Nuclear fusion in an atomic lattice: An update on the international status of cold fusion research

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It is now two years since the first reports of the occurrence of nuclear reactions at ambient temperatures in deuterated metals such as Pd or Ti were published. 'Cold fusion', as this phenomenon has now come to be known, has, however, become embroiled in intense controversy with the scientific community becoming sharply polarized into 'believers' and 'non-believers' of this novel phenomenon. This ambivalence is primarily because of the non-reproducibility of the claimed results by many reputed research groups that have often used sophisticated experimental equipment. However, as the present review clearly shows, a large number of laboratories in many different countries have now obtained very reliable experimental evidence confirming the generation of 2.45-MeV neutrons, tritium, charged particles, X-rays, etc., both in electrolysis experiments and in a variety of other D_2-/plasma-/ion-beam-loading experiments, thereby confirming the nuclear origin of the phenomenon. These experimental results are such that they cannot be dismissed as being 'experimental artefacts' any more. It is understandable that the scientific community finds it difficult to accept a phenomenon that is not repeatable at will as 'science'. It would seem that the sporadicity of the results is due to some as yet unknown parameters that seem to be controlling the onset of nuclear phenomena in solid deuterated matrices. It has now become apparent that the phenomenon of cold fusion is highly complex. Although simple (d-d) reactions leading to the production of 2.45-MeV neutrons do seem to take place, that appears to be only one manifestation of the phenomenon. The excess-heat measurements of Fleischmann *et al.* have also been confirmed now. The main indication at hand that it is of nuclear origin is the detection of [4]He in the off-gases from an electrolytic cell producing 'excess power' as well as in some 'spent' Pd rods which had produced 'excess heat'. Besides, the enormous magnitude of the energy released, up to a GJ mol^{-1} of Pd, is very difficult to explain by any chemical mechanism. Theoreticians have come up with models that are beginning to explain many of the 'puzzles' raised by the experimental observations. The fascinating new field of cold fusion has thus opened up new vistas in physics and technology.

EVER since the startling announcement in March 1989, by Utah scientists Fleischmann *et al.*[1], and shortly thereafter by Jolies *et al.*[2], of the experimental observation of anomalous excess heat and/or fusion reaction products during the electrolysis of heavy water by means of Pd cathodes, there have been frantic attempts the world over to confirm this unbelievable phenomenon of 'fusion in a bottle' or 'cold fusion' as it has come to be known. Several laboratories, such as the Texas A&M University[3,4], Stanford University[5], Case Western Reserve University[6], Moscow

State University[7], and University of Florida[8], reported obtaining positive results within weeks of the first announcement. The initial euphoria however soon turned sour when many other leading institutions, such as Caltech[9], Lawrence Livermore National Lab[10], Sandia National Lab[11], Chalk River[12], Harwell[13], and Max Planck Institute at Munich[14] failed to reproduce the 'claimed' results of the original authors. In spite of many groups reporting neutrons, tritium and excess heat production at the Santa Fe Workshop on Cold Fusion Phenomena (23-25 May 1989)[15], the overall impression which began to be formed in scientific circles was that cold fusion does not exist and the reported 'evidence' was some peculiar 'artefact' of the experiments. This was reflected in the final report[16] of the US Department of Energy's 22-member Cold Fusion Panel submitted in November 1989, which concluded that 'the present evidence for the discovery of a new nuclear process termed cold fusion is not persuasive'. They went on to surmise: '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 a century; it would require the invention of an entirely new nuclear process'.

Meanwhile more 'positive' results continued to pour in from laboratories such as Los Alamos[17], Texas A&M University[18], University of Minnesota[19], Universidad Autonoma de Madrid[20], Manne Sieghbahn Institute of Physics[21] in Stockholm, and several different groups in Japan[22]. Besides electrolysis, deuterium gas-loaded Ti (ref. 23) and Pd (ref. 24) targets, both with[25] and without[26] application of electric fields, have also indicated the occurrence of cold-fusion reactions, charting a new route for the exploration of the phenomenon of cold fusion. It was the National Science Foundation (NSF) and Electric Power Research Institute (EPRI) sponsored meeting[27] on 'Anomalous effects in deuterated materials' held at Washington, DC during October 1989, in the presence of Edward Teller, that perhaps served as a turning point in the acceptance of cold fusion as a fact to be faced by the physics community, although the number of firm 'believers' was small at that point of time.

In India experimental studies to verify the authenticity of the cold-fusion phenomenon commenced immediately after the Fleischmann-Pons announcement with groups from the Bhabha Atomic Research Centre (BARC)[28], Tata Institute of Fundamental Research (TIFR)[29], Indira Gandhi Centre for Atomic Research (IGCAR)[30], and Variable Energy Cyclotron Centre (VECC)[31] reporting positive results. By December 1989 a detailed description of the impressive work carried out at BARC during the first six months of the 'cold fusion era' had been released[32] as report BARC-1500. The experimental papers of this collection of notes have since been published in *Fusion Technology*[33]. Since the early BARC results are by now well documented and publicized, in the present review they will only be commented upon very briefly.

During the year 1990 there were two major international conferences devoted entirely to the subject of cold fusion which have helped to take stock of the progress of research in this field. The first[34] was held at Salt Lake City, Utah, late in March 1990 under the patronage of Fleischmann and Pons to coincide with the first anniversary of their epoch-making announcement and emphasized calorimetry and excess-heat studies. The other meeting, which was hosted by Jones' group in October 1990 at the Brigham Young University in Provo, Utah, concentrated on measurement of nuclear effects in deuterium/solid systems[35]. The present review draws mainly from the proceedings of these meetings which together account for over a hundred papers, besides the very significant work reported during the last year from Japan. It is learnt that there are presently over 50 groups involving over 250 scientists engaged in cold-fusion research in Japan alone. In the USSR too, significant results were obtained early on[36]. The status of cold-

fusion research in China was reviewed at a national-level meeting held at Beijing in May 1990.

Bockris *et al.*[37,38] have presented a good summary of the status of cold-fusion research as of mid-1990. Tibor Braun of Budapest has compiled a consolidated list of papers published in the area of cold fusion since the beginning[39]. Another good source of information is *Fusion Facts*[40], a monthly digest of the latest reports on cold fusion. It is not the purpose of this article to give an exhaustive and thorough analysis of each and every published paper in this field so far but rather to give a broad overview of the cold-fusion scene as it stands today, two years after it all began, and to highlight the major new results published during 1990.

1. Calorimetry/excess-heat studies in D_2O electrolysis

The simple electrolytic cell used by Fleischmann *et al.*[1] to demonstrate the production of excess power comprised a Pd-rod cathode and a Pt-wire anode wound loosely around the cathode as shown in Figure 1. The electrolyte was a solution of 0.1 M LiOD dissolved in D_2O. The cell, made of a double-walled vacuum-jacketed dewar-type glass vessel, was immersed in a large constant-temperature water bath. Thermistor probes located both inside the cell and in the water bath helped monitor the cell thermal power output. A built-in immersion-type electrical resistance heater was used to calibrate the thermal-response characteristics of the system under steady conditions. The input joule power dissipation rate was computed as $(E-1.54)I$ watts, where E is the applied voltage to the cell and I the cell current in amperes. The number 1.54 accounts for the energy consumed in splitting D_2O into deuterium and oxygen and is referred to as the 'thermoneutral potential' for this system.

As is well known by now, the initial pioneering paper of Fleischmann *et al.* met with considerable criticism[41-42]. Some of the points raised by his critics were: (i) excess heat was due to recombination of electrolytically generated D_2 and O_2; (ii) inadequate mixing of the electrolyte gave rise to errors in temperature measurements; (iii) inadequate control of water-bath temperature could have produced erroneous results; (iv) Fleischmann and Pons' heat-transfer computations were subject to both random and systematic errors; (v) no blank or control experiments were done; (vi) the gamma-ray spectrum presented by the authors as evidence of neutron production was spurious. All these have now been systematically answered by Fleischmann and Pons in three different papers[43-45]. It is by now clear that their calorimetric measurements were in fact quite reliable and that they (along with more than a dozen other groups in the world) have indeed obtained excess power levels of about 25 to 30% over and above the input joule power dissipation rate.
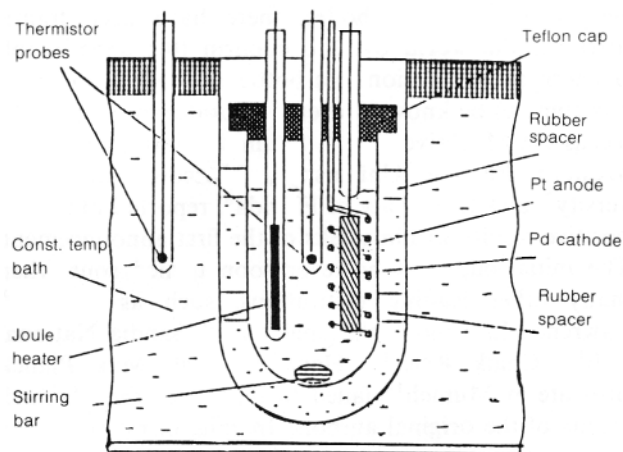
Figure 1. Dewar-type electrolytic cell used for excess-heat measurements. (From Bockris et al. [37])

Table 1. Summary of results of excess-enthalpy measurements of Fleischmann et al.[45]

Rod diameter[a] (cm)	Electrolyte[b]	Current density (mA cm^{-2})	E_{cell} (V)	$/Q_{input}$ (W)	Q_{excess} (W)	Approximate specific Q_{excess} (W cm^{-3})	Specific $|Q_{excess}$ from regression analysis (W cm^{-3})	
0.1	D	64	3.637	0.419	0.042	0.53	0.581	±0.003
0.1*	S	64	2.811	0.032	0.001	0.140	0.1442	±0.0002
0.1	D	128	4.000	0.984	0.160	2.04	2.043	±0.003
0.1*	S	128	3.325	0.089	0.005	0.486	0.5131	±0.0006
0.1	D	256	5.201	2.93	0.313	3.99	4.078	±0.007
0.1*	D	512	9.08	1.51	0.17	17.3	18.19	±0.02
0.1	D	512	6.085	7.27	1.05	13.4	13.77	±0.02
0.1*	D	1024	11.640	4.04	1.03	105.0	112.8	±0.1
0.2	D	64	4.139	1.040	0.123	0.39	0.419	±0.003
0.2	S	64	4.780	1.30	0.006	0.019	0.021	±0.001
0.2	M	64	3.930	0.956	0.024	0.077	0.077	±0.001
0.2	D	128	8.438	5.52	1.65	5.25	5.68	±0.01
0.2*	S	128	4.044	0.250	0.028	0.713	0.714	±0.001
0.2*	M	256	6.032	0.898	0.056	1.42	1.498	±0.002
0.2*	D	512	8.25	2.68	0.66	16.8	17.02	±0.04
0.2*	M	512	9.042	3.00	0.603	15.3	16.03	±0.01
0.2*	S	1024	7.953	5.13	2.80	71.2	75.42	±0.08
0.4	D	64	5.137	2.88	0.502	0.40	0.411	±0.001
0.4	D	64	5.419	3.10	0.263	0.209	0.214	±0.003
0.4†	D	64	4.745	2.24	0.117	0.106	0.145	±0.002
0.4*	M	64	3.519	0.198	0.0005	0.002	0.0023	±0.0002
0.4	D	128	6.852	8.50	1.05	0.84	0.842	±0.009
0.4*	D	256	7.502	2.38	0.311	1.98	1.999	±0.003
0.4*	D	512	8.66	5.70	2.18	13.9	14.41	±0.05
0.4*	D	512	10.580	7.23	1.65	10.5	11.09	±0.02

[a]All rod lengths 10 cm or *1.25 cm or †8.75 cm.
[b]D: 0.1 M LiOD; S: 0.5 M Li$_2$SO$_4$; M: 0.1 M LiOD + 0.45 M Li$_2$SO$_4$. All measurements were made in the same batch of D$_2$O of 99.9% isotopic purity. Measurements using electrolytes labelled S and M have been made since 23 March 1989.

Fleischmann *et al.* have carried out an exhaustive and systematic study of the excess power generated as a function of Pd-cathode diameter (1, 2, 4 and 8 mm) and current density (8 to 1024 mA cm^{-2}) (see Table 1). In general, they find that excess power scales near-quadratically with current density, with the 1-mm-diameter cathodes generating more specific excess power (W cm^{-3}) than the higher-diameter cathodes at a given current density. In their experiments 8-mm rods, for example, did not generate any excess power. At ~ 1 A cm^{-2} the 1-mm rods produced an excess power of ~ 1 W for an input power of ~ 4 W. This corresponds to a specific excess power of over 100 W cm"[3] (or ~ 8 W per g of Pd). Kainthla *et al.*[46] have examined eight possible chemical mechanisms which can in principle contribute to 'excess heat' and have pointed out that, even if all these mechanisms were to operate simultaneously, not more than 3 Wcm^{-3} can be generated. An important conclusion to emerge from the pioneering work of Fleischmann and Pons is that there seems to be a threshold current density of about a 100 mA cm^{-2}, below which the excess heat production becomes negligible, at least in the case of D$_2$O electrolysis.

