm$^2$. The electrolytes in these experiments were mostly LiOD, but also NaOD and KOD.

Tritium and Neutrons

BARC also conducted an extensive study of simultaneous neutron and tritium generation [12, 14]. In 10 separate experiments, performed on palladium, palladium-silver and titanium cathodes, they found total neutron yields from $1.3 \times 10^4$ to $3 \times 10^6$ neutron/cm$^2$ and tritium yields from $4 \times 10^9$ to $5 \times 10^{13}$ tritium atoms/cm$^2$. The neutron to tritium ratio in these experiments amounted to between $1.2 \times 10^{-9}$ and $10^{-3}$.

T. Gamo et al [15] at Matsushita Electric Industrial Co., explored a large number of metals and alloys for their nuclear activity when loaded with deuterium either in electrolytes or in deuterium gas. On a TiZn$_2$ cathode, they observed 2.45 MeV
neutrons at 10 x background and tritium enhancement in the electrolyte 5 x above the initial amount. Tritium enhancement up to 10 x background was found on ZrV0.5 Ni1.5. When using the same alloy in pressurized deuterium gas, neutron bursts 1000 x background were observed for 1 minute. Likewise, tritium enhancements of about 4.5 times background were observed during heavy water electrolysis using Ti2 Ni cathodes.

Claytor et al [16] at Los Alamos National Laboratory performed studies in deuterium gas, employing a stack of alternating layers of palladium-silicon and of titanium and silicon. After applying pulsed high current densities to this solid state device, he found tritium enhancements of 3 sigma in 8 out of 30 such cells. He also found neutron bursts slightly above background, that is at up to 760 counts per hour as compared to a background of 712 counts per hour. The tritium to neutron ratio was also found to be significantly larger than 1, often of the order of 10^9 : 1.

Recently, several groups at the National Cold Fusion Institute have found tritium and neutrons in both electrolytic and gas phase experiments on palladium as well as titanium. Cedzynska et al [17] developed a technique to reproducibly generate high D:Pd loading ratios and tritium, employing palladium cathodes in D2SO4 solutions. Tritium enhancements of up to 100 x background were observed in both electrolyte and palladium. Neutron generation was observed only on rare occasions, at rates from 4 to 12 counts in 300 to 400 μsec. No tritium generation or neutron emissions of this type were observed on light water controls, equal in number to the heavy water cells. Peterson et. al [18] observed tritium enhancements of up to 120 x in palladium, loaded in D2 with the Wada technique. Neutron bursts up to 280 neutrons in 120 μsec were observed in the same experiment. McIntyre et al [19] found tritium in D2 gas-loaded titanium after temperature-cycling. Neutron emissions of 5 to 10 neutrons in 400 μsec were observed in these experiments.

**Charged Particles**

Taniguchi [20] was the first to detect the emission of charged particles from thin Pd foils used in heavy water electrolysis. He employed a cell design in which one side of the Pd foil was exposed to the electrolyte and the other side was in contact with a silicon surface barrier detector. Charged particle emissions were observed in 6 out of 23 experiments conducted in D2O solutions, whereas none of 7 light water controls showed particle emissions. The maximum energy of the particles was 2.1 MeV. This
observed energy is consistent with 3 MeV protons originating in the palladium and being attenuated in the Pd; this is indicative of cold fusion, since 3 MeV protons would be generated in the tritium-proton branch of a d-d fusion reaction.

Cecil et al. [21] at the Colorado School of Mines found evidence for charged particle emissions when conducting experiments on titanium in deuterium gas. The titanium foils were subjected to temperature cycling from -190 to 25°C and a d-c current density of 4A/cm². He also used a silicon surface barrier detector to determine the energy spectrum of the emitted charged particles. Such particles where omitted in bursts at 25°C with one second to a few hours duration. The energies of the emitted particles were measured to be between 1 and 10 MeV. Cecil suggested that the charged particles were either tritons, ³He or ⁴He ions. Twelve out of 26 deuterated titanium samples showed such bursts, whereas none out of eight hydrogenated control samples showed bursts. Similar bursts have been observed on deuterated palladium foils.

