TECHNICAL STATUS OF COLD FUSION RESULTS

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ABSTRACT

Experimental results in cold fusion research up to the end of the 1989 are reviewed to gain a perspective on the credibility of the phenomena. The review does not attempt to be comprehensive but concentrates on the highest quality experiments claiming to give positive results. The results are used to formulate a strategy for continuing to support cold fusion research in 1990.

INTRODUCTION

During the past 12 months, many improvements have been made in experiments done to attempt to verify the Fleischmann-Pons phenomena. These changes have, in part, been a response to valid criticisms of the early work, and in part due to a natural process of refinement that has come with having more time and resources. Considerable attention has been paid to 1) reducing the probability of contamination in experiments finding tritium, 2) reducing backgrounds and increasing efficiency in neutron counting, 3) improving calibration methods and reducing sensitivity to spatial variations of temperature in calorimetry, and 4) using closed cells. Many different laboratories including some national laboratories and organizations in foreign countries have reported positive findings.

Despite these advances we have not yet succeeded in producing a recipe that can be handed to independent research groups that will lead to reproducible results.

Furthermore, we see the positive results against a background of statistically over-whelming negative evidence from other research groups too numerous to mention. In many cases, these groups are just as credible and experienced as those producing positive results. Because of this, most of us are still undecided as to the truth of the cold fusion claims, and there is no question that scientific demonstration of the phenomena has simply not been achieved.

How should we view this situation? It is not hard to find reasons why many experiments may have failed. One issue is the way in which adequate loading of the metal lattice with deuterium can be hindered, particularly since concentrations of electrolyte contaminants of order ppb or less can obscure the cathode surface after a period of electrolysis. Further reasons can be found, perhaps, in too long integrating times for neutron counting(~hr) when the adventitious neutron signal may endure for no longer than a few minutes. Whatever the reasons, they amount at best to plausible rationalizations. On the other hand, just as plausible rationalizations may be stated, a priori, for the neutrons to be background-related artifacts, or for the tritium to be the result of occasional spot contamination of the materials, perhaps more deeply trapped than expected. To get beyond such trite rationalizations requires a close look at a large fraction of the data. We should be willing to let the evidence accumulate and let the data speak for itself, without allowing beliefs or prejudices about the outcome to influence our judgement. Long before the final outcome is known, however, we have to make decisions about research funding and which experimental directions to emphasize.

This paper reports a technical review of the results available at the end of 1989 and focuses on the factors that lend support to their credibility and those which point to remaining problems. The review is not comprehensive. It leans heavily on results that have been published or that have been presented at specialist meetings. Most of them either preceded or are part of results discussed or reported in the proceedings of this meeting. I have scarcely referred to the original published data of Fleischmann and Pons [1] nor of Jones *et. al.* [2] because, as the progenitors of all that followed, they hardly need further comment. Including them would not change my conclusions.

TRITIUM

At Texas A&M University Bockris and Wolf have reported [3] that 11 electrolytic cells using a single source of palladium for cathodes and nickel anodes produced tritium in amounts from 7×10^3 to 5×10^7 dpm/ml (10^6 times background). In a controlled batch of 6 cells having external recombiners and 6 accompanying H_2O cells, one D_2O cell has given ~10^6 dpm/ml. The first Bockris cell reported to give a significant amount of excess heat has been the first cell to produce tritium twice while in a calorimeter [4]. Detailed assay

procedures and results are described in references 1 and 2. More than 25 other cells have not produced any tritium, including those operated by Appleby.

At Los Alamos National Laboratory, Storms and Talcott [5] have reported that seven of nine new closed cells have produced tritium in amounts up to six times the background concentration in the electrolyte. At least two earlier open cells (of 16) produced tritium, one of which had 80 times the background. A further batch of 16 closed cells gave no tritium. No H_2O control cells have been run.

Several groups at the Bhabha Atomic Energy Research Center (BARC) have reported [6] that at least nine electrolytic experiments were conducted yielding more than sixty samples where tritium was not produced. However, in experiments described in papers A1, A2, A3, A6, and A8 of reference 4, quantities of tritium were produced exceeding 10^{12} atoms. Some of the experiments used reflux condensers and cold traps to remove D2O carryover, a recombination catalyst to remove stoichiometric D2 and O2, a copper oxide catalyst to remove desorbed D_2, further cold traps and a bubbler. These experiments desorbed all D2 at the end of the experiments by heating the cathodes in a similar apparatus. All fractions were counted and added to give a tritium assay to better than 10%. Table 1 summarizes the results.