A new phenomenon noticed by Fleischmann and Pons since their first publication is that, superimposed on the 'baseline' excess heat, sometimes large 'bursts' of excess enthalpy, 20 to 40 times the input power values (see Figure 2), are observed[45]. The event depicted in Figure 2 lasted for a duration of almost a fortnight.' This type of sporadic heat excursions has however been seen only by a few other workers so far[47-49]. But the baseline excess heat, which is directly correlated with the current density, has been observed by many laboratories now[3,18,19,22,50-55] including two independent groups from the Oak Ridge National Laboratory[56,57]. The impressive work of Appleby *et al.*[3,18] of Texas A&M University was carried out using a very sensitive 'microcalorimeter' and tiny Pd cathodes of only 0.01 cm^3 volume. It is noteworthy that several groups[49,50,56,57] have now confirmed the production of excess heat using 'closed cells', wherein the electrolytic gases are recombined *in situ* using a suitable catalyst, in contrast to the 'open cells' used by many early workers including Fleischmann and Pons. This is relevant because doubts had been raised that perhaps the excess heat may have arisen from recombination of D$_2$ and O$_2$ in the case of open-cell experiments.

The integrated energy generated during baseline-excess-heat runs is found to be as high as 0.1 GJ cm^{-3} and in 'heat bursts', 16 MJ cm^{-3}. While Fleischmann and Pons have conjectured that these phenomena must be a 'volume effect' occurring over the whole bulk of the cathode, Appleby *et al.,* Bockris and others have provided many strong arguments in favour of its being a 'surface phenomenon'.
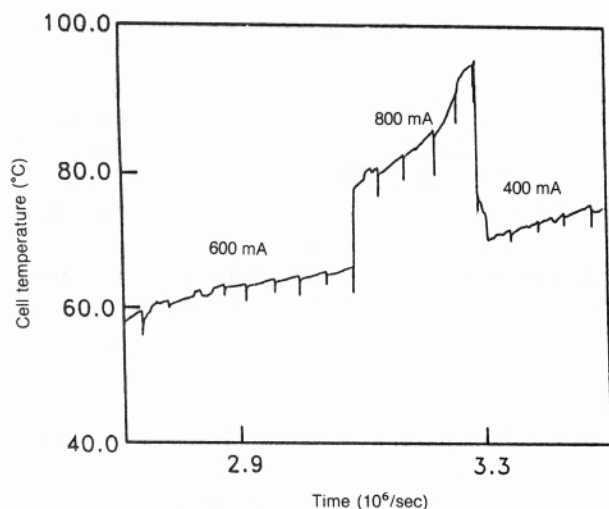
Figure 2. Heat burst event lasting several days during which electrolyte temperature approached boiling point. (From Fleischmann et al.[45])

A very significant experimental finding regarding ^{4}He production in electrolytic experiments has been reported in early 1991 by Bush and his collaborators[58]. These investigators carried out a mass-spectrometric analysis of the effluent gases issuing from the electrolytic cell of Miles *et al.*[55], which was earlier found to be generating excess power. Rather than look for helium in the spent Pd rods like most other groups, these investigators analysed the effluent gases. They collected the off-gases in 500-ml gas flasks, taking great pains to eliminate possible contamination by air which would have given rise to false helium signals. For this purpose they flushed all flasks with 'boil-off nitrogen' for at least 10 min prior to connecting them to the electrolytic cell. They had earlier satisfied themselves that boil-off N_2 did not contain any ^{4}He within the detection threshold of their mass spectrometer. The electrolytic gases collected in the flasks' were first passed through an activated charcoal cryofilter system to remove all gases except helium prior to mass-spectrometric analysis.

Several blanks from H_2O electrolysis were run to optimize the procedure and ensure that no inadvertent air leaks occurred. Their ^{4}He detection limit was established to be 8×10^{11} atoms in the gaseous contents of a 500-ml flask. This corresponded to an excess power of 0.14 W or 8% of input joule power in their case. They observed large ^{4}He peaks at four different excess power levels in the 0.22-W to 0.52-W region and at detection limit on two occasions, when excess power was 0.14 W and 0.17 W respectively. Their experiments have demonstrated a clear correlation between the generation of excess power and production of ^{4}He. The concentration of ^{4}He in the gaseous products maintained an approximate correspondence to the amount of excess power measured in the electrochemical cell. They have also concluded that the ^{4}He is produced at or near the surface of the Pd electrode rather than deeper in the bulk metal and that the preponderance of ^{4}He escapes along with the effluent gases. Significantly they found no ^{3}He in any of the electrolytic effluent-gas samples. Ref. 58 details the arguments of the authors as to why the ^{4}He could not have come from the Pd cathode as prior contamination.

2. Molten-salt electrolysis experiment

At the cold fusion symposium organized during the 8th World Hydrogen Energy Conference held in Honolulu in July 1990, Liaw *et al.*[59] of the University of Hawaii presented some very spectacular excess-heat measurements obtained with a molten-salt electrolytic cell. Drawing upon several years of experimental experience at Stanford University with a similar system for loading hydrogen into Pd (in the context of hydrogen-storage studies), they carried out electrolysis at temperatures of about 350 to 400°C with a eutectic salt comprising LiCl and KC1 in which a small amount of LiD was dissolved to act as the main current carrier. Since LiD dissociates into Li^+ and D^-, in this cell Pd or Ti was deployed as anode. An electrical heating tape of 100-W capacity wound outside the A1 vessel containing the electrolyte served to keep the salt molten. The entire set-up was housed inside a glove box in an oxygen-free dry argon atmosphere. Using a 0.5-g button of Pd as anode and a consumable Al cathode they measured, after several days of precharging at very low currents, excess power levels as high as 25 W for an input cell power of just 1.68 W, representing a power gain by a factor of ~ 15 (see Table 2). The excess power in this experiment increased near-linearly with current density. At three current densities in the range 290 to 692 mA cm^{-2}, the excess-power episode lasted for almost 4 days generating in all ~ 5 MJ of energy (see Figure 3). The experiment was terminated only because the LiD was exhausted in the electrolyte. The authors have cited the total absence of oxygen in the electrolyte ('reducing environment') as the prime cause for its superior performance. This helps eliminate formation of hydrogen-impeding oxide layers on the surface of the electrodes.

Table 2. Summary of results of molten-salt electrolysis experiment with Pd anode (capital Liaw *et al.*[59])

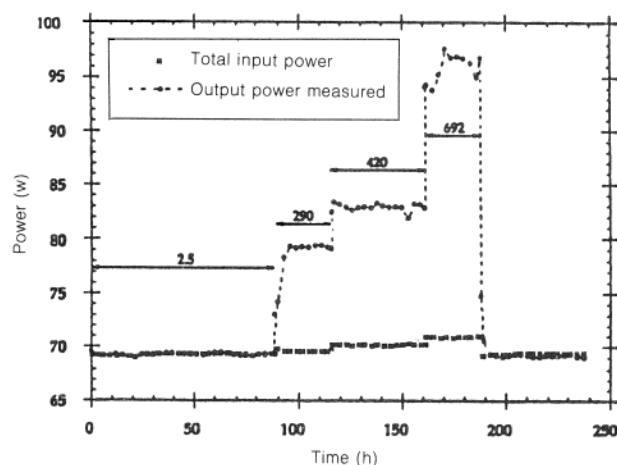| Cell voltage (V)	Current density (mA cm^{-2})	Power to heating tape, P_r (W)	Electro-chemical power (W)	Total input power (W)	Power output measured (W)	Excess power (W)	Excess power gain (%)	Excess heat (MJ per mole D_2)
3.230	606	71.91	1.94	73.85	86.76	12.91	665	-4.15
2.188	290	69.25	0.63	69.88	79.24	9.36	1486	-6.27
2.270	420	69.30	0.94	70.24	82.81	12.57	1337	-5.83
2.453	692	69.25	1.68	70.93	96.34	25.41	1512	-7.16

Figure 3. Excess power generation during molten-salt electrolysis experiment with Pd anode. (From Liaw *et al.*[59])

The Pd button used in this experiment when analysed by mass spectrometry was found to contain 4×10^{10} atoms of ^{4}He, up to 14 σ over that in a control sample of Pd taken from the same stock[60]. This quantity of helium is about seven orders of magnitude lower than that expected on the basis of the 5 MJ of integrated excess energy produced by the 0.5-g Pd sample. Liebert *et al.* have suggested (and it has now also been confirmed by Bush *et al.*[58] recently) that most of the ^{4}He produced escapes from the PdD$_x$ matrix. In spite of it the result is significant to the extent that it probably represents the first instance when ^{4}He has been found unambiguously in any electrode which has produced excess energy in an electrolytic cold-fusion experiment.

The authors have also reported[59] measuring excess heat levels of up to ~ 100% with a titanium anode but there was considerable fluctuation in the excess power output even at constant current density in that experiment.

The importance of the molten-salt electrolysis experiment with Pd anode lies in the fact that the specific excess power generated, namely 25 W per 0.5 g or 50 Wg^{-1}, is already several times that of the UO$_2$ fuel elements of an atomic power station. For example, for the Rajasthan Atomic Power Station (RAPS) the specific power is 15 Wg^{-1} while for a light water reactor (LWR) the corresponding value is ~ 20 W g^{-1}. Since the densities of UO$_2$ and Pd are 10 g cm^{-3} and 12 g cm^{-3} respectively, the power density in the Pd fuel of the molten-salt cold-fusion cell works out to 600 W cm^{-3} which is four times the 150 W cm^{-3} of RAPS fuel or three times that of the LWR. (If an LWR or one of the RAPS reactors were to be operated at 600 W cm^{-3} of fuel, it would result in a core-meltdown incident!) Likewise the integrated energy yield of this cell, which was > 1 GJ per mole of Pd, corresponds to ~ 7 fusion reactions per 1000 (d-d) pairs. For RAPS fuel the fissions per 1000 heavy atoms of the fuel element is also about 7 at its average burn-up level of 7 MWd per kg of UO$_2$. Thus, even within three days of operation of the molten-salt cell, the specific nuclear reaction yield of the Pd anode has equalled that of a CANDU-type nuclear power plant. Had the LiD stock lasted, it may well have exceeded this performance. Needless to stress, specific energy yields of GJ per mole of Pd cannot be explained on the basis of any non-nuclear phenomenon. All this is pointed out only to emphasize the fact that cold fusion is not to be treated as an academic curiosity but deserves to be given the respect due to a prospective new

source of energy which has already matched (if not exceeded) the performance of a present-day nuclear power plant! This remarkable experiment has been highly acclaimed by the cold-fusion community and several advanced institutions in the world, including the Oak Ridge National Laboratory (USA) and BARC, have initiated efforts to try and reproduce the results.

3. Tritium production in electrolysis experiments

   Right from the beginning of the cold-fusion frenzy, efforts have been under way in many laboratories[37.38,61], including BARC, to establish the nuclear origin of the phenomenon in an unambiguous manner. Hence an intense search was on to detect the production of neutrons and/or tritium from electrolytic cells. Texas A&M University[4], BARC[62], and Yang *et al*[53] of Taiwan are some of the well-known groups to have reported detection of large amounts of tritium during the electrolysis of D_2O with Pd cathodes. Many other laboratories, including Los Alamos[63], have also obtained clear-cut evidence for tritium generation, but at a lower level. Ref. 62 gives details of over 20 separate experiments conducted at BARC wherein excess tritium was measured. Of these, in 11 experiments which include one result from IGCAR in Kalpakkam (see Table 3), both neutrons and tritium were produced. The most interesting outcome of the BARC experiments is the observation that the neutron-to-tritium yield ratio is significantly smaller than unity by almost eight orders of magnitude, i.e. it is as small as 10^{-8}. This finding has since been corroborated by many other groups around the world[20,64,65] and represents one of the many 'puzzles' of the cold-fusion phenomenon (since in the (d-d) reaction it is well known that the branching ratio for neutron and tritium production is almost unity). But as this aspect has been well discussed in the BARC papers[28,32,33,62], it will not be dwelt upon further except for one important aspect, namely the 'simultaneity' of generation of neutrons and tritium. Of the 11 experiments in which neutrons and tritium were detected in at least three instances where frequent sampling of electrolyte was resorted to, it was noticed that the tritium level in the electrolyte jumped immediately after detection of a neutron burst (see Figures 4 and 5). Similar observations have also been made by at least two other groups, notably Sanchez *et al.*[20] of Spain (see Figure 6) and Gozzi *et al.*[64] of Italy. The importance of this will be appreciated if viewed in the context of the so-called Wolf episode of the summer of 1990.