**c. Excess Heat and Nuclear By-Products**

Bockris et al. at Texas A&M University [22] found large amounts of tritium in both the electrolyte and the gas phase in conjunction with excess heat. The group conducted heavy water electrolysis, employing Pd cathodes. The excess heat generation amounted to values between 10 and 22% for over one month. Tritium accumulated in the electrolyte to values as high as 2 x 10¹⁴ tritium atoms. Similar peak values were measured in the gas phase after recombining the gas to water. More generally, however, values in the gas phase were between 3 and 7 x 10¹¹ tritium atoms/cm². Such values are very similar to the tritium findings at BARC [12].

Scott et al. [23], employing an accurate flow calorimeter cell, found the simultaneous occurrence of excess heat, neutrons and gamma radiation. The studies were conducted on Pd in LiOD. The excess power ranged from 5 to 10% for periods of up to 300 hours. In several cases, the neutron and gamma count rates increased slightly, in apparent correlation with the time periods of excess heat generation. While the increases of the count rates over background were small, the coincidence with induced excess power were seen as giving added credence to the results. Addition of light water to the electrolyte resulted in reduction of the excess power and decrease of the neutron and gamma signals to background levels.
Gozzi et al. [24] at the University of Rome were able to associate neutron and tritium generation with excess heat production when charging a Pd cathode in LiOD solution. In a 4-minute period, in which the temperature rose from 36 to 150°C, $7 \times 10^5$ neutrons were emitted and excess tritium amounted to $2 \times 10^{11}$ atoms. The amount of tritium generated on this porous, high-surface area Pd is similar to the values found by Bockris et al. [22] and BARC [12] on smaller area electrodes but over longer times. The excess heat released in the 4-minute period amounted to 176 Joules (Wattseconds).

Szpak and Mosier-Boss [25] observed the generation of excess heat, concurrent with tritium generation and low-energy radiation, possibly soft x-rays. In their approach, they deposited Pd onto a Ni screen from a heavy water PdCl₂ solution. The Pd absorbed D while it was being deposited. Excess power amounted to between 10 and 40% and excess energy production was 2500 Joules. Tritium enhancement in the electrolyte amounted to a factor 10 over background. No excess heat or nuclear by-products were observed on a light water control cell.

Yamaguchi and Nishioka [26] at the National Telephone and Telegraph Laboratories in Tokyo, Japan found evidence for excess heat and nuclear by-product formation on palladium foils in deuterium gas. These researchers employed a solid state cell, comprised of a palladium foil with a gold film sputtered on one side and a manganese oxide film on the other side. They passed a current density of several A/cm² perpendicular to the face of the palladium foil. Temperature excursions of several hundred °C were observed, accompanied by the generation of products with mass three, most likely tritium or ³He. In one case out of 20 experiments, several large neutron bursts were observed in a 90-minute time period. Two of the bursts amounted to $10^6$ neutrons/sec.

Will and Yang [27] observed excess power excursions and tritium generation on a Pd cathode in a high-pressure, sealed electrolytic cell under conditions of evolving no oxygen. The standard-type of anode had been replaced with a fuel cell-type deuterium oxidation electrode. Excess power of up to 20 and 33 % was observed in two time intervals of 36 and 26 hours, respectively. Excess energy amounted to approximately 500 Joules. The tritium content in "hot spots" of the Pd cathodes was $4 \times 10^8$ tritium atoms, compared to a maximum initial content of $5 \times 10^7$. 
Probably the most dramatic finding of excess heat accompanied by nuclear by-product formation was recently made by Miles at the Naval Weapons Center in collaboration with Bush at the University of Texas [28]. They found excess heat up to 27% during heavy water electrolysis using palladium cathodes and were the first to show helium in the off-gas in very approximate proportion to the excess heat generated. They collected the deuterium and oxygen gas, generated during electrolysis, in a sealed glass flask. After cryogenic absorption of these gases, the helium was detected in a mass spectrometer. \( ^4\text{He} \) was observed at values up to 1000 times the detection limit of the mass spectrometer which amounted to \( 10^{12} \) \(^4\text{He} \) atoms. Light water control cells yielded no excess heat and no \(^4\text{He} \). Likewise, no \(^3\text{He} \) was found in any of the experiments.

**d. Theoretical Aspects**

A number of theoretical approaches have been advanced in an attempt to explain why fusion reactions might proceed in deuterium-loaded metals at ordinary temperatures. The principal challenge is to explain how the Coulomb barrier can be penetrated such as to raise the tunneling probability by some 50 to 60 orders of magnitude as compared to the barrier that inhibits d-d fusion in a \( \text{D}_2 \) molecule.

