PREFACE

Energy production in the Universe is mostly based on nuclear reactions especially fusion reactions of light element nuclei. Energy production in the Sun on the basis of fusion of hydrogen, its isotopes and elements up to carbon have been well theorized by now. It is natural to expect that there will be a large variety of nuclear reactions which will lead to the production of nuclear energy. In fact there is a whole gamut of fusion reactions in astrophysics which suggest various combinations of nuclear interactions and modes of decay for energy production. The collapse of binary stars and the transformation of neutron stars into black holes are the ultimate phases of stellar evolution and production of fusion energy therefrom. Even before the discovery of the neutron, scientists had predicted and even tried to prove that nuclear energy could be generated through fusion of hydrogen nuclei (protons). It was however only after detailed accelerator based research in nuclear physics, that the cross sections and Q values for these reactions became available. This enabled many conjectures to be made. Some of the candidate reactions considered for the generation of fusion energy are: (p+p), (p+d), (d+d), (d+t) etc.

The familiarity of scientists with accelerator based nuclear reactions, however, led them to believe that fusion reactions can take place only on the basis of overcoming the potential barrier caused by the electrostatic interaction. This demands that the particles have considerable relative velocity and from the analogy of what is happening in the Sun, thermonuclear fusion was considered as the most appropriate technique for releasing fusion energy on a large scale. We are all aware of the many experimental attempts that have been made over the last, four decades to obtain conditions appropriate for thermonuclear fusion. The principle of confinement of these hot plasmas by means of complex magnetic fields in special configurations was invented in the early fifties. Of these the Tokamak has been a major success and has almost reached the stage of breakeven in energy production. However, the large size and the expensive equipment needed to attain even this breakeven stage have raised doubts about its commercial viability. The technique of generating temperatures of 100 million degrees using the principle of inertial confinement was first demonstrated in a thermonuclear bomb. The same principle has been borrowed and adapted in making fusion reactions possible in small pellets using lasers, electron beams and heavy ion beams. However even this approach of releasing nuclear energy through a series of fusion micro-explosions has not lived up to its early expectations as the power and energy of the driver beams for obtaining the requisite pellet energy gain became uncomfortably high. Small and more elegant methods are therefore being attempted. Techniques such as Z-pinches, combined magnetic and inertial confinement schemes etc are under experimentation. As an interim measure it has meanwhile been suggested that fusion devices may be employed as a source of neutrons for producing fissile fuel for use in fission reactors. Thus in quest of establishing the best method of producing fusion energy there has been considerable innovations and cross fertilization of new ideas during the last couple of decades. However new ideas are always welcome and must be tried out.

Cold fusion which we are discussing here is one such innovation which on the face of it looks so simple that it seems too good to be true. It has generated considerable speculation on the processes which cause fusion in the solid state at room temperatures. The basic problem is

essentially to bring together ions of hydrogen isotopes at distances of a few Fermis so that fusion takes place. It is worth recalling here previous attempts to bring together hydrogen nuclei to distances at which the spontaneous fusioning rate would increase considerably. The most effective method has been the replacement of the orbital electron of a molecular hydrogen ion by a μ meson or muon as it is called. Because of its heavier mass, the muon is able to squeeze the nuclei into a more compact molecule and cause a fusion reaction. Besides, the muon is found to have an additional advantage, because of its longer life time (2 μs), freed after a fusion reaction, it is able to catalyze more fusions. Almost 200 catalyzed fusions per muon have been experimentally observed in (d-t) mixtures to date. It is some of the same scientists who were concerned with the physics of muon catalyzed fusion who have now reported cold fusion in a lattice of palladium.