Table 3. Summary of results of BARC electrolysis experiments[62] wherein both neutrons and tritium were detected.

| Sr. No.	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
Division	DD/ HWD NtPD	NtPD/ HWD	NtPD/ HWD	DD/ HWD NtPD	HWD/ NtPD	AnCD	ROMG	ROMG	ApCD	ApCD	IGCAR
Cell (Name)	Ti-SS	MR-1	MR-2	5 Module	Par. Plate	PDC-I	RCS-11	RCS-19	Nafion-1	Nafion-2	RCP-II
Date	1989 21 May	1989 21 April	1989 12-16 June	1989 5 May	1990 15 March	1989 21 April	1989 June - Aug.	1990 Jan. - Apr.	1989 July	1990 Feb.	1989 Dec.
Cathode: Material	Ti	Pd-Ag	Pd-Ag	Pd-Ag	Pd	Pd	Pd	Pd	Pd	Pd	Pd
Geometry	Rod	Tubes	Tubes	Discs (5)	Plate	Hollow Cyl.	Cube	Pellet	Ring	Coil	Button
Dimensions (mm)	22 $\Phi \times$ 150 long	3 o.d. $\times$ 200 ht	3 o.d. $\times$ 200 ht	115 $\Phi \times$ 0.1 thk	40 $\times$ 50 $\times$1 thk	–	1cm^3	11 $\Phi \times$ 11.2 ht.	25 $\Phi \times$ 10 ht $\times$ 1 thk	1 $\Phi \times$ 140 long	–
Area (cm^2)	104	300	300	78	20	5.9	6	5.7	18	4.4	8
Anode	S.S. Pipe	Ni–Pipes	Ni–Pipes	Porous-Ni	Ti Plate	Pt Mesh	Pt Mesh	Pt Mesh	Pt Mesh	Pt Mesh	Pt Mesh
Electrolyte	NaOD (5M)	NaOD (5M)	NaOD (5M)	NaOD (5M)	NaOD (5M)	LiOD (0.1 M)	LiOD (0.1 M)	LiOD (0.1 M)	LiOD (0.1 M)	Li$_2$SO$_4$ (.05 M)	LiOD (0.1 M)
Volume (ml)	135	250	250	1000	300	45	150	120	250	140	–
Current Density (mA/cm^2)	≤400	~300	~300	~800	~200	≤340	~100	~700	~60	~50	<100
Switching On: Charge (A-hrs/cm^2)	1.2	0.6	–	3.2	0.8	3.0	2.5	650	34	0.15	36.7
Time (hrs)	3	5	0.5	4	4	9	24	930	330	3	300
Active Life	Few hrs	~3.5 hrs	~2hrs	≤3 mine	<1 min	~5 hrs	~5d	~100 sec	~40 hrs.	~5 d	8 hrs
Neutron Yield: No. of Bursts	Continuum	9	1	1	1	3	17	1	Many	Many	2
Total	3×10^7	4×10^7	$.9\times10^7$	5×10^6	1×10^6	3×10^6	1.4×10^6	3×10^6	1.8×10^8	5.8×10^6	2.4×10^6
n/ cm^2	2.9×10^5	1.7×10^5	1.3×10^4	1.3×10^4	5×10^4	5×10^5	2.3×10^5	5.2×10^5	10^7	1.3×10^6	3×10^5
Tritium Yield: Total (Bq)	2.6×10^5	1.5×10^7	3.8×10^6	7×10^6	–	1.42×10^5	1.3×10^3	7.7×10^3	325	32.5	6.3×10^3
Total (Atom)	1.4×10^{14}	8×10^{15}	1.9×10^{15}	4×10^{15}	–	7.2×10^{13}	6.7×10^{11}	4×10^{12}	1.8×10^{11}	1.8×10^{10}	3.5×10^{12}
t/cm^2	1.3×10^{12}	2.7×10^{13}	6×10^{12}	10^{13}	–	1.2×10^{13}	1.1×10^{11}	5.2×10^{13}	1×10^{10}	4×10^9	4.4×10^{11}
(n/t) Ratio	2×10^{-7}	0.5×10^{-8}	0.5×10^{-8}	1.2×10^{-9}	–	4×10^{-8}	1.7×10^{-6}	10^{-6}	10^{-3}	3.2×10^{-4}	7×10^{-7}
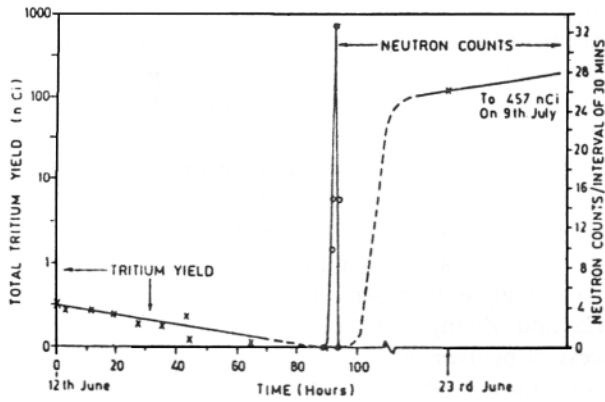
Figure 4. Concomitant generation of neutrons and tritium by a Milton Roy electrolytic cell. (From Iyengar *et al.*[62])
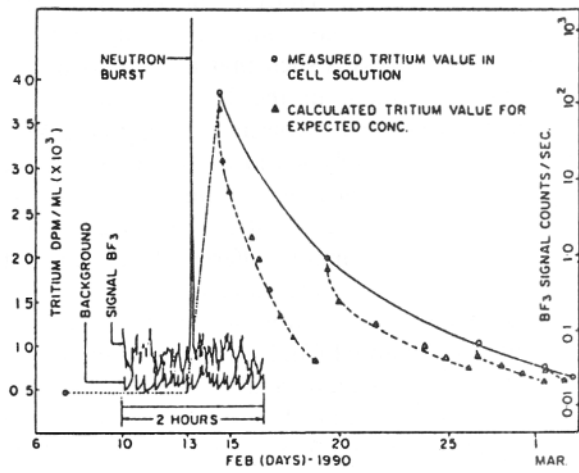

Figure 5. Observation of increased tritium activity following a neutron burst during an electrolysis experiment. (From Iyengar *et al.*[62])

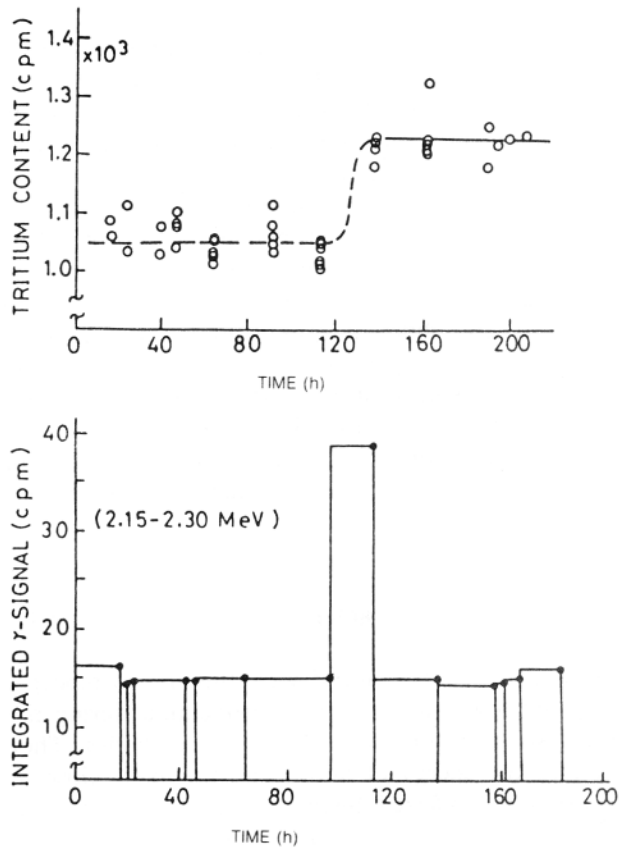**Figure 6. Another example of simultaneous production of tritium and neutrons in D₂O electrolysis. (From Sanchez et al.[20])**

Kevin Wolf of the Cyclotron Institute of the Texas A&M University created a sensation when he claimed that he had found significant levels of tritium in one virgin Pd wire procured from the market[66,67]. It is worth noting here that Pd membranes are supposedly used to separate tritium from its decay product ^{3}He in nuclear weapons establishments of advanced countries and it is alleged that some of this recycled and contaminated Pd probably finds its way into the open market. Wolf found 10^{11} to 10^{12} atoms of tritium in three samples each of 1-cm-long wire (out of 45 such samples) taken from one lot of Pd received from one manufacturer, namely Hoover Strong Co., USA. However, this firm has since clarified that their manufacturing process is such that it is 'impossible' for any tritium to remain in the Pd after the tortuous treatment to which it is subjected. In any case Wolf's 'finding' was immediately seized by the skeptics of cold fusion as 'proof of their long-standing 'contention' that the significant quantities of tritium measured by cold fusion researchers in many different laboratories the world over was due to the sudden release of tritium present as 'spot' contaminant in the Pd electrodes[68]. Meanwhile the National Cold Fusion Institute of Utah has carried out a systematic analysis of over 40 samples of virgin Pd procured from three different manufacturers, including Hoover Strong Co., using a microdistillation technique which is devoid of chemiluminescence interference effects and has found no tritium contamination whatsoever in any of the market samples[69]. Independently Storms and Talcott[70] of Los Alamos have carried out an electrolysis experiment using a Pd cathode intentionally preloaded with tritium. They find that most of the contaminated tritium

goes directly into the gas stream rather than into the electrolyte. In the context of Wolfs 'finding' of tritium in virgin Pd, the simultaneous generation of neutrons and tritium discussed earlier acquires great significance[71]. Even Wolf has conceded that more such simultaneous observations of neutrons and tritium would confirm the nuclear origin of cold fusion[66]. Besides, how can one explain the tritium and tritons (see sections 8 and 9) seen by several different groups in the gas-/plasma-loaded titanium samples on the basis of contamination since titanium is never used for the separation of t and ^{3}He? Thus, by the end of the Provo meeting of October 1990, the 'accusation' that contamination is the cause of tritium observations in so many different countries has been virtually rejected[72].

4. Neutron yield characteristics of electrolytic cells

Jones and his collaborators[2] were the first to report a steady but low rate of neutron production during the electrolysis of D_2O using Ti (or Pd) cathodes. They measured the energy of these neutrons to be close to 2.45 MeV and inferred therefrom that (d-d) reactions occur within the cell, presumably in or on the surface of the cathodes. Their experiments[2] yielded an estimate for the absolute magnitude of the (d-d) reaction rate to be in the range of 10^{-23} to 10^{-20} fusions per d-pair per sec. Other groups who have since observed similar low-level ('Jones level' as it has come to be called now) steady neutron yield are from Italy[73,74], Argentina[75], the USSR[76] and Japan[77]. The Argentine group carried out their experiment[75] in a submarine (non-nuclear) 50 m under the sea, in order to reduce their background neutron count rate to a level as low as 0.001 cps. As noted already, many other groups, at BARC[33,62] and elsewhere[20,21,78-80], have however observed neutron production in the form of bursts (see Figures 4-6) rather than as a steady output. In these experiments the burst neutron production phase was found to last for a period ranging from a few minutes to several hours and at times even for several days, altogether stopping thereafter. Table 3 indicates the duration of the 'active life' of the neutron production phase of the BARC cells.

Several researchers have observed that pulsing the cell current between a high and a low value improves the chances of neutron production. Interestingly, at least two groups have reported observing neutrons from a Pd-D_2O cell after the cell current was switched off[33,81]. These observations indicate that creation of some sort of non-equilibrium condition within the cathode helps induce the occurrence of nuclear reactions.