G. Preparata [29] has recently reviewed existing theories of cold nuclear fusion. Hence, several of the theories will only be highlighted here.

Bush [30] has proposed a transmission resonance model which applies the well-known quantum mechanical result that a periodic set of potential barriers becomes transparent (may be penetrated) if the diffusing particles—"diffusons"—have certain well-defined wave lengths, that is, move with well-defined velocities. Recently, Bush has used his model to calculate excess heat and to predict optimal trigger points for excess heat generation.

Hagelstein [31] has developed a model involving electron capture by a deuteron, resulting in two off-shell neutrons and a neutrino. The neutrons then proceed to react with protons or deuterons, requiring no Coulomb barrier penetration. Neutron capture by a proton, yielding a deuteron, is favored \( 10^4 \) times over capture by a deuteron, yielding a triton. The former reaction is exothermic, with the generated heat coupling to the metal lattice.
Rafelski et al. [32] proposed a model involving the interaction of yet undiscovered heavy negative particles with deuterium in the metal lattice. These particles are thought to be of ancient cosmic origin and cause a catalytic reaction similar to that of muon-catalyzed fusion which is well established.

Bressani et al. [33] and Preparata [34] applied superradiance theory to cold fusion phenomena in condensed matter. Their model involves the application of quantum electromagnetic field theory. The moving or oscillating charges, such as electrons, deuterons and palladium nuclei, have electromagnetic fields (plasmas) associated with them that provide for strong coupling. A central feature of the model is the coherent interaction of large numbers of charged particles. Coulomb barrier penetration is made possible by the presence of a sufficient electron density between two deuterons. Another factor $10^{10}$ enhancement of the fusion probability is predicted from an interaction between loosely bound deuterons and the entire system of strongly bound deuterons contained in a coherency domain. This leads to the theoretical prediction that high fusion rates will exist only if the D:Pd loading ratio has attained a critical value just larger than one. Under these circumstances, the model predicts the generation of large amounts of excess heat (tens of W/cm$^3$ Pd) by ultra-fast coupling of the fusion energy to the electron plasma. This process is predicted to vastly enhance the $^4$He channel while suppressing the neutron and tritium channels.

**e. Conclusions**

Cold fusion work continues in many countries with considerable pace in spite of the fact that the known funding level is fairly low. The degree of activity in cold fusion is evidenced by the attached bibliography which lists over 500 items. The occurrence of nuclear reactions in deuterium-loaded solids, such as palladium and titanium can no longer be reasonably denied. The generation of nuclear by-products, especially neutrons and tritium, has now been confirmed by a large number of groups worldwide. However, with the exception of one recent finding involving helium, the level of the nuclear by-products generated is smaller than the reported levels of excess heat by a factor of one million or more. If the observed heat is generated by deuterium fusion, then helium could still be the missing link that has not been pursued sufficiently by most groups. Other nuclear reactions may be involved, but then other nuclear by-products must be generated in sufficiently large quantities such as to correspond to the observed heat levels. The possibility that the excess heat is not of nuclear origin can
not presently be ruled out. Considerably more research is required to understand the phenomena involved and to explain the origin of the observed excess heat. This poses a significant challenge for both experimentalists and theoreticians.

The progress obtained in cold fusion work is impressive. Reproducibility of some of the phenomena appears to be in hand, enabling more systematic scientific work to be pursued.

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II. Executive Summary of National Cold Fusion Institute Effort

1. Introduction

The National Cold Fusion Institute was established in August 1989 with a State appropriation of $5 million dollars of which $4.5 million were earmarked for research and development and $0.5 million for patent and legal services. The forerunner of the Institute was the Cold Fusion Program, established in May 1989 under the direction of Hugo Rossi, who continued as Director of the Institute until December 1989. James Brophy served as Interim Director of the Institute from December 1989 - January 1990 until Fritz Will joined the Institute as Director in February 1990. The original research and development strategy of the Institute was based upon the hope that cold fusion phenomena could soon be exploited to build demonstration devices and engineering models. Thus, a broad-based interdisciplinary approach was initially taken, including efforts in all fields of interest to cold fusion work, that is, Electrochemistry, Metallurgy, Physics and Engineering. Strong emphasis was placed on increasing excess heat generation by devising an extensive parameter study, expected to culminate in building a heat demonstration device. The research strategy was reevaluated in the early summer of 1990, to address the following selected key scientific issues: 1) Increasing the understanding of cold fusion phenomena. 2) Developing an excellent analytical capability for analyzing tritium in palladium. 3) Expanding the study of loading of metals in deuterium gas. 4) Improving the neutron detection and developing charged particle detection capabilities. More specifically, emphasis was placed on identifying the factors influencing reproducibility and to explore possible methods to trigger and quench cold fusion phenomena. On the other hand, the budget for fiscal year 1991 made it necessary to de-emphasize the engineering effort and the visiting scientists/collaborative program.