Two pressure loading experiments (papers B3 and B4 of ref. 4) have given tritium after D_2 gas was absorbed into Ti and Pd-Ag alloy discs, wafers and cones and Pd-black powder. Tritium presence in amounts $>10^{10}$ to 10^{11} atoms was confirmed by a combination of surface activity measurement using 1) direct contact with scintillation cocktail, 2) autoradiography, 3) X-ray spectrum analysis, and 4) desorption in H_2O followed by scintillation counting. The count rates correspond roughly to an enhancement of the t:d ratio by factors of 10^2 to 10^4. The overall hit rate in gas absorption experiments was low. No blanks had been run using H2 gas. Several blanks had been run without gas absorption or after annealing the samples. No tritium activity was observed in these controls.

Several other laboratories have reported tritium generation in the electrolyte at only three to six times the initial concentration, often but not exclusively in open cells. Electrolytic isotopic concentration in open cell electrolyte using palladium can account for about a factor of two at room temperature although this factor depends on the metal at the surface of the cathode and on the temperature. Impurities on the cathode surface may, therefore, affect the isotopic concentration. Such results may be significant but assay technique details, surface conditions, and systematic and random errors are not generally available. It is, therefore, even more difficult to assess the significance of these particular results.

Also at Los Alamos, Claytor [7] claims almost reproducible tritium production from a non-electrolytic device involving the passage of a pulsed electric current through a stack of thin discs made alternately of Si and Pd. The stack had previously absorbed D2 gas to equilibrium at 110 psi to a D/Pd ratio of 0.7. In a 90-hour run, 10^{12} to 10^{15} tritium atoms were produced. Annealing the sample before the experiments at

TABLE 1. BARC TRITIUM RESULTS

No.	Cathode	Anode	Tritium Concentration/ Background	Atoms of Tritium	Duration of Tritium Generation (Days)	Controls
A1	Pd/Ag Alloy	Ni	20,000 4,000	8.10^{15} 5.10^{14}	3 2	No No
A2	Pd/Ag Alloy	Ni	3,455	4.10^{15}	<1	No
A3	Ti	Stainless Steel	1,000	$1.4.10^{14}$	<1	One
A6	Pd	Pt	12,500 >5	2.10^{15} $\geq 10^{12}$	2 7	No No
A7	Pd	Pt	3	2.10^{11}	17	Several
A8	Pd	Pt	1.5	7.10^{11}	49	Three

high temperature should have eliminated the most obvious potential source of tritium contamination.

The tritium facility at Los Alamos National Laboratory contains some of the country's foremost experts on tritium handling and assay. The Isotope Production Group, Health Physics Division and Heavy Water Division personnel at BARC have been dealing with tritium for over 20 years. Their approach displays considerable expertise in tritium handling and assay. They have performed the most comprehensive total tritium assays in the field so far, without appearing to be on a learning curve.

The laboratories at Texas A&M University, BARC and LANL each adopt several independent instruments and give extensive attention to calibration, background, chemiluminescence, quenching and spectrum analysis. Independent assays (by five different laboratories in the case of Texas A&M) confirm that tritium is present in the samples.

The extraordinary spectre of intentional contamination should be essentially ruled out by the facts that 1) the results occur in different organizations, 2) security measures are in effect at all three laboratories, 3) at least one of the Texas cells was inaccessible beneath shielding and detectors, 4) in at least one instance, tritium was increasing in samples taken over 3 days, and 5) Storm's data show evidence of many small tritium bursts in some cells.

The chance of accidental contamination should be reviewed in light of the following facts: 1) most of the experiments were sealed; 2) pre-annealing was done on many metal samples; 3) post-test analysis of blank (unelectrolyzed or unused) cathode samples yielded no tritium; 4) Texas A&M assay of glassware, plastic tubes, rubber bungs and syringes yielded no tritium; 5) LANL assay of Bockris' Ni anodes yielded no tritium; 6) careful pre- and post-assay of D_2O and D_2 gas used at all stages verified background levels of tritium; 7) strongly differing partition of tritium between electrolyte, off-gas and cathode can be explained for several different experimental set-ups; 8) BARC, at least, regularly monitors tritium activity in the laboratory atmosphere in the Heavy Water Division; 9) amounts of tritium in the neighborhood of 10^{14}-10^{16}atoms exceeds conceivable contamina-tion sources (e.g., even a standard laboratory solution of 1 m Ci/ml contains only 2×10^{13} tritiums/ml, whereas most of the Texas cells had only 15 ml volume); 10) the laboratory at Texas A&M Cyclotron Institute had never been used for tritium production or assay; 11) the overwhelming majority of cells only gave tritium once, inconsistent with random in-process contamination; 12) adjacently placed cells were not contaminated by those producing tritium; 13) H_2O control cells gave no tritium; 14) no tritium was produced often during many weeks of charging during which it would have been flushed out of either electrode, if present initially; and 15) previously contaminated Pd would lose tritium by diffusion to air at room temperature in <100 hours for the dimensions used.