Arata and Zhang of Osaka have pursued this approach further and have discovered an intense 'on-off effect' during the electrolysis of D_2O using a large (20-mm-dia × 50-mm-long) Pd cathode which resulted in the generation of intense bursts of neutrons[82]. They have shown that their 'on-off effect' is tens of times stronger than the weak on-off effect induced by current pulsing mentioned earlier. They have exploited the temperature-loading characteristics of PdD_x and the high mobility of the deuterium in the Pd lattice to make the Pd cathode absorb and exhaust deuterium in a controlled manner. The essence of their argument is brought out by the hysteresis curve characterizing deuterium absorption/desorption with temperature of the Pd sample (see Figure 7). They have argued that this property, coupled with the fact that deuterium absorption in Pd is exothermic while desorption is endothermic, is what is responsible for the 'on-off effect'. By raising the temperature of the water bath in which their electrolytic cell was immersed to levels close to 90°C they observed that the Pd cathode temperature started oscillating on its own between 80°C and 110°C with a period of approximately 10 to 20 min. In one experiment the phenomenon occurred 50 times during a 20-h period. This behaviour caused

the rapid movement of deuterium into and out of the lattice, leading to the occurrence of (d-d) nuclear reactions. Over 10 intense neutron bursts (or 'avalanches') occurred during one such month-long experiment[82]. The authors have reported that each avalanche lasted between 30 min and 40 h, the maximum number of neutrons produced being as high as 10^{13} per event. From their experiments Arata and Zhang have concluded that the secret of success of neutron production in electrolysis of D_2O is use of a massive Pd cathode (20-mm-dia × 50-mm-long) rather than the Pd rods of a few mm diameter recommended by Fleischmann *et al.* for obtaining excess heat.

5. Observation of a 4- to 6-MeV-energy neutron component in electrolysis

As noted earlier Jones *et al.*[2] were the first to establish that the neutrons emitted in cold-fusion cells had an energy corresponding to 2.45 MeV, thereby giving the first clue that (d-d) reactions are the source of these neutrons. Many other groups[67,74,77] have since independently measured and confirmed that the energy of cold-fusion neutrons is indeed 2.45 MeV.

Recently Akito Takahashi[83] and his collaborators of Osaka University have obtained clear-cut evidence for the presence of a 4- to 6-MeV-energy neutron component besides the 2.45-MeV neutron peak in an electrolysis experiment (see Figure 8). They have cited this as proof of occurrence of the 3-body reaction 3D → d + α + 23.8 MeV, using the 'excitation-screening model' developed by Takahashi. According to his explanation the 15.9-MeV deuterons released in such 3D reactions will give rise to neutrons in the 3- to 7-MeV region during their slowing down in the PdD_x lattice. Takahashi admits that at a time when physicists find it difficult to accept the occurrence of even 2-body (d-d) fusion reactions in solids, conceiving of 3D fusion reactions postulated by him is an understandably arduous task.

It is noteworthy in this context that Bonazzola *et al.*[84] of Torino (Italy) have also obtained results from experiments with D_2-gas-loaded Ti shavings (see section 8), which indicate the presence of a 6- to 7-MeV-energy neutron component besides the 2.45-MeV peak.

6. Charged particles in electrolysis experiments

Taniguchi *et al.*[85] of Osaka have carried out an electrolysis experiment with a 10-μm-thick copper foil coated with Pd which formed the cathodic base of their cell (LiOD or LiCl + D_2O solution, Au anode). Below the cathode foil was a surface barrier detector. In six runs out of 23 they measured charged particles of energy less than 2.1 MeV after a charging time of several hours to a few days. The charged-particle counts continued for several days at times (see Figure 9). They have argued that 3-MeV protons produced in (d-d) reactions while passing through the 10-μm-thick Cu-Pd foil will emerge with an energy less than or equal to 2.1 MeV, while 1-MeV tritons or 0.82-MeV ^{3}He, if any are present, will not be able to penetrate the full thickness of the cathode foil.
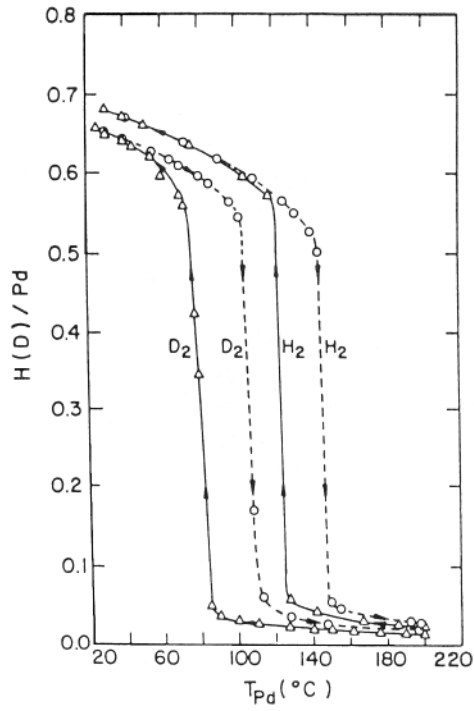
Figure 7. Hysteresis effect in the solubility of H and D in Pd. (From Report No. PNTG-90-16, October 1990, by Y. E. Kim, Purdue University, USA)
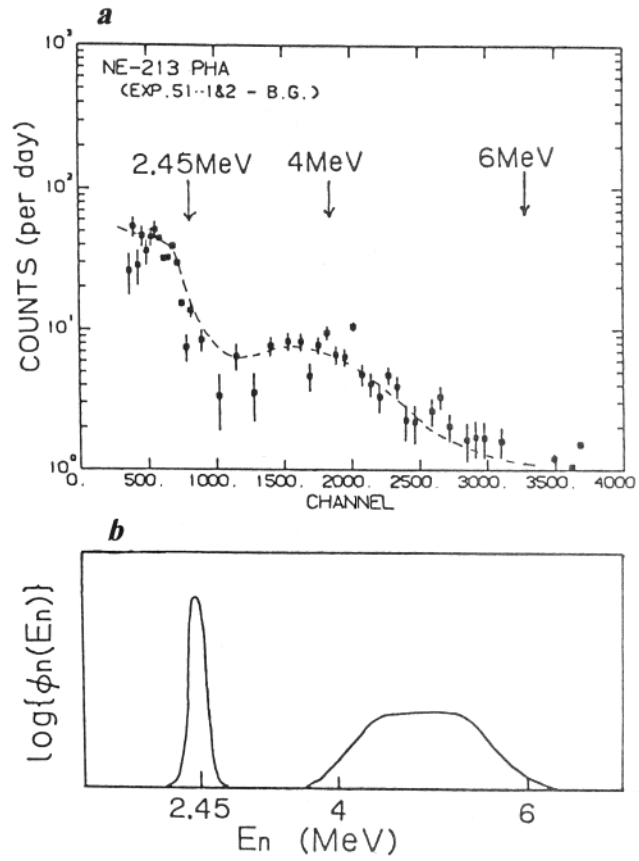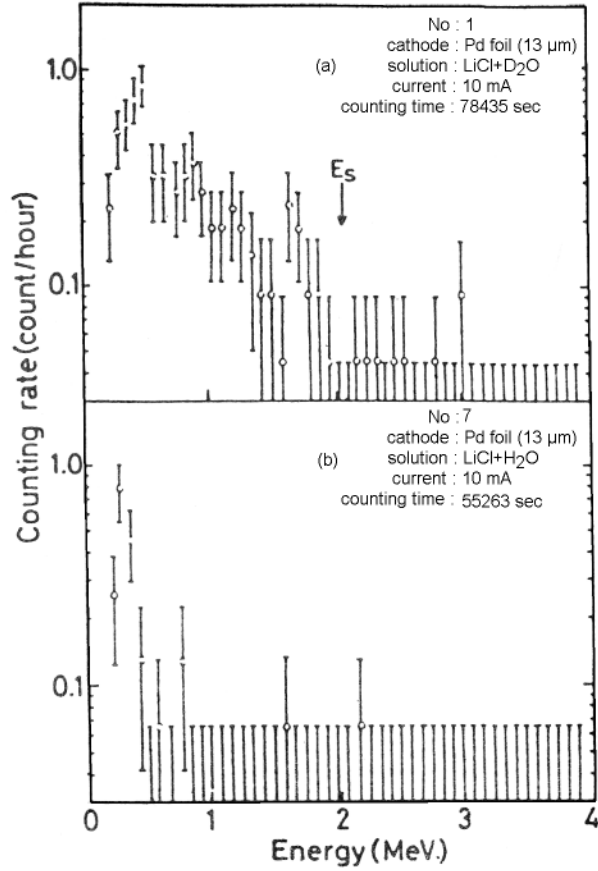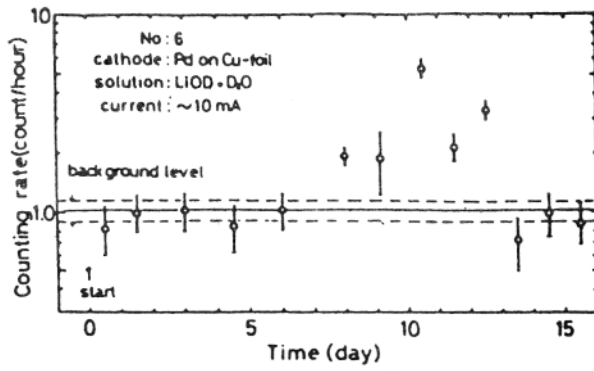
Figure 8. Evidence for 4- to 6-MeV-energy neutron component besides 2.45-MeV peak in D₂O electrolysis. (From Takahashi et al.[83])

Energy spectra measured with (a) D_2O-electrolytic solution and (b[1]) H_2O-electrolytic solution.

Time dependence of counting rate for the run with a palladium layer on a copper foil, a good anode, and LiOD solution.

Figure 9. Detection of charged particles from thin Pd cathode during D_2O electrolysis. (From Taniguchi *et al.*[85])

7. Evidence of X-rays in electrolysis

Stan Szpak[86] of the Naval Underwater Systems Centre in San Diego has carried out a very interesting experiment which demonstrates that low-energy X-rays are generated at the Pd cathode during electrolysis of D_2O. He used a Ni-mesh cathode and a Pt anode. The electrolyte was 0.05 M $PdCl_2$ + 0.3 M LiCl. Very close to the Ni mesh was a Polaroid film sealed in a light-tight and water-tight packing. After several hours of electrolysis the film on developing showed an impressive chequered pattern identical in image to the Ni mesh. Presumably, in the initial stages of electrolysis Pd gets deposited on the Ni mesh and in later stages gets loaded with deuterium, which eventually supports anomalous nuclear reactions resulting in the generation of low-energy X-rays.

Ref. 58 reports that Miles and his coworkers have also observed significant fogging of dental X-ray films positioned near the outer surfaces of two operating D_2O-LiOD electrolytic cells. An H_2O-LiOH cell did not cause similar fogging.

8. Burst neutron emission from gas-loaded titanium turnings

At least a dozen independent groups[17,23,73,84,87-92] have so far successfully carried out experiments involving the loading of deuterium gas into Ti lathe turnings (or chips) contained in a deuteriding bottle following high temperature (200 to 800°C degassing under vacuum. This technique, which was first suggested by Scaramuzzi of Frascati[23], has since been substantially improved by the Los Alamos[17] and Brigham Young University[81] teams. The novel feature of these experiments is the use of liquid nitrogen to subject the TiD_x chips to repeated cooling-warm-up cycles. A high-efficiency neutron detector system comprising a large number of ^{3}He or BF_3 neutron detectors embedded in a hydrogenous moderator is employed to measure neutron output. It has been observed consistently by all the twelve groups that neutrons are invariably produced during the warm-up phase following a cooling cycle when the temperature of the chips is in the sub-zero range (- 60°C to 0°C) (see Figure 10). From the known efficiency of neutron detection it has been established that between 30 and 300 neutrons are typically produced in each burst from the bottle as a whole. One or two groups have made preliminary measurements of tritium generation in such experiments by degassing and recombining the extracted deuterium gas back into D_2O and analysing it for tritium content. Zelensky *et al.* of Kharkov[92] appear to have independently developed and demonstrated this method as early as in April 1989, with the difference that they used an ion-implantation technique to load deuterium into metallic titanium samples. Zelensky *et al.* who monitored neutron output while steadily increasing the sample temperature (1 to 3° C/per sec) observed a very interesting double peak, one at - 30°C and a second at 600°C (see Figure 11).