From the point of view of understanding the physics behind cold fusion, one needs to discuss the lattice structure and its rearrangement when hydrogen is absorbed in palladium, titanium or other alloys used for the storage of hydrogen. It is the fact that enormous (quantities of hydrogen can be stored in these materials at densities comparable to or higher than that of liquid hydrogen that first gave a clue that perhaps the internucleax distances can be brought down in such lattices. .Many attempts have been made by theorists to evaluate the fusioning rate in such lattices. Some of these are based on an extension of the well known theory for muon catalyzed fusion, wherein both the internuclear distances and the height of the potential barrier are varied. Both will have the effect of increasing the fusion rate from 10^{-64} per second/per ion pair in heavy water to something of the order of 10^{-23} per second per ion pair which is required in order to explain the experimentally observed neutron production rate in cold fusion experiments. Whether it is possible to have such drastic changes in the fusion probability, which is essentially dictated by quantum mechanics considerations, is a matter of intense debate and discussion.

I would like to invite your attention to a novel application of the principles of quantum mechanics to such a problem. Several years ago Rand McNally had speculated on the feasibility of the occurrence of nuclear reactions at room temperature and was perhaps the first person to coin the phrase "cold fusion" as early as in 1983. To quote his own words "The problem of neutron transfer in solid media is no longer an elementary binary collision process involving Coulomb barriers and brief collision times but rather one in which the nuclei are continuously in each other's proximity. Since ^{135}Xe has a slow neutron capture radius approaching that of the inter atomic distance the nuclear barrier would perhaps be grossly reduced. Thus it is remotely possible that some combination of natural processes may permit barrier penetration to occur much more readily and a nuclear reaction to ensue". He also proposed the term "de Broglie interaction length" to emphasize the fact that the de Broglie wave length of particles with small kinetic energy is very long. The importance of the de Broglie interaction length can be seen in the extraordinarily high cross section for absorption of slow neutrons by certain nuclei. It is therefore of interest to know what the de Broglie interaction length of a deuteron with very small energy is in a palladium lattice. Further, what happens to the charge distribution of such a deuteron extended in space and the effects of its polarization are too speculative. If the charge distribution has dimensions of the order of a de Broglie interaction length, then the potential barrier due to Coulomb interaction may perhaps become much smaller. If so then fusion should be much more probable at very low temperatures.

From the experimental point of view, the proof of cold fusion must come from a demonstration of the production of neutrons, He^3, He^4, tritium, gamma rays and other end

products of nuclear transmutation reactions. Unfortunately experiments performed so far have used very small electrodes and small cells, and there have not been sufficiently large sized experiments which can give unqualified proof of the number of neutrons or radioactivity produced from this process. Our attempts in different groups at Trombay have however all shown reliable data on neutron and tritium production. These are described in the various papers included in this compilation. It is interesting that fusion reactions also take place when deuterium ions are introduced into a metallic lattice by simply absorbing deuterium gas into titanium or palladium. The group at Frascati in Italy first succeeded in producing neutrons by this method.

It is not our expectation that cold fusion will become an energy source tomorrow or the day after. After all even in 1939 when neutron induced fission in uranium was discovered, it took several years to find out how to set up a fission chain reaction and release fission energy in a large scale. Without detailed measurements of the number of neutrons produced in fission by the Columbia University group and the invention by Fermi of the heterogeneous neutron multiplying system, the nuclear reactor would not have become a reality. Similarly one has to explore and understand the basic mechanisms of fusion in a lattice and determine how this could be used either to produce energy directly or to produce neutrons and tritium in a sustained manner. It is too early to predict the time frame in which this will happen but for those of us familiar with the historical evolution of nuclear technology, one can foresee how it can change our perspective drastically. It is therefore necessary for us to involve ourselves deeply into understanding the mysteries of this new phenomenon. The source of such energy, namely deuterium, is ordinary water which is available in plenty and the technology to separate and concentrate deuterium from water is by now well established in our country.

I would therefore end this Preface by quoting from what Dr. Homi Bhabha said at the first International Conference on Peaceful Uses of Atomic Energy in 1955. He predicted that "in a couple of decades from now fusion energy will become possible and that will ensure energy production for man's needs as long as there is sea water on this earth". It is therefore a historical occasion for us to renew our efforts in research and development in an area so vital for human prosperity. I hope this report will stimulate the interest of scientists and engineers from various disciplines in this centre to channelise their efforts in such a way that we lead in this emerging technology.