CONCLUSION ON TRITIUM

Although better controls are needed and reproducibility is clearly lacking, the evidence is becoming stronger that tritium is generated in the experiments. This evidence is from three credible and experienced organizations with multiple independent checks in many different kinds of experiment. We shall see that the evidence on tritium generation is the strongest of the three types of evidence for cold nuclear reactions, i.e. tritium, neutrons, and heat. It seems no longer reasonable to assume these results are necessarily wrong solely because of theoretical improbability based on current understanding. My view is that the results deserve to be taken seriously even though they are a long way from providing proof of the phenomena.

NEUTRONS

The earliest confirmation of neutrons from electrolytic cells was reported by Bertin *et al.* [8] in a low background tunnel under the Gran Sasso Massif. Two NE213 scintillation counters recorded similar count rates when exposed alternately to a group of three cells. In each case, the alternate counter measured the background simultaneously eitht meters away. The energy specrtum and a Monte Carlo simulation indicated the neutrons had 2.5 MeV energy. The source rate was 14.5 neutrons per minute (~58 n/min/cm^3). This background corrected rate was almost 5 σ.

In 200 early experiments on 25 electrolytic cells at Texas A&M University, statistically significant neutron emission from three separate experiments using the same piece of palladium was obtained by Wolf *at. al*[9]. In more recent experiments, five different electrodes (6 mm ϕ x 2 cm) have given neutrons for ~10 hours. Count rates were three to five times background corresponding to source strengths of 50 n/min (~500 n/min per cm^3).

A fast plastic scintillation counter in an electronically shielded low background configuration gave 0.8 c/min overall background, and 0.5 background c/min in the energy range 1 to 2.5 MeV. The counting system obtained the neutron energy spectrum with energy discrimination against cosmic background. Two different pulse shape discrimination systems were used against gamma background. Large geometric efficiency, common-mode electronic noise rejection, broad range frequency noise scans, thermal isolation of the detector, and detector temperature monitoring give additional confidence against artifacts. The detector neutron efficiency was determined with three techniques including ^{252}Cf time-of-flight measurement specific for 2 MeV neutrons, and the cyclotron was always off during measurements. Two independent theoretical calculations of response of the detector to 2.45 MeV neutrons are consistent with the measured spectrum shape. Additionally, one $1/r^2$ test confirmed neutrons from a source at the cell.

In addition, the neutron spectrum is quite different from that observed from a fission source, from (α,n) reactions of light elements and neutrons from cosmic ray shower-induced reactions in surrounding materials. The same spectrum and signal was measured with a second detector of the same type. The 200 experiments contained several H_2O blanks and

TABLE 2. SUMMARY OF BARC NEUTRON RESULTS

EXPERIMENT NO.	A1	A2	A3	A7	A8
CATHODE	PdAg	PdAg	Ti	Pd	Pd
NEUTRON DETECTORS	BF_3, ^3He, Plastic	BF_3,Plastic	^3He, Plastic	^3He	BF_3
SEPARATE B/G DETECTOR	^3He, Second run	No	Plastic	No	BF_3
BACKBROUND COUNT RATE (per second)	0.2(BF_3), 2 (plastic)	1.3 (BF_3), 1.7 (plastic)	24 (^3HE)	1.6	20
NEUTRON COUNT) (TIMES B/G)	2-200(BF_3), 2-40 (plastic)	150 (BF_3), 120 (plastic)	2	1,000	56
DURATION OF NEUTRONS (minutes)	5 to 150	4	150	2,400	8
DELAY BEFORE NEUTRONS	2 days; 1 hour	4 hours	3 hours	14 days	a fewhours
NEUTRON YIELD (source)	4×10^7	4×10^6	3×10^7	2×10^8	1.4×10^6
TRITIUM YIELD (atoms)	8×10^{15}	4×10^{15}	10^{14}	$>2 \times 10^{11}$	7×10^{11}
NEUTRON/TRITIUM RATIO	10^{-8}	$>10^{-9}$	2×10^{-7}	$<10^{-3}$	1.7×10^{-6}
NEUTRONN 10^4 n/min/cm^3	6	20	0.3	10	1.4
SOURCE 10^6 n/cm^3	6	0.8	0.5	300	1.4
10^5 n/cm^2	1.3	0.1	3	100	2

dummy cells. None produced neutrons.