2. Organization of Final Report

The presentation of the technical results in this final report will be made in three volumes: Volume I - Introduction and Executive Summary, Chemistry, Gas Reactions, Metallurgy and Physics. Volume II - Engineering. Volume III - Theoretical and Collaborative Studies. The results of the Electrochemistry Group are anticipated to be presented in Volume IV, together with the results of a review of the calorimetric data, currently being undertaken.
3. Highlight Results Obtained at National Cold Fusion Institute

a. Chemistry

It is generally accepted that tritium generation comprises one of the most important manifestations for the occurrence of deuterium fusion. Following widely published claims of one group at Texas A&M University that tritium, found in cold fusion studies, results from contamination of the palladium and not from nuclear reactions, we decided to address this issue in depth and to develop a reliable analysis procedure. An open-system analytical procedure, essentially identical to that used by the Texas group, was first developed and shown to be subject to erroneous results unless extraordinary precautions were employed. We, therefore, developed a new closed-system analytical procedure for the analysis of tritium in palladium. This procedure has a sensitivity and accuracy of $5 \times 10^7$ tritium atoms and is not subject to the shortcomings of the open-system procedure. We have applied this new procedure to over 100 as-manufactured palladium wire sample of various lots and sizes from two different sources. We have found none of these samples to have any tritium contamination within a detection limit of $5 \times 10^7$ tritium atoms. This closed-system procedure proved to be a key tool in our later successful demonstration of tritium generation in deuterium-loaded palladium and titanium.

In the past four months, we have successfully applied a continuous, reliable technique for the determination of the deuterium to palladium loading ratio, developed earlier by the Engineering Group. Application of this technique enabled us to develop, probably for the first time anywhere, a procedure to reproducibly attain D:Pd loading ratios of unity or slightly higher.

We were able to show that tritium could be generated reproducibly when loading ratios in the vicinity of one were achieved, whereas no tritium was found when the loading ratio was substantially smaller than one. Moreover, the tritium concentration in the electrolyte was found to increase linearly with time after a loading ratio close to one had been attained. These results were obtained in hermetically sealed cells in which the oxygen generated at the anode did not contact the palladium cathode. Tritium analysis was performed in the deuterium gas, the electrolyte and the electrode. Tritium enhancements in the electrolyte of up to 50 x and in the palladium of at least 10 times were observed. Light water control cells were always run in
electrical series with heavy water cells under identical conditions. None of the control cells ever showed tritium enhancements in the electrolyte or palladium cathode in spite of achieving loading ratios of one or slightly higher than one.

Several periods of neutron emissions were observed in these experiments. Neutron counting was done with an efficiency of about 2%, employing two $^3$He counters each at the D$_2$O cell and the H$_2$O control cell. On eight D$_2$O cells, a total of five neutron events were monitored with 4 to 14 neutrons counted in a time interval of 400 $\mu$s. Although such events occurred very infrequently in the D$_2$O cells, we regard their occurrence as significant, since none of these events occurred in an equal number of H$_2$O control cells. Single, double or triple neutron counts were, furthermore, disregarded.