Similar deuterated-chips experiments have also been carried out by us at BARC recently[93], with the variation that the TiD_x chips were as such dropped into a canister containing liquid nitrogen. We measured the tritium production by directly counting the LN-treated chips using beta and X-ray detectors. In earlier BARC studies[94] it was shown that the 18.3-keV (maximum energy) beta particles released during the decay of tritium (12.3-yr half-life) excites the K_α (4.5 keV) and K_β (4.9 keV) (characteristic X-rays of titanium and this serves as an excellent tool to detect the presence of tritium. The BARC groups have also pioneered the use of the technique of autoradiography for studying cold-fusion targets. Using these techniques it was found that < 1 %

of the several thousand TiD_x chips treated in liquid nitrogen had generated MBq levels of tritium. The main outcome of this work is the finding that not only are the anomalous fusion reactions found to take place in only a very few chips, but even in those chips tritium production is restricted to a small number of selected localized 'hot spots' only (see Figure 12)[89,93].
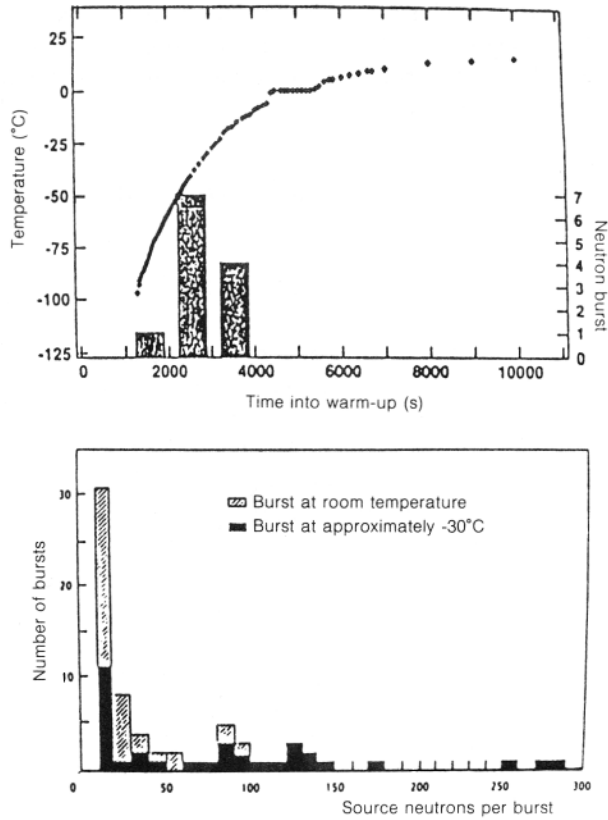

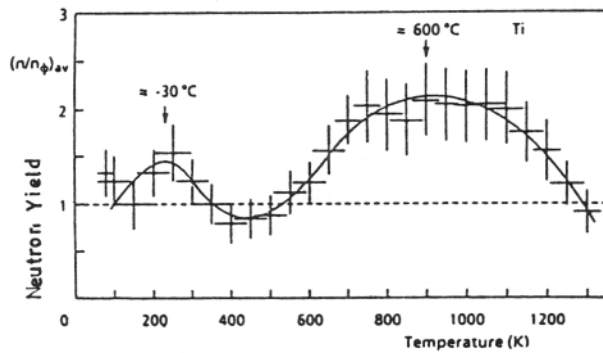**Figure 10. Characteristics of neutron burst production from TiD_x chips subject to thermal cycling. (From Menlove et al.[17])**

Figure 11. Neutron count-rate variation during heating of a deuterated Ti foil. (From Zelenski et al.[92])

Figure 12. Autoradiograph of a deuterated Ti chip showing tritium-containing hot spots. (From Kaushik et al.93)

9. Charged particles from gas-loaded titanium foils

Ed Cecil[95] of the Colorado School of Mines has been successful in measuring the emission of charged-particle bursts from deuterium-loaded thin titanium foils subjected to liquid nitrogen cooling-warm-up cycles. The foils (0.1 mm thick) were prepared on a lathe using a broad cutting tool (> 10 mm wide), much like the shavings obtained while sharpening an ordinary lead pencil. The shavings were vacuum-annealed for 2 h at 700°C and loaded with D_2 gas (2 atm, 1 h). They were then gently flattened out and clamped onto an SS backing using a ring-type washer such that a surface barrier detector could view the central part of the foil for measuring charged-particle emissions. The SS holder in turn was mounted on a copper cold finger in such a manner that the temperature of the foil could be cycled between -180°C (liquid nitrogen) and +20°C. Cecil's group observed bursts of high-energy events spanning the 2- to 5-MeV band. When a 13.2-μm-thick Al foil was used to cover one half of the surface barrier detector, pulse height decreased as expected resulting in a double peak. Twelve samples out of 26 gave bursts; there were in all 24 bursts in 56 days. The burst duration varied from 1 to 100 min (see Figure 13). Most of the bursts were observed 6 to 10 h after removal of liquid-nitrogen cooling. No such bursts were observed with hydrogen-loaded foils. Species identification plots indicated that the observed charged particles were most probably tritons. The present experiments are a continuation of the preliminary work reported by Cecil *et al.*[96] at the Santa Fe meeting. In the earlier studies they had used an ion implantation method to load deuterium. They have also attempted to determine if passage of a current along the length of the deuterated foil would have any beneficial effect on charged-particle emission; so far they have not been able to establish conclusively that a definite correlation exists between these. The results of Cecil's triton measurements complement the neutron and tritium measurements on deuterated titanium samples described in the previous section.
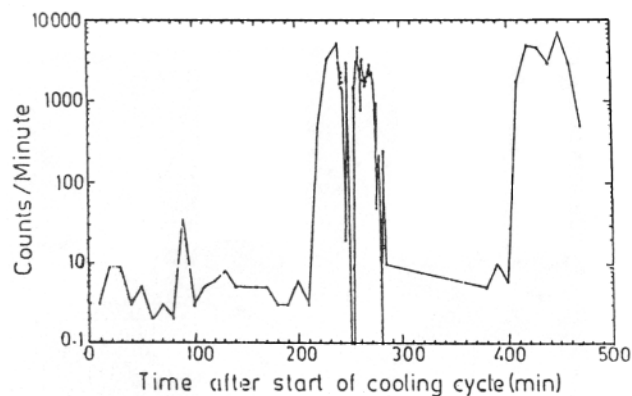
Figure 13. Count-rate variation of 5-MeV tritons from a TiD$_x$ foil. (From Cecil *et al.*[95])

10. Charged particles from ion-beam-loaded Ti foils

George Chambers *et al.*[97] of the Naval Research Laboratory in Washington, DC, have reported the detection of 5-MeV triton bursts from 1-μm- and 3.8-μm-thick Ti foils bombarded with 300-eV-energy deuteron beams in a vacuum chamber. They used an ECR-type ion source. Only virgin Ti foils gave results, that too about 30% of the time. They never obtained results with either Pd foils or with predeuterated titanium, i.e. TiD$_x$. samples. When the bias to the charged-particle detector was turned off, the pulse height dropped to 3.5 MeV as expected (owing to decrease of effective depletion layer thickness in the detector). The most interesting part of their results is that the charged particles were of 5-MeV monochromatic energy, clearly ruling· out (d-d) reactions as the source of these tritons, since in a (d-d) reaction one expects either a 0.8-MeV ^{3}He nucleus or a 1-MeV triton or a 3-MeV proton. 5-MeV tritons can however be explained on the basis of 3D reactions, surprisingly in conformity with the conclusions of Takahashi based on the 4 to 6-MeV-energy neutron component observed by him in the D$_2$O electrolytic cell experiments discussed in section 5 above.

11. Precursor to charged-particle emission from gas-loaded Pd

A 14-member multi-institute team from Beijing led by Li of Tsinghua University has reported[98] observation of precursor emission in the form of some electromagnetic radiation, presumably in the UV to soft-X-ray region, prior to the production of charged particles from a D$_2$-gas-loaded Pd foil. They used CaF$_2$ TLD detectors for the soft-X-ray detection and CR-39 track detectors (SSNTD) for registering charged particles. The CR-39 detector on chemically etching showed clusters of charged-particle tracks at many locations. They found that H$_2$ loading also gave TLD signals but no charged-particle tracks, giving credence to their suspicion that 'electromagnetic radiation might originate from electrons which are transiting from state to state when palladium foils are filled with hydrogen or deuterium'. They have further conjectured that 'these photons must be in the 10-eV to 3-keV region since the electron should approach to an orbit similar to that of muons in order to screen the coulomb barrier effectively'[98]. One of the interesting findings reported by them is that Pd samples cleaned with aqua regia never gave any charged particles. Subsequent Auger electron scanning probe analysis indicated that these Pd samples had significant quantities of chlorine on their surface. The inhibiting role of chlorine in suppressing the generation of charged particles is not yet understood. (I have learnt that these

experiments have since been successfully repeated by two different groups at Brigham Young University recently[99].)

12. Solid-state-cell experiments of Los Alamos

Claytor *et al.*[25] of Los Alamos have continued to develop their 'solid state cell' concept which they first reported at the NSF/EPRI Workshop of October 1989 (ref. 27). In these cells, a packed bed of alternate layers of Pd and Si powder is mounted between a pair of electrode plates (see Figure 14) in a pressurized (8 bar) D_2-gas atmosphere and an intermittent current passed through this solid-state cell by application of a pulsed high voltage (1.2 to 2.5 kV, 100 pulses, pulse width > 150 μs). Eight out of 30 cells have so far produced excess tritium (greater than 3 sigma above background levels). At least one cell (cell # 2) produced both neutrons and tritium (6 MBq), the neutron-to-tritium yield ratio being 3×10^{-9}. At the Provo meeting Claytor reported that since the last few months they had been investigating the use of Pd metal foils (Johnson and Matthey) in place of Pd powder and this had considerably improved the reproducibility of results. The tritium activity, as measured in the gas stream, is now 'reproducible', being on the average ~ 20 Bq h^{-1}.

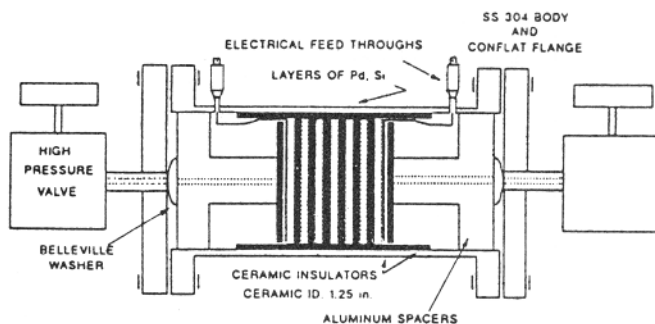**Figure 14. Solid-state cell of Los Alamos. (From Claytor *et al.*[25])**

13. Neutron production in a Pd surface barrier plate

Yamaguchi and Nishioka[100] of NTT laboratories, Tokyo, have demonstrated a novel technique for inducing anomalous nuclear effects in a Pd surface barrier device. This technique, which is based on the metal-insulated semiconductor concept, uses a thin MnO film deposited on one face of a deuterium-loaded Pd plate, thereby providing a surface barrier for ionic transport of deuterons. The other face of the Pd plate is coated with a thin impervious film of gold to prevent the escape of deuterium. When a vacuum is suddenly created in the chamber in which the device is mounted, rapid out-transport of deuterons takes place, resulting in the accumulation of deuterons at the junction of Pd and MnO. This sudden entrapment of deuterons results in a big burst of > 10^6 neutrons, accompanied by explosive release of gas, biaxial bending of the Pd plate following plastic deformation, besides considerable heat evolution. The temperature is estimated to cross 800°C momentarily owing to rapid phase change near the surface bordering MnO. All the phenomena except neutron output are however observed with hydrogen loading also, indicating that the heat release is due to non-nuclear causes. These investigators were able to induce a neutron burst from the same Pd sample a few times consecutively by redeuterating the

sample after each burst followed by rapid outgassing (see Figure 15).

Note the similarity of this approach to the 'on-off effect' reported by Arata and Zhang[82] (section 4). While Arata and Zhang have used temperature change to create explosive desorption of D_2, Yamaguchi *et al.* have used rapid pressure release to achieve the same result.
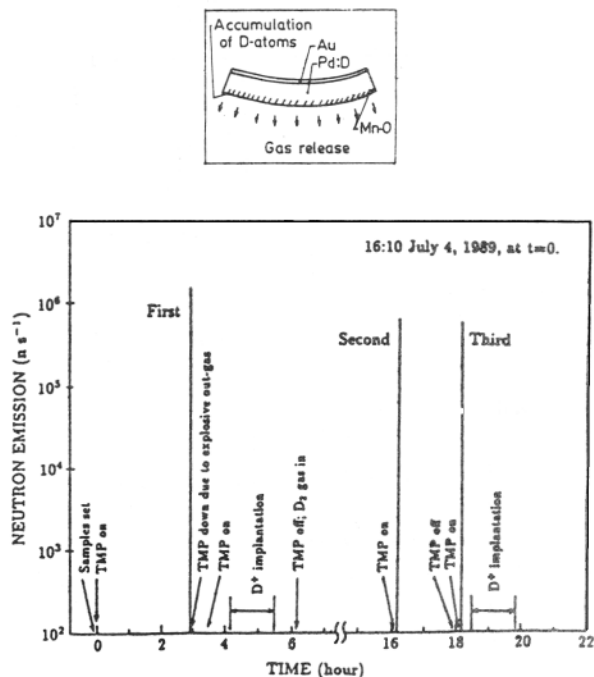

Figure 15. Burst neutron production from deuterated Pd surface barrier device. (From Yamaguchi *et al.[100]*)

14. Neutron emission from a D_2 gas discharge tube with Pd electrodes

Wada and Nishizawa[101] of Nagoya University have carried out a simple gas-discharge experiment with a pair of Pd electrodes (2-mm-dia $\times$ 35-mm-long each). The electrodes, mounted on copper stems inside a 300-ml glass bulb (see Figure 16), were first activated by the application of 12 kV, 60 Hz AC voltage under vacuum (10^5 bar). The bulb was then filled with D_2 gas at 1 bar pressure. The absorption of the gas by the activated Pd was measured by the drop in pressure (see Figure *16,a).* About 55 h later, when the pressure had attained a steady value, the Pd rods were 'stimulated' by creating a HV discharge once again. (The duration for which the HV was applied is not given in their paper.) A large burst of 10^5-10^6 neutrons was observed over a period of 63 sec. This was followed thereafter by several smaller bursts intermittently over the next 50-h period. Wada *et al.* have attributed the occurrence of these spontaneous neutron bursts to a 'breathing' process akin to the on-off effect of Arata and Zhang described earlier. A second HV-discharge stimulation at 95 h from the commencement of the experiment resulted in yet another neutron burst, as may be seen in Figure *16,b.* Two more such neutron bursts were observed subsequently following HV stimulation but their peak values were weaker. Interestingly the used Pd rods never showed neutron emission again, although they did soak up considerable amounts of deuterium following 'activation'. Similar experiments with H_2 gas did not yield neutrons, even though the absorption characteristics of H_2 in Pd were noted to be similar.