Iyengar [6] reports at least five different kinds of experiments done by different combinations of Neutron Physics Division, Heavy Water Division, Water Chemistry Division, Desalination Division, Isotope Production Division, Analytical Chemistry Division and Reactor Operations and Maintenance Division at the Bhabha Research Center (i.e. groups of varied expertise were brought together). Table 2 gives a summary of the neutron results.

In general, the experiments were not significantly shielded and little electronic processing was done on the detector signals. A combination of ^3He, BF_3 and plastic scintillation detectors was used. BARC neutron counting details equivalent to the Texas information are not at hand to enable confidence to be stated in count rates only 2 to 5 times the background; for example, the extent of efforts to eliminate and monitor noise sources or variation of count rate with mass close to the detector. Conclusions included here are, therefore, only from higher signal-to-noise ratios. However, the Neutron Physics group apparently conducted extensive searches for noise sources and demonstrated counter stability and background rates over a period of about five weeks prior to some of the experiments [10].

In three of the experiments a separate, sometimes diverse, counter monitored background about 2 meters from the cell. At least four experiments (A1, A2, A7, A8) gave count rates from 30 to 1,000 times the background, although the background rate was relatively high at 2 to 20 per second. In experiments A1 (BF_3, NE102A), A2 (BF_3, NE102A) and A3 (BF_3, NE102A) neutrons were recorded simultaneously in the two detector types, at high rates in A1 and A3. Control experiments with H_2O or stainless steel cathodes did not give neutrons. Neutron emission is also reported from TiDx gas absorption experiments.

Menlove and Jones report [11] several hundred neutrons occurring in bursts less than 120 μsec in duration from palladium electrolytic cells, as well as from TiDx in gas absorption experiments. These neutrons have no time correlation with accompanying acoustic emissions. But the bursts are repeatable in a statistical sense.

The reported random (multiplicity one) neutron emission of Jones [2] corresponds to a source strength of 24 n/min (~240 n/min/cm^3), about the same as Wolf (500 n/min/cm^3), and two to three orders of magnitude less than those found at BARC. Jones' H_2O control experiments did not give neutrons.

CONCLUSIONS ON NEUTRONS

Although the quality of experiments claiming to measure neutrons is high at least at BYU, Texas A&M, LANL, and BARC, the low counting rates at Texas A&M and BYU do not support high confidence in these results. The burst nature of neutrons at LANL at rates well above background are a clearer signal but conceivably could be due to micro-hot fusion. The results at LANL and at Texas A&M have so far been observed only using a single detector at a time. On both these bases the BARC results appear, perhaps, to be the most definitive. We will benefit greatly from having more specific input on the quality of these results at this meeting. Until then, the neutron evidence must be seen as less compelling than that from tritium.

NEUTRONS, TRITIUM AND HEAT COMPARED

Neutrons are not always, or even usually, observed concurrent with tritium. In electrolytic experiments where neutrons and tritium were observed simultaneously or close in time correlation, Table 3 shows total neutrons, tritium and their ratios. This measured ratio is very different from the expected value of approximately unity for d-d fusion proceeding through ^{4}He compound nucleus levels.

TABLE 3. NEUTRON TO TRITIUM YIELD RATIO

	NEUTRONS	TRITIUJM ATOMS	RATIO (n:t)
Wolf, Texas A&M BARC, Bombay	7×10^4	$>10^{13}$	$<5 \times 10^{-8}$
A1	4×10^7	8×10^{15}	5×10^{-9}
A2	4×10^6	4×10^{15}	10^{-9}
Claytor, LANL	10^3	10^{12}	10^{-9}
Claytor, LANL	10^6	10^{15}	10^{-9}

Although excess heat levels are not discussed until later, I will assume an excess power of 1 watt for comparison. 2×10^{12}/sec d-d fusions leading to the n, ^{3}He branch are needed to supply 1 watt. The Jones and Wolf neutron rates are ~ 10^{-12} of this. Table 3 shows total numbers of tritium atoms supposed to have been produced, concurrent with neutrons, over periods of roughly 10^5 second (1 day). They correspond to 10^9 -10^{11} tritium atoms per second. The maximum amount reported from the Bockris laboratory is 10^{16} tritiums. It is not known if excess heat accompanied this tritium production.