This Preface is an edited version of the Inaugural talk delivered by Dr. P.K. Iyengar, Director, BARC at the one day meeting on 'Cold Fusion' held at Trombay on 18th May 1989.

SUMMARY

This report is a compilation of the work carried out at BARC, Trombay during the first six months of the "cold fusion era" namely April to September 1989. Over fifty scientists and engineers besides a large number of technicians from more than ten Divisions of this Centre have been associated with these studies. This report comprises of three parts. Part A covers cold fusion investigations based on the electrolytic approach. Part B summarises the work based on D_2 loading in the gas phase and Part C covers the theoretical papers. Since most of the theoretical papers have either been published or are in the process of being published in scientific journals they are not commented upon in this Summary.

Electrolysis Experiments

Several groups having expertise in various areas such as hydriding of metals, electrochemistry, isotope exchange processes in the concentration of heavy water and neutron and tritium measurements, devised and set up a variety of electrolytic cells. In the initial experiments the emphasis was on detection of neutrons and tritium rather than excess heat. In a centre such as BARC the equipment and expertise for neutron measurements was readily available. The tritium levels in the D_2O electrolyte after operation of the cells were measured by expert groups (belonging to the Isotope and Health Physics Divisions of BARC) who have been engaged in this type of work for over two decades. Well known liquid scintillation counting techniques applicable for low energy beta emitters were used, taking adequate precautions as described in detail in Paper A9. Prior to the commencement of electrolysis, samples of the initial electrolyte also were analysed for their tritium content.

The first bursts of cold fusion neutrons were detected at Trombay on 21st April 1989 in two separate electrolysis experiments. At the Heavy Water Division a readily available commercial (Milton-Roy) electrolytic cell with Pd-Ag alloy tubes as cathodes and Ni as anode, originally meant for the generation of H_2 gas was adapted for the electrolysis of 5 M NaOD in D_2O (see Paper A1). Both a bank of BF_3 detectors embedded in paraffin and a proton recoil fast neutron detector (NE 102A) were employed to look for possible neutron emission. An initial burst of neutrons was detected when the cell current attained 60 amps. Later the current increased to 100 amps and the cell became overheated, resulting in the built-in trip circuit automatically switching off the power. This was followed by a big burst of neutrons approximately two orders of magnitude larger than background levels during a five minute interval. Fig. 2 of Paper A1 shows plots of the neutron counts data from the two detectors. From the efficiency of the neutron detection system measured using a standard Pu-Be source, it was surmised that $\approx 4 \times 10^7$ neutrons were emitted in all by this cell.

On the same day another cell set up by the Analytical Chemistry Division (ACD) also produced neutron bursts (see Fig. 7 of paper A5). Table I presents a summary of the six successful electrolytic experiments conducted at Trombay wherein both neutron and tritium production has been confirmed. These cells have employed a variety of cathode-anode configurations. While some groups selected NaOD as electrolyte, others used LiOD. One of the successful cells has deployed titanium as cathode material. However many cells did not give positive results and these are not included in Table I.

The most important result to emerge out of the Trombay measurements is the surprisingly low overall neutron to tritium yield ratio. As evident from Table I five out of the six successful Trombay cells have given a value in the region of 10^{-6} to 10^{-9} for this ratio, while one (WCD) has given a comparatively large value of $\sim 10^{-3}$ for this ratio. However it must be pointed out that in this cell the absolute amount of tritium generated was very small. On the whole however the Trombay results clearly demonstrate that cold fusion is essentially "aneutronic" in nature.

It is worthwhile carefully scrutinising Table I to see what additional information can be extracted from these results. The current density in all the cells (except the last) was in the region of 170 to 800 mA/cm^2 and the total charge passed per cm^2 of cathode area prior to the detection of the first neutron burst (the "switching on charge" as it may be called) was in the range of 0.6 to 3.2 amp-hrs/cm^2. In the last cell however wherein the charging current density was only 60mA/cm^2 the switching on charge was an order of magnitude higher (34 amp-hrs/cm^2). Significantly however one ampere-hour or 3600 coulombs approximately corresponds to the charge carried by the number of deuterons required to load a few grams of Pd (associated with each cm^2 of cathode area) to a D/Pd ratio of $\sim$ 0.6. Thus the fact that the switching on charge more or less corresponds to the defined deuterium loading requirement of the cathode is a noteworthy experimental finding.