Kim[102] of Purdue University has recently analysed this experiment and pointed out that the neutron emission here could be explained on the basis of a conventional beam-target process. Measurement of the tritium yield in such experiments may give a clue to whether 'cold fusion' is taking place.

15. First observation of neutron emission from chemical reactions

Arzhannikov *et al.*[103] of the Institute of Nuclear Physics in Novosibirsk have reported the generation of neutrons during the reaction of LiD crystals with D_2O (ref. 104) as well as during certain oxidation-reduction reactions of complex deuterized salts of Pd and Pt such as $Pd(ND_3)_2C_3$ and $(ND_4)[PtCl_6]$ with Zn (ref. 105). In the former experiment about 30 g of D_2O was placed in a test tube and LiD crystals 0.3 mm to 4 mm in size were dropped into the test tube one at a time. The reaction of LiD with D_2O being exothermic, the temperature of the test tube increased to about 80°C. Neutron production was observed during this phase, as evident from the lower part of Figure 17, and corresponded to a few tens of neutrons per gram of deuterized matter. It is noteworthy that neutron emission was observed only during reactions with deuterized salts of these metals; no neutrons were detected when the hydrogen version of these salts were used (see upper part of Figure 17). Arzhannikov *et al.* have not attempted to provide any theoretical explanation for the origin of these neutrons.
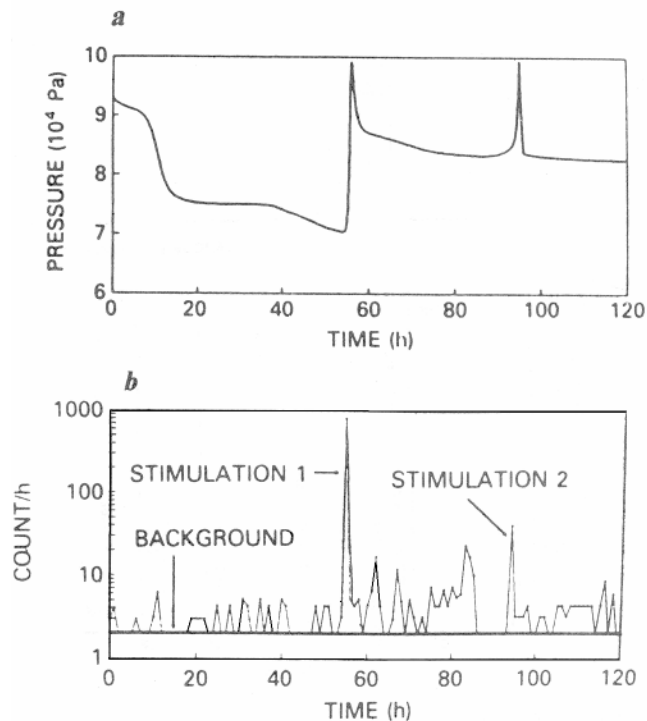

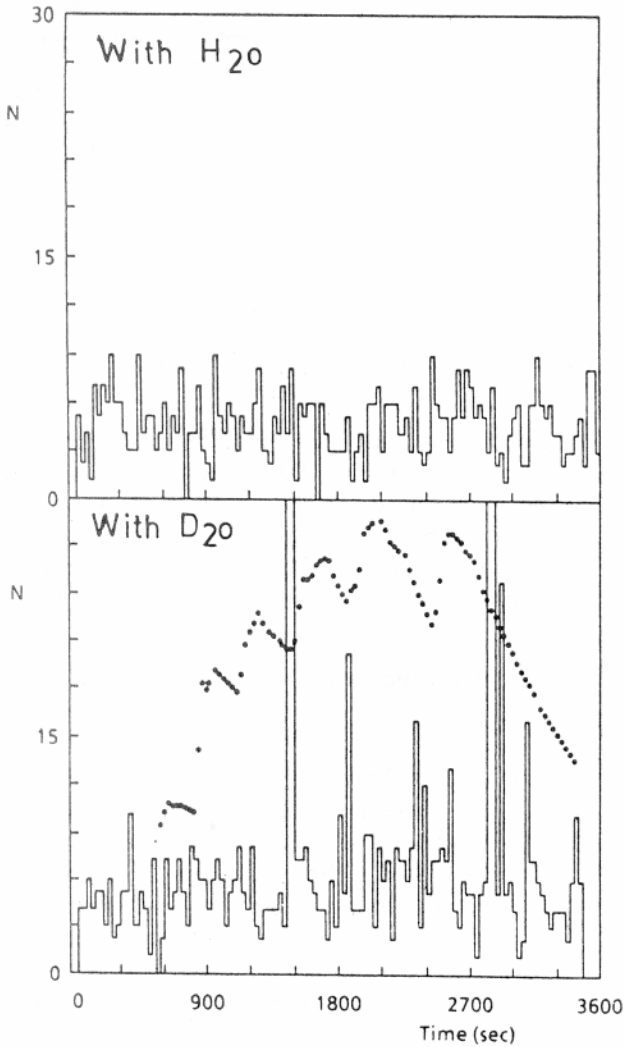**Figure 16. Neutron production from D_2-gas-discharge experiment using Pd electrodes. (From Wada *et al.*[101])**

Figure 17. Neutron emission in LiD-D$_2$O experiment. Dotted graph in lower figure shows temperature variation. (From Arzannikov _et al._[103])

16. Cluster impact fusion

Beuhler _et al._[106] of the Brookhaven National Laboratory discovered that nanoampere beams of singly ionized clusters of D$_2$O ice crystals carrying energies of 200 to 325 keV each, corresponding to 10 to 1000 eV per deuteron, when impinged on deuterated targets such as TiD, ZrD$_{1.65}$ and CD$_2$, produced an anomalously high yield of (d-d) reactions. No reactions were observed either with H$_2$O clusters impinging on TiD or with D$_2$O clusters bombarded on TiH targets. The fusion rate with D$_2$O on TiD was maximum when the number of D$_2$O molecules per cluster was about 100, and corresponded to 0.1 reaction per sec per d-pair. This implies a discrepancy by a factor of over 10^{10} with respect to expected rates based on known low-energy (d-d) reaction cross-sections in the incident deuteron energy range of a few hundred eV. This experiment was immediately interpreted by physicists as implying that (d-d) cross-sections in the low-energy range were perhaps much higher than accepted hitherto. However, more detailed analysis of the experiment carried out by Echenique _et al._[101], Cheng _et al._[108] and Rabinowitz _et_

al.[109]*,* modelling the phenomena occurring from the instant the D_2O cluster impacts the target, properly accounting for the enhanced maxwellian tail that results following energy sharing between the target and cluster atoms involved, have brought out the important role of heavy atoms such as O in D_2O, and Ti, Zr or C in the target in the dynamical processes occurring immediately following the impact. These computations have however used only the presently accepted (d-d) cross-section data. Thus it appears that the phenomenon of cluster impact fusion, which has also been labelled 'lukewarm fusion', may have no direct relevance to cold fusion after all, although it has certainly helped bridge the gap between hot and cold fusion[110].

17. Fracto-fusion

Almost from the beginning of the cold fusion 'era' it has been conjectured that the reported neutron emission (see sections 3 and 8) could be explained on the basis of what has come to be known as 'fracto-fusion', namely (d-d) reactions caused by deuterons accelerated by the high electric field generated between opposite faces of an internal fracture in the deuterated metal matrix[111,112]. It is well known from the exhaustive studies of Dickinson *et al.*[113] that transient electric fields of more than 15 kV cm^{-1} are generated across cleaved surfaces of ionic crystals or fractured insulators. In fact Klyuev *et al.*[114] of the USSR carried out an experiment as early as 1986 specifically to verify the possibility of neutron emission through such a mechanism by impacting a 'striker' of 50-g mass accelerated to a velocity of 200 m s^{-1} on an LiD single-crystal target. They detected on an average 10 neutrons per shot in a 75-shot experiment. In the case of hydrides of Pd and Ti also it is well known that large cracks and fissures are formed following a high degree of hydrogen (or deuterium) loading in them. Cohen and Davies[115] have computed the electric potential that may be expected to be generated when a crack is initiated and 'propagates' in PdD_x or TiD_x and show that the observed neutron bursts, particularly in the Frascati-type experiments involving the thermal cycling of TiD_x chips in liquid nitrogen, can indeed be explained by such a fracto-fusion mechanism. In fact many experimenters have detected the occurrence of such fractures by means of piezoelectric acoustic sensors[116]. But so far no clear-cut correlation has been established between acoustic pulses and neutron bursts.

In a beam-target-type neutron-production process relevant to fracto-fusion, however, one expects the neutron- and tritium-yielding branches to have near-equal probability, and hence the anomalously low ($\sim 10^{8}$) neutron-to-tritium yield ratio observed in some experiments is inconsistent with the fracto-fusion postulate. Besides, it also appears to be difficult to reconcile fracto-fusion with the highly localized production of large amounts of tritium (10^{12} to 10^{14} atoms) in certain site-specific hot spots observed in only a few TiD_x chips out of several thousand[93]. In this context it may be of interest to point out that my colleagues and I have speculated that perhaps the neutron bursts and tritium hot spots may be the result of some sort of cascade reaction or micronuclear explosion[89]. Experiments are currently under way in several laboratories of the world to establish conclusively whether in the TiD_x-chips experiments the neutron bursts and tritium hot spots are correlated at all, and also whether the n/t yield ratio is unity or really as small as 10^{8}, and thus settle the question as to whether fracto-fusion or microexplosion or some other mechanism is the root cause of nuclear reactions in these experiments.

18. Indication of anomalous enrichment of ^{106}Pd during electrolysis

Rolison and O'Grady[117] of the Naval Research Laboratory in Washington, DC, reported some preliminary but startling results at the NSF/EPRI meeting[27] of October 1989 on their probable detection of a change in the isotopic composition of the Pd in the near-surface layers of two Pd cathodes electrolysed in D_2O. Their very careful and painstaking mass-spectrometric analysis carried out using a sophisticated time-of-flight-secondary-ion mass spectrometer (TOF-SIMS) had indicated that two D_2O-electrolysed Pd samples exhibited a greater-than-20% enrichment in the intensity of the $m/z = 106$ peak with a corresponding decrement in $m/z = 105$ intensity, whereas both a control Pd sample as well as one electrolysed in H_2O showed only natural-Pd isotopic composition. This result created great excitement among physicists as it implied the possible involvement of Pd nuclei in the anomalous nuclear phenomena associated with cold fusion. Specifically it suggested the possible occurrence of direct neutron-transfer reactions between deuterons and ^{105}Pd, resulting in the formation of ^{106}Pd.

At the Salt Lake City cold fusion meeting of March 1990, Rolison *et al.*[118] presented a summary of their further investigations, which indicated the possibility of the existence of some experimental artefacts that could have contributed to some errors in their previous conclusions. They found that presence of trace levels of ZrO species as a surface contaminant in LiOD-derived Pd samples could have given rise to an m/z signal in the same region as that of ^{106}Pd. But their Li_2SO_4-derived Pd samples were found to be Zr free. After an involved and very exhaustive experimental campaign and after eliminating or accounting for all other possible sources of error they concluded[118] that 'a relative enrichment at m/z of 106 that cannot be attributed to heretofore identified plausible chemical interferents still exists', thereby keeping the door open to the possibility that cold fusion may still encompass nuclear reactions involving Pd and perhaps Li nuclei as well. In particular, there has been considerable speculation that the well-known reaction between ^{6}Li and d leading to two alpha particles plus 22.3 MeV of energy may have occurred on the surface of Pd cathodes during the excess-heat experiments of Fleischmann *et al.* and some others. But, to be fair, all talk of any nuclear reactions occurring in the electrolytic cells involving particles other than deuterons can only be treated as 'speculation' for the present.