One watt from the p,t branch of the d-d reaction requires 1.6×10^{12} events/second. The tritium observed accounts for less than 1% of this. In a recent experiment [4] Bockris claims excess heat roughly concurrent with tritium (the first cell to give two episodes of each concurrently). The amount of tritium accounts for only about 0.1% of the excess heat.

If tritium is the nuclear product associated with excess heat we must explain why heat has many times been observed without tritium. Even in the Bockris cell giving heat and tritium there was an extended period of excess heat before any tritium appeared.

OTHER NUCLEAR MEASUREMENTS

Protons must accompany tritium from d-d fusion whatever the mechanism or the n:t branching ratio is. Taniguchi [12] claims to have observed protons in 6 out of 23 experiments using a 10 μm palladium foil cathode as one side of an electrolytic cell. The count rate was of the same order of magnitude as the Jones and Wolf neutron rates (~10 to 100/hour but from a much smaller volume). The surface area was about the same.

The protons had energies extending down from 2 MeV. The 3 Mev protons from d-d fusion would lose about 1 MeV in traversing the palladium foil. Very few protons had 2 MeV energy. The spectrum implies that the protons were produced close to the inside surface or, if distributed through the bulk, have lower energy than energy conservation demands. Even if all protons were initiated on the surface at 3 MeV, the authors state the spectrum shape is inconsistent with integration over the angular acceptance of the detector. The (ambiguously stated) implication is that no matter where the protons were produced, energy is only conserved if d-d fusion is not responsible or if it leads to three or more bodies in the final state. This is to be compared to Wolf's observation that lack of 14.1 MeV secondary neutrons implies the tritium has lower energy than expected from d-d fusion.

Taniguchi did not have positive particle identification, so it is possible he is not seeing protons at all.

Rasmussen (UC Berkeley) [13] observed no protons in a similar experiment, but he used cathode foils 76 μm thick, beyond the range of 3 MeV protons in palladium. Rasmussen also maintained low current densities throughout the experiments, but so did Taniguchi *et al* . (only about 5 mA/cm^2). Ziegler [14] did not observe any protons in a similar experiment. However, Cecil has pointed out that Ziegler's foils (25 μm Pd) were thick. Only if the protons had >3 MeV energy or some were produced close to the outside surface would they have been observed.

The story on protons is extremely important because of the low sensitivity of small volume silicon surface barrier detectors to neutrons and gammas. Extremely low count rates in the MeV region can be measured with good energy resolution and close to 100% efficiency. Positive findings in such experiments could greatly improve confidence in the nuclear products.

Wolf, Lewis [15] and others have searched unsuccessfully for palladium coulomb excitation gammas. High resolution detectors were used. The inference from the work to date seems to be that there are no energetic gammas accompanying neutron or tritium emission, strongly implying that the protons have lower energy than expected or do not exist at all. Gammas from possible (n,γ) reactions are also not observed. This is important with respect to data from the Naval Research Laboratory concerning palladium isotope ratios (below). No 23.84 MeV gammas are seen (from the d-d threshold to ^{4}He ground state) nor gammas from other transitions in ^{4}He.

21 KeV Pd K-Xrays would probably not have been observable with confidence in any electrolytic experiments done to date. However, it should be possible to observe them with an appropriate cell design if they are present. Given the adventitious occurrence of neutrons, tritium and excess heat, it is essential that cells active in all of these three ways be moni-

TABLE 4. SUMMARY OF ROUND ROBIN ^{4}HE ANALYSIS

Laboratory	As Received (x 10^{13} atoms)	Electrolyzed (x 10^{13} Atoms)	Factor Increase
#1	2.0	6.3	3.15
#2	1.25	7.0	5.60
#3	0.31	2.4	7.74
#4	0.37 0.35	1.6	4.32 4.57
#5	0.84	4.6 8.3	5.48 9.88

tored over long periods for X-ray emission.