We have also developed a novel electrochemical cell, operating in high-pressure deuterium and featuring continuous and automatic determination of the D/Pd loading ratio as well as no oxygen evolution. With this cell, we have found a tritium content in hot spots of the Pd cathode, corresponding to $2.2 \times 10^9$ atoms/g Pd, whereas the maximum tritium contamination level in the Pd is $3 \times 10^8$ tritium atoms/g Pd. In this 12-day experiment in which we achieved loading ratios in excess of 0.84, two periods of excess power generation occurred. In the first time interval, lasting 36 hours, the excess power amounted to approximately 20%, whereas in the second time interval of 26 hours, the average excess power was 15%, with peak values as high as 33%. In other heavy water cells with D/Pd ratios smaller than .75, no excess heat and tritium were observed. Also, none of several light water controls showed tritium or excess heat. Nevertheless, we regard these findings as tentative, pending duplication of the excess heat and tritium results.

b. Gas Reactions

In gas phase loading experiments of palladium with deuterium, employing the Wada-technique, we have found evidence for tritium generation in the palladium as well as neutron bursts. In this technique, two palladium electrodes are subjected to an electrical discharge, applying an a.c. voltage of typically 1 keV to activate the surface, followed by deuterium absorption. Neutron generation is monitored after the 10-20 minute electric discharge has been completed. Using one of NCFL's $^3$He neutron detection facilities with a collection efficiency of approximately 5%, six neutron generation events with between four and eight neutrons each were observed in a time
frame of less than 400 \( \mu \text{sec} \). Two more neutron events at 4.7 and 7.2 sigma levels were monitored in the early phases of the study with a germanium crystal gamma detector. These 8 neutron events were observed on a total 19 experiments conducted after the process conditions were under control. Several of the palladium electrodes showed definite tritium generation. The tritium distribution in the palladium electrode was usually highly non-uniform. In "hot spots" we observed tritium levels of up to \( 4 \times 10^{10} \) atoms/g Pd. Before the experiment, the Pd did not contain tritium within our detection limit of \( 3 \times 10^{8} \) atoms/g Pd. The most successful experiment was carried out in collaboration with Jones at Brigham Young University. In a time period of 120 hours, four neutron bursts were observed with three of the bursts amounting to between 20-30 source neutrons in a 115 \( \mu \text{sec} \) time gate and one burst amounting to 280 neutrons in the same time gate. Both of the palladium electrodes used in this experiment showed significant tritium levels of up to \( 1.5 \times 10^{11} \) atoms/g Pd.

In deuterium gas loading experiments on titanium powder, we have also observed significant tritium levels in the titanium and several neutron emission events. These experiments are similar to those originally carried out by the Frascati group in Italy. They involve deuterium loading of titanium, followed by temperature cycling between -190 and 25°C. We have found values up to \( 9 \times 10^{10} \) tritium atoms/g Ti on samples that had been temperature-cycled. A deuterated titanium sample that was not temperature-cycled and a hydrogen control sample showed no tritium. Neutron generation was also observed in these experiments, with 4 to 9 neutrons counted in 400 \( \mu \text{sec} \) with 5% counting efficiency. One, two and three-neutron events were not considered. Background measurements and an experiment performed on a hydrogen control never showed multiplicities of 4 or more neutrons.

c. Metallurgy

The dilatometer technique, measuring increases of the length of a palladium wire during loading with deuterium, was applied to determine the D/Pd and H/Pd loading ratio on Pd and Pd alloys. The effect on loading of various parameters, such as microstructure, hardness, surface condition, alloying, electrolyte composition and current density was investigated. Loading ratios between 0.7 and 0.93 were achieved and loading was found to change with applied cathodic overpotential. Addition of alloying elements reduced the maximum achievable loading ratio to less than 0.8. Microstructural studies indicate that at almost all practical current densities employed by different investigators, from a few hundred \( \mu \text{A/cm}^2 \) to 600 mA/cm\(^2\), plastic
deformation of the palladium electrode occurs. The resulting dislocation density is likely to result in an overestimation of the D/Pd ratio. Extensive micro and macrocracking observed in palladium at high current densities or after extended charging times lowers the maximum loading that can be achieved. Diameter changes of the wire (on a percentage basis) are larger than changes of the length. Therefore, simultaneous measurement of the diametral and axial expansion would be required to accurately determine the D/Pd loading ratio. This was not undertaken in this study.

The effect of ultrasonic energy input to electrochemical cells containing palladium cathodes and D₂O solutions was investigated. Cells which were subjected to ultrasonic energy always exhibited slightly higher temperatures and cell power than comparable cells without ultrasonic excitation, operated under otherwise identical conditions. Higher cell power persisted even in those cases where ultrasonic input was provided for only one hour each day. In several cases, excess power levels disappeared after a few days of cell operation. Stimulation of large excess power excursions what not observed.