Since cold fusion in electrolytic cells appears to be essentially a surface phenomenon the integrated neutron yield per cm^2 of cathode area may of interest. This quantity lies in the range of 1.7 to 2.9×10^5 neutrons/cm^2 for four of the cells. For the five module cell (Paper A2) it was an order of magnitude smaller while for the last cell it was two orders of magnitude higher. The specific tritium yield (μCi/cm^2) shows a somewhat wider scatter in the data. This quantity lies in the range of 0.5 to 1.3 μCi/cm^2 for the three cells wherein significant amounts of excess tritium were generated in comparison to the stock D$_2$O levels. In the case of the titanium cathode cell although the total amount of tritium generated was significant (7 μCi) the specific tritium yield is an order of magnitude smaller (0.07 μCi/cm^2). But it must be pointed out that neither the tritium lost via the gas stream nor that entrapped in the solid electrode were accounted for in that experiment. The specific tritium yield is much smaller for the last two cells wherein not much tritium was produced.

All in all it may be concluded that the behaviour of most of the electrolytic cells is reasonably consistent with each other considering the rather wide disparity in their designs, except perhaps for the last cell (WCD) whose behaviour is anomalous in many respects. The reason for this discrepancy is not immediately apparent.

Statistical Characteristics of Neutron Emission

There has been wide speculation in cold fusion literature that the observed neutron emission could be due to the phenomenon of crystal cracking or fracture. In the beginning it was even suspected that cosmic ray produced muons could be catalyzing fusion reactions in the deuterated Pd or Ti cathode. If these mechanisms were the source of cold fusion neutrons then it may be expected that neutron emission would be in multiples or bunches rather than one at a time. It is with a view to throwing some light on this question that the multiplicity spectrum of neutron emission was measured. The number of neutron pulses issuing from a bank of BF$_3$ (or He^3) counters (embedded in paraffin) monitoring the cold fusion source was totalled over 20 ms sampling intervals and stored in a personal computer. There were 1000 such sampling intervals during a real time of 5 minutes. Data was simultaneously also recorded from a paraffin encased

bank of thermal neutron detectors placed at a distance of ~1.5 m from the source, serving as a background monitor. The data accumulated during periods of significant neutron emission were statistically analysed to yield the probability distribution of neutron counts. The details of these measurements are discussed in Paper A4. It is concluded from these studies that neutron emission essentially obeys Poisson distribution i.e. neutrons are mostly produced one at a time. However it is also found that occasionally 4 or more and even up to 20 neutron counts are registered in a single 20 ms interval. The background monitor has never yielded such high multiplicity events even once. Careful analysis of these measurements leads to the conclusion that about 15 to 20% of the neutrons produced in cold fusion are due to bunched neutron emitting events, possibly from phenomena such as crystal cracking. But the bulk of the neutrons generated i.e. 80 to 85% obey Poisson statistics implying emission as singles.

Gas Loaded Titanium Target Experiments

Following reports of neutron emission having been detected by the Frascati group with pressurized D_2 gas loaded Ti shavings, two variants of this experiment were carried out at Trombay. One group (Chemistry Division) followed the Frascati procedure with ~ 20 g of cut Ti pieces and D_2 gas pressures increasing up to 50 bars. These experiments are described in Paper B1. The neutron detection system comprised of 24 He^3 counters arranged in a well-like array and having a counting efficiency of ~ 10%. The neutron count rate reached a peak value of $10^5/40s$ as compared to initial background levels of 60 per 40s (see Fig. 2 of Paper B1). The neutron emission phase lasted for several hours at times.