O'Grady and Rollison [16] reported substantial changes in palladium isotopic abundance after electrolysis in D_2O/Li_2SO_4 and D_2O/LiOD. The changes were confined to the outer surface layer of the cathode. They did not appear when using an H_2O based electrolyte or when using non-electrolyzed palladium. The isotope ratios reverted to the natural abundances at depth. The inference is that a total of several percent of the palladium atoms in the outer 1 μm were transmuted in some nuclear reaction. For the active agent to be completely absorbed in this small thickness would need an interaction cross-section of order 10^5 barns. The result is so far unconfirmed.

ETEC/Rockwell has analyzed cathode samples from Texas A&M University that had apparently produced some excess power and has found no helium 3 or helium 4 above a detection threshold which is $5x10^9$ atoms. If produced at the surface, helium would all escape with evolved gases. EPRI, through ETEC/Rockwell, participated in a double-blind Round Robin assay by five laboratories of samples as received and as electrolyzed by Pons. The Round Robin results are shown in Table 4. There is a wide scatter on results from different laboratories (and within each laboratory depending on the spot selected for analysis) but all found an increase by a factor of 3 to 10 between the as received and the electrolyzed samples. The most accurate result has probably been obtained subsequently by ETEC as an average of 13 measurements. Although small in absolute terms, the number of helium atoms "produced" (~2.7 x 10^{13} - ETEC) in the test sample is about right to account for the heat claimed (only 3-4 mW for 10^5 sec). The background ^{4}He in the as-received material from Johnson Mathey was curiously high (by a factor of ~10^4) indicating some exposure to ^{4}He in the manufacturing process. This anomalous ^{4}He in the as-received material makes it impossible to interpret the results of the Round Robin experiment.

In a one gram sample of metal, it is not possible to detect less than about 10^{11} helium atoms. For comparison, atmospheric helium at a concentration of 5 ppm in air represents 10^{16} atoms in a minimum sample of ~125 cm^3 of air at STP. This means that samples of gas must be free of air (to <10 ppm) to take advantage of the detection limit. When vastly diluted with deuterium helium detection becomes even more difficult. Even if all the helium that might be produced at the electrode surface were collected in ~100 ml of gas, to exceed that due to atmospheric contamination would require 40 KJ of excess heat. A good signal to noise ratio and the added difficulty of detection against the deuterium background would probably require one to two orders of magnitude more than this --0.4 MJ to 4 MJ. This is at the limit of what has been oberved but such assays for helium in the off-gas have not yet been done.

Rao (BARC) reports an assay for He which failed to find any above their detection limit of 10 ppm.

IMPLICATIONS OF NUCLEAR RESULTS

The mysteries are: 1) charged particle nuclear reactions seem to occur at high rates at thermal energy, 2) d-d fusion branching ratio is wrong by 10^8, 3) energy conservation in d-d reaction is violated unless the final t+p state has a third body, 4) tritium or ^{4}He do not appear to account for the heat by many orders of magnitude, 5) nuclear products do not correlate with each other, 6) excess heat is seen unaccompanied by neutrons or tritium 7) no radiative deexcitations are seen, 8) effects are stochastic and not reproducible.

No known reactions can explain these results. The reaction is certainly not normal d-d fusion and whether nuclear or

chemical in origin might involve many different reactions.

EXCESS HEAT

Appleby and Srinivasan at Texas A&M University [17] have used a sensitive heat flow commercial calorimeter not dependent on temperature distribution. The particular instrument appears to be working properly; for example, it gives the same calibration with the same resistive heat input whether an electrolytic cell is in position or not. They claim excess power up to 50 mW in 0.5 mm ϕ palladium cathodes ~ 0.01 cm^3 in volume in at least 10 cells with 90% reproducibility (up to ~15 W/cm^3 when extrapolated). The cells are open but the results could therefore be conservative, i.e. heat losses through the top are ignored.

Excess power could be result of ~20% O_2/D_2 recombination in the cell. So far, a clear demonstration of the absence of recombination is lacking, although in many experiments in this laboratory and in others it has been shown there is less than a few percent (<5%) recombination for cases not producing excess heat. Calibrations have been done using a resistance heater. The cells are not run isothermally. A smaller number of H_2O and Pt/D_2O control cells have not produced excess power.

Bockris [4] at Texas A&M University has obtained recent results using a calorimeter cell, closed to tritium but having a recombiner external to the calorimeter. Sensitivity to temperature distribution is greatly diminished by vigorous stirring inside the cell.