19. Remarks on the poor reproducibility of results

One of the unique features of cold-fusion experiments, and possibly the main reason for this phenomenon to be looked upon with considerable degree of skepticism[119] by the scientific community in general, is the poor reproducibility of the experimental results. During the crucial months immediately following the first announcement by Fleischmann and Pons there was a scramble the world over to replicate the apparently simple 'battery and bottle' electrolysis experiment. After months of patient experimentation, however, many experienced research groups failed to obtain any positive evidence for the claimed phenomena. They neither found excess heat nor neutrons, tritium or gamma rays[120-134]. Some experiments that were tailored to look for charged particles also failed to give any positive results[123,134]. By December 1989 there were perhaps more experimental papers with 'negative results' published on the topic of cold fusion than those with 'positive results'. However, as of the present writing, the situation has been fully reversed, following the appearance of a large number of papers with positive results during 1990, as described already. The persistent efforts of many dedicated experimentalists appear to have turned the trend and the reproducibility has begun to improve significantly, as

may be seen for example from the title of one of the recent papers[135] from Los Alamos, namely 'Reproducible neutron emission measurements from Ti metal in pressurised D_2 gas'.

20. Summary of experimental findings

In the two-year period since the appearance of the first reports of cold fusion, it is obvious that the authenticity of the phenomenon, namely occurrence of 'anomalous nuclear reactions in solid-deuterium systems' has been established beyond doubt, although admittedly the phenomenon is still 'sporadic' in nature and not yet reproducible at will. The main findings of the cold fusion experiments to date may be summarized as follows:

(i) The production of excess heat in D_2O electrolysis with Pd (or Ti) electrodes has been fully confirmed. The steady-state or baseline excess heat is found to increase with current density and is typically not more than about 30% of the input joule heat in the case of D_2O electrolysis with Pd cathodes. The maximum excess power observed so far is ~ 100 W cm^{-3} of Pd. (This translates to ~ 10^{14} fusion reactions per sec per cm^3 or ~ 10^{-9} fusions per sec per d-pair.) The integrated energy yield has been over 50 MJ cm^{-3}. However, during the sporadic heat bursts (observed only by a few groups so far), peak power levels have been 20 to 30 times the input power. In molten-salt electrolysis with Pd anodes the excess power has been as high as 15 times the input electrolytic power for more than a day at a specific power of 0.6 kW cm^{-3}.

(ii) ^{4}He has been detected by mass-spectrometric analysis in the electrolytic gases of the Miles experiments[55,58] as well as in the 0.5-g Pd button which generated 5 MJ of energy in the molten-salt experiment. While the quantum of ^{4}He measured in the gas stream was substantial, that in the Pd button was still much below that expected from the magnitude of the integrated excess heat. These results point to the generation of ^{4}He on the surface of Pd rather than in the bulk matrix.

(iii) Neutrons have been measured both in electrolysis and gas-loaded targets. They appear at a very low (10^{-20} to 10^{-23} neutrons per sec per d-pair) steady-state level ('Jones level') a few sigma above background count rates or in the form of bursts lasting from microseconds to minutes to even hours at times. Neutron-multiplicity and statistical-analysis measurements indicate that neutron emission has both a single component following Poisson distribution (one neutron emitted at a time) as well as bunches of several hundred neutrons[79,80,136]. Several groups have measured the neutron energy to be 2.45 MeV. However, at least two groups have reported observing an additional 4- to 6-MeV component. Surprisingly no group has detected any 14-MeV neutrons so far.

(iv) The production of tritium in both electrolytic and gas-loading experiments stands confirmed. The suspicion that tritium seen in cold-fusion experiments is due to prior contamination of Pd has been ruled out by the fact that in several experiments neutrons and tritium were generated 'concomitantly'.

(v) The neutron-to-tritium yield ratio appears to be very small; it is mostly ~ 10^{-8} although in some cases values as 'large' as 10^{-3} have been reported.

(vi) Charged particles with energies varying from < 1 MeV up to several MeV have been observed in many experiments. One group has reported measuring monochromatic tritons of 5-MeV energy from deuterium-gas-loaded titanium samples. (It may appear to be difficult to reconcile this last observation with the non-observation of 14-MeV neutrons by any group so far,

but it must be appreciated that the 14-MeV-neutron production rate in Cecil's experiments for example would have been hardly 1 neutron per hour as it would be only 10^{-5} times the triton generation rate; it is impossible to detect such a low neutron production rate in experiments.)

(vii) Soft X-rays have been detected from Pd in a D_2O electrolysis experiment through radiographic imaging of the cathode.

(viii) Acoustic signals have been measured both in Pd electrolysis experiments as well as Ti gas-loaded targets.

(ix) Electromagnetic signals (radio emission) have been picked up in electrolysis experiments using a Rogowsky coil.

This plethora of experimental evidence obtained using a variety of experimental techniques points to the occurrence of many different nuclear reactions, induced by deuterons.

For the benefit of potential new entrants to the field of cold fusion who wish to try their 'luck' in carrying out similar investigations I have summarized in the Appendix the various steps involved in conducting such experiments as I perceive it.

21. 'Puzzles' of the cold fusion phenomenon

The experimental findings listed above can be condensed in the form of a series of 'puzzles' that any theoretical model which seeks to explain cold fusion phenomena should account for.

(a) The first puzzle is the very occurrence of nuclear reactions in a solid atomic lattice at near-ambient temperatures. It is believed that the free electrons and deuterons in the metal lattice play a crucial role in screening and lowering the coulomb barrier and help increase tunnelling probability.

(b) The second important puzzle is the several-orders-of-magnitude mismatch between experimentally observed excess power/heat and neutron or tritium yields. This clearly indicates that excess heat in electrolysis is definitely not due to simple (d-d) reactions, which would have given rise to copious levels of neutron or tritium production. It was recognized right from the beginning that 'excess power' levels in the watt range, for example, would imply production of more than 10^{12} ns^{-1} and this would have resulted in lethal levels of radiation. Hence excess heat, if indeed of nuclear origin, has to be due to some other nuclear reaction in which the product is a non-radioactive charged particle. For example, a 2-body (d-d) reaction leading to ^{4}He has been postulated as the most probable candidate for this, although a (^{6}Li + d) reaction leading to two ^{4}He nuclei is also a possibility. Two recent experiments[58,60] have provided the first 'confirmation' that ^{4}He is indeed being produced in electrolytic cells wherein excess heat is measured.

(c) The third puzzle needing explanation is the experimentally observed correlation between current density and excess power, both in D_2O electrolysis and in Molten-salt electrolysis. In other words, the precise role or influence of the 'electrochemical compression process' (or the so-called fugacity) on the fusion reaction rate needs to be understood. A 'sub-puzzle' in this context is the reason for the inordinate delay between commencement of electrolysis and commencement of excess heat, which needs justification. Among the various models put forward to address this question, the transmission resonance model (TRM) of Bush[37] appears to be the most successful so far.

(d) The fourth puzzle is the fact that no tell-tale high-energy X-rays, which would give a signature of energetic charged-particle generation, have been measured so far, although very soft X-rays which cannot escape from the cell but barely escape the Pd cathode have been indirectly detected through fogging of X-ray film[58,86]. This could imply that no high-energy fusion products are released during these nuclear reactions. The common explanation offered for this is the postulate that the energy released in the nuclear reaction is somehow directly absorbed by the lattice (as phonons)[138] or electromagnetically transferred to the electrons akin to an internal conversion process. Walling and Simons[139] have attributed this to 'radiationless relaxation' (RR) of the transient excited ^{4}He.

(e) Although the excess-heat phenomenon is obviously not due to simple (d-d) reactions, the very fact that ~ 2.45-MeV neutrons have been measured in a variety of experiments indicates that (d-d) reactions do nevertheless occur in deuterated Pd and Ti simples. But the puzzling part here is: Why is the n/t ratio not unity? This 'branching-ratio anomaly' may be characterized as the fifth puzzle of cold fusion. Some theorists have invoked a Phillips-Oppenheimer-type process for explaining this[139,140].

(f) The sixth puzzle is the apparent non-generation of 14-MeV neutrons. So far nobody has detected any 14-MeV neutrons in cold-fusion experiments. The tritium generated in (d-d) reactions is expected, according to present day 'vacuum nuclear physics' concepts, to have about 1 MeV of energy, in which case it should have produced 14-MeV neutrons with a probability of 10^{-5} during the slowing down of the suprathermal tritons in palladium deuteride. This puzzle has so far been explained by invoking the postulate that excess energy is carried away directly by the metal lattice as discussed in (d) above.

(g) The seventh puzzle is the recently measured 4- to 6-MeV neutron component, which, according to Taka-hashi[83], suggests the occurrence of 3-body 3D reactions. He has proposed that the 15.9-MeV deuterons generated in 3D fusion give rise to 4- to 6-MeV neutrons during their slowing down in PdD$_x$. The puzzle then is how does it happen that energetic charged particles are generated in 3D reactions but not in 2D reactions.

(h) The eighth puzzle is the possible occurrence of nuclear reactions involving host metal nuclei such as the Pd nuclides or the Li isotopes deposited on the cathode surface during electrolysis. This possibility arises from the inconclusive but highly suggestive and speculative Pd isotopic analysis results of Rolison *et al.*[117] discussed in section 18.

(i) The ninth and last puzzle is the poor reproducibility of the results, be it in electrolytic experiments or gas-loading experiments or other techniques, strongly suggesting that all the experimentalists are missing an important and key 'element' that is crucial to achieving 'success'. The question is: Is it a metallurgical factor or a chemical impurity or a nuclear trigger or some other physical parameter that is responsible for the poor reproducibility? That is a puzzle yet to be solved.

The above list of puzzles clearly indicates that the cold-fusion phenomenon is, in the words of Hagelstein[138]: 'in direct contradiction to very basic precepts of nuclear physics. . . . it seems that an extremely fundamental and totally unexpected change in our understanding of physics would be required to even begin accounting for the various 'miracles' that have been claimed.' Indeed, this was also reflected in the conclusions of the final report of the US Department of Energy's Cold Fusion Panel[16], quoted in the introduction to this article.

22. Approaches to a theoretical understanding of cold nuclear fusion

A number of theoretical attempts[137-171] have been made during the last couple of years to explain some or all of the above 'puzzles'. Broadly speaking there appear to be three basic issues that any theory of cold fusion must address. These are: (i) How exactly does the host metal lattice help in increasing the fusion rate in spite of the deuteron energy being apparently small? (A deuteron in thermal equilibrium, for example, would have only a few tens of millielectronvolts of energy.) (ii) What are the mechanisms, if any, by which the energy released in the nuclear reactions can be directly transferred to the host metal lattice? (iii) The more general but fundamental issue of what Preparata[141] calls the problem of 'asymptotic freedom', namely how does it happen that lattice interactions with their typical time-scales of 10^{-16} sec and distances of 10^{-8} cm 'tamper' with nuclear forces with typical times of 10^{-21} sec and distances of 10^{-12} cm?

The majority of the theoretical studies have addressed the first of these issues, namely the possible methods of enhancement of fusion-reaction probability (p) from a negligible value of about 10^{-70} sec^{-1} for a D_2 molecule in free space[142] to levels in the range of 10^{-9} to 10^{-23} sec^{-1} experimentally observed in the solid environment. Traditionally the fusion-reaction probability p_r is expressed as the product of two factors: The first factor is the barrier-penetration probability, which pertains entirely to the electrical forces of repulsion. The second factor is the intrinsic nuclear reaction rate, which refers entirely to the nuclear forces. Thus p_r is expressed as $p_r = [e^{-G}] \cdot A$. For example, for the (d-d) reaction, factor A is given by $[3 \times 10^{-13} \cdot E_d^{-1/2}]$ where E_d is in eV and p_r is in sec^{-1}. The first factor, namely (e^{-G}), represents the barrier-penetration probability and is dependent crucially on the modified Gamow tunnelling parameter G. Clearly the magnitude of G is significantly decreased in a solid environment owing to charge screening and other effects, leading to an enormous enhancement of the tunnelling probability.

In order to account for the fusion reaction rates that seem to be seen in cold-fusion experiments, the value of G has to decrease from about 175, applicable to D_2 molecules in free space, to about 80 (for Jones-level reaction rate) or ~ 70 (for Fleischmann-Pons heat rates). The physical phenomena that have been considered as contributing factors for decreasing G are: (a) conduction electron screening, (b) deuteron screening, (c) heavy-electron concept, (d) effective deuteron mass, (e) velocity distribution of the deuterons, and (f) deuteron channelling effects.