In a second variation of the gas loading experiment, described in Papers B2 and B3 small machined targets (discs, cones, cylinders etc) of Ti metal (mass between 0.2 to 1 g) were individually loaded with D_2 gas by inductively heating them to 900ºC in D_2 atmosphere at 1 Torr pressure and then switching off the power to the induction coil. D_2 gas was absorbed by the Ti target in the course of its cooling. The quantity of D_2 absorbed could be measured from the observed pressure drop. This corresponded to a gross (D/Ti) ratio of hardly 0.001. However it is believed that most of the absorbed D_2 gas was accumulated in the near surface region. A disc shaped Ti button loaded by this procedure began emitting neutrons on its own, almost 50 hours after loading, producing ~ 10^6 neutrons over a 85 minute active phase (see Fig. 1 of Paper A4). The background neutron counter did not show any increase in counts during this time.

A new result from the BARC work is the observation of tritium in D_2 gas loaded Pd foils, possibly for the first time. These are described in Paper B4. The tritium produced in these foils was extracted through a novel isotopic exchange technique, by keeping the deuterated foils in contact with a small quantity of ordinary water for several hours. The tritium content in the water was later measured through standard liquid scintillation techniques.

Autoradiography of Deuterated Ti and Pd Targets

An important outcome of the Trombay work is the demonstration of autoradiography as a simple and elegant technique of establishing the presence of tritium in metallic samples wherein cold fusion reactions are suspected to have taken place. Deuterated samples of Ti or Pd were placed over standard medical X-ray films and exposed overnight. The radiographs of Ti discs showed about a dozen intense spots randomly distributed within the disc boundary, besides a large number of smaller spots, especially all along the periphery forming a neat ring of dots (see Fig. 1 of Paper B3). Repeated measurements with the same disc target with exposure times

varying from 10 to 40 hours gave almost identical patterns of spots, indicating that the tritium containing regions were well entrenched in the face of the titanium lattice. Spectral analysis of the X-ray emissions from such targets using a Si (Li) detector clearly depicts the characteristic Kα (4.5 keV) and Kβ (4.9 keV) peaks of titanium excited by the betas from tritium decay.

In the case of Pd samples however the autoradiographs were more uniform. Interestingly it was found that the tritium betas (< 18 keV energy) were unable to excite the characteristic K X-rays of the Pd. The fact that even the second film of a stack of X-ray films exposed to the deuterated Ti and Pd samples gave a similar image, rules out the possibility that the image formation could be due to pressure or chemical reduction effects as may be suspected.

Conclusions

Investigations of cold fusion phenomena carried out at Trombay during April to September 1989, have positively confirmed the occurrence of (d-d) fusion reactions in both electrolytic and gas loaded Pd and Ti metal lattices at ambient temperatures. Neutron emission has been observed at times even when the current to the electrolytic cell was switched off or in case of gas loaded Ti targets when no externally induced perturbation such as heating, cooling, evacuation etc was effected. The main findings of the Trombay investigations to date may be summarised as under:

(a) Tritium is the primary end product of cold fusion reactions with the neutron to tritium yield ratio being approximately 10^{-8}. The variation of tritium content in electrolyte samples taken at frequent intervals in some cells supports the contention that neutron and tritium production occurs at the same time.

(b) Cold fusion in electrolytic cells appears to be predominantly a surface phenomenon, with a specific charge requirement of a little over an ampere-hour/cm^2 to switch on the neutron and tritium producing reactions. The fact that this roughly corresponds to the charge carried by the deuterons in a sample of Pd of a few grams/cm^2 loaded to a D/Pd ratio of 0.6 is particularly significant.

(c) Once initiated the cathode produces typically about 10^5 neutrons/cm^2 and almost a μCi of T/cm^2, irrespective of the detailed nature of the cell design. It is imperative that we investigate the nature of the quenching mechanism that thwarts the ability of the cathode surface to sustain nuclear reactions.