Attempts were also undertaken to induce cold fusion events by explosive compaction of deuterated metals, alloys, as well as various deuterides. The compacted materials included Pd, Pd-Ti, PdDₓ, TiDₓ, Au-Pd-Pt, NiTi and metal matrix composites, such as TiAl-SiC. It was hoped that the unique compositions and microstructures, obtained by explosive compaction, might lead to cold fusion events. Slight enhancements in the tritium level, amounting to 20% above background were observed in several cases. In a single experiment involving TiD₂, indication for low-level neutron generation was observed, but could not be reproduced in further experiments.

A mathematical technique - called the Kalman filter - was developed to enable on-line calculation of excess heat produced during heavy water electrolysis employing Pd (or other) cathodes. The method proved particularly useful owing to its capability to determine excess heat in the presence of electric noise and process disturbances. The method was applied successfully to analyze excess heat data of a large number of cells. The calculated values were in agreement with values using other approaches.

Extensive calorimetric measurements were performed on over 40 palladium cathodes in electrolytic cells, employing LiOD solutions. Large temperature
excursions were observed in experiments with an initial cell design having large heat losses. These results were later explained on the basis of intermittent gas recombination, resulting in thermal transients in the cells. Two later cell designs with lower heat losses did not exhibit such large temperature excursions, and no excess heat was demonstrated in any of these cells within the accuracy of the calorimetry, that is, 2-3%. Electrolyte boil-off during a time period of a few hours was observed on one cell. Heat balance calculations resulted in the finding that no excess heat had been generated in the cell either before or during the boil-off.

d. Physics

The major thrust has been on building up and improving the nuclear by-product detection capabilities, collaborating with the other groups in detecting neutron generation, operating the liquid scintillation counter for tritium counting and making preparations for charged particle measurements in electrolytic-type and gas phase experiments. Initially, germanium single crystal counters and later helium-3 counters were used for neutron counting. This allowed neutron measurements with increased collection efficiency and in a time frame as short as of a few 1/1,000,000 of a second. Sophisticated electronics and event loggers were developed to make such measurements possible with a total of 12 helium-3 tubes. These neutron counting capabilities were successfully applied to detect small, but significant, neutron generation events in a variety of electrolytic and gas phase loading experiments, carried out, in particular, by the Chemistry and Gas Reactions Groups. Neutron generation events were observed (1) on palladium electrodes, highly loaded with deuterium in electrolytic solutions, (2) on palladium electrodes loaded in deuterium gas using the Wada-type of procedure and (3) on titanium powders, loaded in deuterium gas and then thermally cycled. Neutron generation events, that could not be ascribed to cosmic ray events, were detected in the form of 4 to 12 neutrons in a time frame as short as 100-400 μsec. Such events were never observed on a large number of light water and hydrogen controls. Such high-multiplicity results are quite rare. To detect lower multiplicity events reliably, a low-background environment would be required. Plans were, therefore, developed to conduct future neutron measurements in an underground laboratory. This proved no longer possible within the remaining time and funding.
e. Engineering

Flow calorimeter cells of various designs, employing internal or external gas recombination, were designed and applied successfully. Long-term electrolysis was carried out in (all but one case) D₂O solutions of LiOD, using Pd cathodes. Tritium was found in 5 out of 9 cells. In 6 experiments, the Pd cathode was allowed to outgas in D₂O for 8 days, after completion of the electrolysis; tritium was observed significantly above background in 3 of the 6 experiments. The level of tritium showed surprising uniformity, ranging for all 5 cells from approximately 1.7 x 10¹⁰ to 2.1 x 10¹⁰ T atoms/cm² of Pd cathode. These values are in the middle of the range of T findings at BARC in India, in experiments run for similar lengths of time. The values are also very similar to those found by the Chemistry Group at the NCFI. Evidence for excess heat was found in 3 of the 5 tritium-producing cells. No excess heat was found in the cells that had not produced tritium. One cell, in particular, showed excess power in a time interval of 13 days, with an average and peak excess power level of about 10% and 28%, respectively. The excess energy generated in these 13 days was more than 10⁶ Joules.