Interestingly, writing under the title 'Cold fusion prospects', Rand McNally[143] had discussed the theoretical possibility of achieving a reduced coulomb barrier in solid media even as early as 1983. Parmenter *et al.*[144] have computed the tunnelling probability on a simple model considering the interacting particles to be composite particles comprising a bare deuteron plus an associated screening cloud of electrons. They have adopted a modified Thomas-Fermi-Mott equation methodology and derived p_r values in the range of 10^{-25} to 10^{-23} sec^{-1}. Vaidya and Mayya[145] account for the combined screening effect of electrons and deuterons using a 'Jellium model' to obtain values in the range of 10^{-36} sec^{-1} at 700 K to 10^{-14} sec^{-1} at 50 K. Rabinowitz[146] finds that use of an effective deuteron mass only a tenth of the free deuteron mass is adequate to give fusion rates in the experimental range.

References 147 to 156 discuss various screening and other mechanisms proposed to enhance tunnelling probability. However Leggatt and Baym[157] have argued that, if the effective repulsion of two deuterons is substantially weakened by solid-state effects, then these effects should also lead to a greatly increased binding energy of alpha particles to the metal, which clearly is not

borne out by experimental observations. Thus, working within the framework of the lowest-order Born-Oppenheimer approximation, they have carried out a rigorous computation of the many-body screening effects in Pd under equilibrium conditions and conclude that coulomb-barrier penetration cannot be enhanced to anywhere near the rates required to match the experiments. They thus imply that non-equilibrium conditions may be important.

Dasannacharya and Rao[158] have pointed out that, in a system with large anharmonicity such as palladium deuteride, there could be short-lived large energy fluctuations of a small number of particles, resulting in large momentum transfers, 10^2 to 10^3 times $(mKT)^{1/2}$. This could result in a few deuterons acquiring energies as high as 50 eV, enabling thereby high fusion rates. Kim *et al.*[159] and Rice *et al.*[160] have shown how the deuteron velocity distribution, especially an enhanced maxwellian tail, can significantly influence fusion rates in the presence of electron screening effects also. Using an essentially classical model Gryzinskii[161] has propounded a quasi-molecular mechanism of coulomb-barrier tunnelling. His theory hinges on the postulated presence in the PdD lattice of a high concentration of relatively long-lived, compact quasi-molecular ions, namely D_2^+, which radiatively collapse to cause fusion. Tabet and Tenenbaum[162] look upon cold fusion as resulting from a lattice collapse leading to 'deuteron drag' following thermodynamic instability. Chatterjee[163] has considered the influence of the kinetic energy available to the final nuclear particles in the (d-d) reaction on the neutron-to-tritium branching ratio. Hora *et al.*[164] have applied a surface double-layer model of metals with a 'swimming electron layer' of about 0.1 nm thickness on the crystal surface and computed fusion rates. They have accordingly predicted the possibility of achieving power densities in the range of kW cm^{-3} using multilayered samples.

Bush[137] has propounded a novel transmission resonance model (TRM) treating the diffusion of deuterons in a solid lattice as a wave-mechanics problem. Building upon an idea first outlined by Turner[165], Bush has shown that a 100%-transmission condition would be satisfied when 'an odd integral multiple of the average quarter-wavelengths of the de Brogue waves of the deuterons matches the potential well widths of the particles situated in the PdD$_x$ lattice'. He then postulates that when the resonance (or high-transmittivity) condition is satisfied, the diffusing deuterons get close enough to the stationary particles in the host lattice which form the potential wells (either d or Pd or Li), to have a high probability of undergoing nuclear reactions. Even though Preparata[141] has criticized Bush's model for not clearly spelling out how exactly the barrier-penetration probability improves when the resonance condition is satisfied, the TRM model nevertheless seems to be remarkably successful in fitting the highly nonlinear structure of a wide base of experimental calorimetric data. Figure 18, reproduced from ref. 137, illustrates the ability of his model to explain the excess-power results of one of their own experiments.
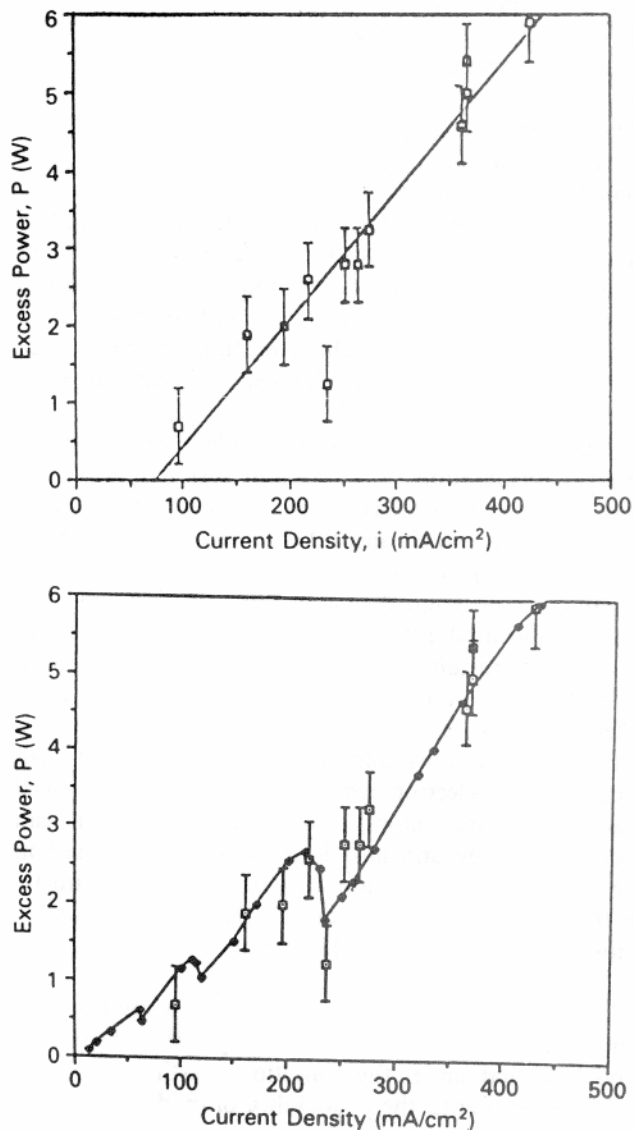
Figure 18. Example of fit of Bush's model to experimental calorimetric data. Upper figure shows straight-line fit ignoring low-lying point as a bad data point. Solid curve in lower figure shows TRM prediction. (From Bush[137])

Preparata[141] has recently carried out a critical analysis of some of the more important theoretical papers and arrives at the conclusion that in the ultimate analysis one must invoke collective processes wherein the elementary components of condensed matter, namely nuclei and electrons, act in a coherent fashion. Bressani *et al.*[167] have shown how the barrier-penetration problem can be tackled by considering the important role played by the coherent interactions with the quantized electromagnetic field. They have applied the 'quantum field theory of superradiance', formulated by Preparata[168], to the cold-fusion problems.

Schwinger[169] has pointed out that the conventional two-factor approach applicable under hot-fusion conditions, namely of separating overall nuclear reaction rate as a barrier-penetration probability followed by an intrinsic nuclear reaction probability, may not be relevant and meaningful for understanding very-low-energy nuclear reactions in the solid state. He has argued

that it is not proper to totally isolate the effect of the electric forces from that of nuclear forces and has advocated dispensing with the 'collision-dominated mentality of hot-fusioneers' to understand cold-fusion phenomena. He has formulated a 'coherent screening mechanism' provided by the vibrations of the lattice deuterons and successfully derived Fleischmann-Pons excess power levels.

Hagelstein[138] of MIT has independently developed a detailed formulation of a coherent fusion theory. His novel approach is based on a two-step reaction mechanism in which incoherent electron capture by deuterons first generates 'virtual neutrons' accompanied by coherent neutrino emission; these 'virtual neutrons' are then captured either by deuterons or Pd or even Li to generate tritium or heat. He refers to the latter step as 'virtual fusion reaction'. The basic premise of his extensive work is that off-resonant coupling between two fusing nucleons and a macroscopic system can occur through electromagnetic interactions. His detailed theoretical work shows how neutrino emission can occur coherently and also how the energy released in the 'virtual fusion reaction' can be transferred directly to the lattice modes as phonons. (Hagelstein is widely known for his very original contributions to the theory of X-ray lasers.)

One of the intriguing conclusions to emerge from the computational results of several independent theoretical models is that under the conditions pertinent to cold fusion experiments, the probability of (p-d) reactions is surprisingly higher than that of (d-d) reactions[138,161]. In other words, it is theorized that the small H_2O component of D_2O is playing an important role in cold fusion phenomenology and hence, it has been suggested, that a systematic study of various effects as a function of the magnitude of the H_2O fraction in D_2O should be carried out.

In summary it may be stated that it is becoming increasingly apparent why and how the physics of nuclear 'fusion' reactions in cold condensed matter can be very different from that under hot plasma conditions. In fact already the new phrase 'solid state nuclear physics' as distinct from 'vacuum nuclear physics' is beginning to be applied when discussing coldfusion phenomena.

23. Concluding remarks

I have summarized all the experimental results obtained so far in the area of cold fusion. A majority of scientists, particularly physicists, hold the view that the phenomenon popularly referred to as cold fusion is a 'myth' and an 'illusion'; one physicist[172] has even consigned cold fusion to the realms of Langmuir's 'pathological science'! However, I have found that many physicists who are staunch 'non-believers' are simply not aware of the many excellent experimental results that have been accumulated during the past one year. When confronted with the mounting experimental evidence most skeptics were willing to concede that maybe 'something interesting was going on after all' in deuterated solids. The purpose of this review is mainly to draw the attention of the Indian scientific community to the recent developments in cold fusion.

While physicists find it easy to accept that (d-d) reactions at the 'Jones level' (10^{-20} to 10^{-23} per sec per d-pair) can possibly occur in deuterated solids, there still seems to be considerable reluctance on their part to accept the idea that the 'excess heat' generation in electrolytic cells could indeed be of nuclear origin. So far the main justification for the nuclear origin of 'excess heat' had been the argument that the magnitudes of both excess power (W cm^{-3}) and excess energy (MJ mol^{-1}) involved are such that they are orders of magnitude more than what can be

explained on the basis of known chemical phenomena (reaction enthalpies, phase-change effects, stored-energy release, etc.). However, the recent observation of significant quantities of ^{4}He in the off-gas stream of electrolytic cells generating 'excess power', besides a marginal excess of ^{4}He in one electrolysed Pd button, should perhaps begin to convince the scientific community that proof of excess heat being of nuclear origin is now on hand. However, this information is not yet widely known.

In my judgement, the infant field of 'cold fusion' is rapidly acquiring the status of a respectable new branch of science, and the mysteries behind what a growing number of 'converts' firmly believe is one of the most fascinating scientific breakthroughs of our times are slowly being unravelled[173,174]. Indeed, the humble 'battery and bottle' experiment may well have unexpectedly opened the door to uncharted new realms of physics and nuclear technology.

APPENDIX
Steps in a typical cold-fusion experiment

1. Choice of host metal/alloy. (Pd, Ti, Zr, Mg, V, Nb-Ti, any hydrogen storing alloy; even a high-temperature superconductor (HTSC)!)

2. Preparation of samples. (Degassing, surface cleaning, annealing)

3. Loading of deuterium. (Electrolysis, gas, plasma, ion implantation, etc.)

4. Measurement of degree of loading (or deuterium-to-metal atom ratio). (Weighing, volume increase, resistivity, X-ray diffraction, etc.)

5. Stimulation/triggering of fusion reactions (to create non-equilibrium conditions). (Current pulsing, thermal cycling, electrical discharge, application of intense magnetic field, pressure changes, shock wave, projectile impact, etc.)

6. On-line diagnostics. (Heat, neutrons, charged particles, X-rays or gamma rays, acoustic or radio emissions)

7. Off-line (or post-experiment) analysis. (^{4}He, tritium activity, activation products)

8. Theoretical interpretation/modelling/analysis.

Note added in proof:

I have just received a short communication on a national-level conference entitled 'Workshop on Nuclear Fusion Reactions in Condensed Media' held at the Joint Institute for Nuclear Research (JINR), Dubna, USSR, during 22-26 March 1991. The concluding day of the workshop was held in Moscow. The meeting was restricted to a discussion of nuclear effects only, i.e. calorimetry and excess heat phenomena were not covered. Of the 60 papers presented, 45 reported

experimental results. These experiments encompassed the whole gamut of techniques described earlier and summarized briefly in the Appendix. At least four groups have claimed a very high level of reproducibility for neutron production both in electrolysis experiments and in gas-loading/plasma-discharge experiments. Three groups have reported finding neutron-to-tritium yield ratios in the 10^{-5} to 10^{-8} range. On the whole the new Soviet results support most of the findings of other groups in the world.

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Abbreviations used for conference proceedings

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