(d) Neutron emission both from electrolytically loaded Pd and gas loaded Ti is basically Poisson in nature i.e. the neutrons are emitted one at a time. However it is not clear whether the neutrons are generated in the (d-d) fusion reaction itself or whether it is produced in a secondary reaction involving the energetic protons or tritons. In this context it would be of interest to look for the possible presence of 14 MeV neutrons in cold fusion experiments

(e) About 10 to 25% of the neutrons produced appear to be generated in bunches of over 100 neutrons; each within a time span of less than 20 ms. Viewed in the light of the neutron to tritium yield ratio of 10^{-8} noted above, one would be obliged to conclude that a cascade representing approximately 10^{10} fusion reactions occurs in under 20 ms. Since this appears very unlikely, lattice cracking or other mechanisms wherein the neutron to tritium branching ratio is close to unity, could be the source of such bunched neutron events.

(f) Autoradiography of gas loaded Ti and Pd targets demonstrates in a simple and elegant manner the presence of tritium. The experimentally deduced tritium to deuterium isotopic ratio in these targets is several orders of magnitude higher than in the initial stock D$_2$O and as such

cannot be explained away on the basis of preferential absorption of tritium by the Ti or Pd as may be suspected. The existence of highly localized regions (hot spots) on the target surface as well as all along the periphery of the disc wherein tritium is concentrated, points to the important role of lattice defect-sites in the absorption process, at least in the case of titanium.

(g) The very high probability for the tritium branch in cold (d-d) fusion reactions would indicate processes of neutron transfer across the potential barrier as postulated by Oppenheimer over half a century ago and elaborated on more recently by Rand McNally. If neutron transfer as envisaged by these authors does take place so easily, it may have many implications for the future of nuclear technology, for the deuterium nuclide might very well do the work which free neutrons do in present day fission reactors. In the context of the emerging energy production scenario, aneutronic nuclear reactions such as this may give rise to new nuclear technologies providing a cleaner energy source for the twenty-first century.

TABLE I. Summary of Successful Electrolytic Cell Experiments Conducted at Trombay

	HWD/N_tPD	DD/HWD/ N_tPD	HWD/DD/ N_tPD	ACD	ROMG	WCD[†]
Paper No.	A1	A2	A3	A5	A8	A7
Cathode; Material	Pd-Ag	Pd-Ag	Ti	Pd	Pd	Pd
Geometry	16 tubes	Circular sheets	Rod	Hollow Cylinder	Cube	Ring
Surface Area (cm^2)	300	78	104	5.9	6	18
Pretreatment	Activated	–	–	–	Vac. Heated	Vac. annealed
Anode Material	Ni	Porous Ni	SS	Pt gauze	Pt Mesh	Pt Mesh
Electrolyte Type	5M NaOD	5M NaOD	5M LiOD	0.1M LiOD	0.1 M LiOD	0.1 M LiOD
Volume (ml)	250	1000	135	45	150	250
Cell Current (A)	60	62	40	1 to 2	.6 to .8	1
Current Density (mA/cm^2)	200	~ 800	< 600	~ 200	~ 170	60
Total Amp-hrs[#]	180	250	120	17.5	14.7	620
Amp.hrs/cm^2 [#]	0.6	3.2	1.2	3.0	2.5	34
Integrated N-Yield	4×10^7	4×10^6	3×10^7	3×10^6	1.4×10^6	1.8×10^8
Tritium Yield (atoms)	8×10^{15}	3.6×10^{15}	1.4×10^{14}	7.2×10^{13}	6.7×10^{11}	1.8×10^{11}
(μCi)	375	190	7.0	3.8	0.035	0.009
(n/T) yield ratio	0.5×10^{-8}	1.1×10^{-9}	$\sim2\times10^{-7}$	4×10^{-8}	1.7×10^{-6}	10^{-3}
n/cm^2 (10^5n/cm^2)	1.7	0.1[*]	2.9	1.7	2.3	~ 100
T/cm^2 (μCi/cm^2)	1.3	0.5[*]	0.07	0.6	~ 0.01	5×10^{-4}

[*]5 Surfaces considered.
[#]Up to first neutron emission.
[†]This paper was retracted, and it is not included in the LENR-CANR version of this book.