Another significant achievement of the Engineering Group was the development of a feasible, continuous technique to determine the D/Pd loading ratio. This method was key to the later development by the Chemistry Group of a procedure to obtain reproducible D/Pd loading ratios in the vicinity of one, coupled with reproducible tritium generation. The D/Pd ratio is determined volumetrically, by measuring the decrease in the gas volume of a sealed electrochemical cell. The volume decrease is directly proportional to the deuterium absorbed by the Pd cathode. Loading ratios generally between 0.65 and 0.85 were obtained, with the lowest levels occurring in acid solutions. In most cases, prolonged electrolysis did not result in increased loading ratios above 0.85. However, on rare occasions and for unknown reasons, loading ratios of approximately one were achieved.

f. Collaborative and Theoretical Studies

Among the many contributions to the final report in this section, covering a wide range of subject matter, only a few will be highlighted here.

The accuracy of isoperibolic calorimetry was evaluated and was estimated to be the larger of 0.05 W or 5% of the total cell power.
Factors that may enhance the rates of cold fusion reactions are explored on the basis of existing experimental observations and theoretical considerations. The important question is addressed how to explain the large discrepancy between observed amounts of heat and the much smaller amounts calculated from the nuclear by-products that have been measured. The possible role of helium-4 is discussed in this connection. The likelihood for cold fusion to occur on the surface as compared to the interior of Pd (or other metals) is discussed, and it is concluded that attainment of uniform deuterium concentration in the metal as well as rate considerations favor reactions in the interior.

Self-consistent field level calculations were applied to evaluate the possibility of cold fusion in Pd. The calculations were aimed at finding a palladium-deuterium interaction which might give rise to an intermolecular potential sufficient to enable cold fusion at room temperature. This investigation, guided in part by chemical intuition, included a variety of singlet and triplet electronic states, anions and neutrals, with and without lattice deformations. No systems were found which gave a satisfactory modified intermolecular potential. For the arrangement of two deuteriums occupying the same octahedral hole it appears that the hypothesis that the electron density from the palladium lattice might screen the DD interaction is unlikely. This study suggests the opposite. Namely, the palladium-deuterium bonding interactions in the octahedral hole results in a buildup of electron density between the palladium and deuterium atoms and a subsequent depletion of density between deuteriums. For the systems studied it was predicted on the basis of self-consistent field theory, that simple DD fusion enhanced by lattice screening of deuterium atom interaction is not a likely mechanism.

Application of superradiance theory to cold fusion phenomena in condensed matter leads to conclusions opposite to those derived from application of self-consistent field theory. This theoretical model involves the application of quantum electromagnetic field theory. The moving or oscillating charges, such as electrons, deuterons and palladium nuclei, have electromagnetic fields (plasmas) associated with them that provide for strong coupling. A central feature of the model is the coherent interaction of large numbers of charged particles. Coulomb barrier penetration is made possible by the presence of a sufficient electron density between two deuterons. Another factor $10^{10}$ enhancement of the fusion probability is predicted from an interaction between loosely bound deuterons and the entire system of strongly
bound deuterons contained in a coherency domain. This leads to the theoretical prediction that high fusion rates will exist only if the D:Pd loading ratio has attained a critical value just larger than one. Under these circumstances, the model predicts the generation of large amounts of excess heat (tens of W/cm$^3$ Pd) by ultra-fast coupling of the fusion energy to the electron plasma. This process is predicted to vastly enhance the $^4$He channel while suppressing the neutron and tritium channels.

III. Conclusions

Convincing evidence now exists for the occurrence of nuclear reactions, at room temperature, in deuterium-loaded metals, such as palladium and titanium. The generation of tritium, neutrons, protons, helium-4 and gamma radiation provides evidence that deuterium-deuterium fusion comprises at least part of the nuclear reactions that occur. Other nuclear reactions, possibly involving as yet unknown nuclear particles, may well occur at the same time.

The fact that cold nuclear fusion occurs does not mean per se that the excess heat observed by many investigators originates from cold fusion or even from any nuclear reaction. Apart from the findings of a single group, the level of the various nuclear by-products, that have been measured, is approximately one million times smaller than required to explain the observed levels of excess heat. This poses an extraordinary challenge to both experimentalists and theoreticians.

Considerably more research is required to bring about an understanding of the phenomena involved. Only after such understanding is in hand can it be said with certainty what the origin of the nuclear reactions and the excess heat is, and only then does it appear feasible to discuss the potential technological implications.

The progress obtained in cold fusion work is impressive. Reproducibility of some of the phenomena appears to be in hand, enabling more systematic scientific work to be pursued.
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