One cell of five produced two episodes of tritium generation while generating ~15% excess power (ΔT~5°C). Tritium generation episodes corresponded roughly in time, although not quantitatively with increases in excess power (9 W/cm^3 when extrapolated). Total integrated energy exceeded 1.5 MJ. In this case an upper limit on recombination of O_2/D_2 in the cell was placed by one measurement of the recombinant liquid volume in comparison with the coulombic expectation. The limit set was less than 2% recombination. This is not enough to account for the excess heat. Bockris is calibrating using both a resistance heater and electrolytic power scans but is not running isothermally. Data on statistical errors are not at hand.

Oriani at the University of Minnesota [18] has used an open cell in a heat flow calorimeter not sensitive to temperature distributions. An H_2O control gave no excess power. Two D_2O cells gave up to 2 watts excess in ~ 1/50 cm^3 cathode, i.e. up to ~100 W/cm^3 extrapolated. Total integrated energy was 0.075 MJ.

Hutchinson at Oak Ridge National Laboratory originally reported excess power in one open cell of two after 100 days of charging. Hutchinson now reports [19] four cells (of four) have generated up to 9 watts excess power (equivalent to 3 $watts/cm^3$). Total integrated energy is greater than 3MJ. The four cells are closed in a flow type calorimeter with external recombiners. The recombinant volume accurately equals coulomb expectation during excess power generation. So gas recombination is apparently ruled out. The excess power is up to 18% of the input but scales linearly with current giving maximum temperature excesses of 25° C.

More recent results from Scott at Oak Ridge are reported at this meeting.

Huggins at Stanford University [20] has developed a new style calorimeter, insensitive to the temperature distribution, with a cell having internal and external recombiners. The calorimeter's main feature is rapid lateral heat dissipation along aluminum walls combined with a very large thermal impedance in the radial direction. Shakedown tests and 3-D heat transfer modeling confirm the insensitivity to internal temperature distribution. Recombination has been ruled out by measurement.

Huggins has measured 1.4 W (7 $Watts/cm^3$) excess power for 12 days. Total integrated energy was 1.4 MJ. Three of these cells (of five) have given excess power, using Englehardt palladium, after a long period of inactivity. Huggins also reports total excess energy net of the electrical charging energy. More recent results are reported at this meeting.

McKubre at SRI [21] has run a new closed cell in a sensitive flow calorimeter at 850 psi to avoid gas evolution. The cell is extensively instrumented. The calorimeter is run isothermally, backing off a resistance heater to compensate for anomalous heat generation. It is also calibrated using electrolytic power scans. Preliminary indications are that excess power of order 2W (20% of input) was observed for 14 days with subsequent increases to 50% of input. Total integrated energy is about 2.4 MJ. Further results are reported at this meeting.

Wadsworth at the University of Utah [22] has reported that up to 56 W excess power (~60W/cm^3) were generated in 5 open cells on several occasions in a calorimeter somewhat susceptible to non-uniformities of temperature distribution. Only one temperature measuring device was in each cell which was not stirred except by evolved gases. Laser doppler measurements show considerable fluid motion but it is known from subsequent similar cells, with three thermocouples present, that 2° C temperature differences exist in the cells.

Heater calibrations performed on the later cells show all three thermocouples exhibiting the (heater calibration) transients together. However, because of the temperature uncertainties the original large heat bursts can probably not be shown to be real with high confidence.

CONCLUSIONS ON EXCESS HEAT

The excess energies reported are frequently in excess of 1MJ for cathodes of a fraction of a cubic centimeter volume. At the generous investment of 5eV per chemical bond only 0.05 MJ/cm^3 of excess heat can be produced by chemical binding or by solid state phase changes even if every atom of palladium or deuterium in the cathodes were involved.

The best calorimetry method is using a device not sensitive to temperature distributions [flow type (McKubre, Hutchinson) or thermo junction type (Appleby, Oriani), or lateral heat dissipation type (Huggins).]

The cells should be entirely closed within the calorimeter (McKubre) or should at least have external recombiners with checks of recombinent volume against coulomb calculation

(Bockris, Huggins, and Hutchinson) during the period of excess heat. Calibrations should be both electrolytic with ascending and descending power (Bockris, Huggins, McKubre, Hutchinson, Oriani) as well as isothermal checks by backing off a resistance heater (McKubre). The results of McKubre indicate.that the more recent closed cell experiments do appear to have produced excess power, even when mass transfer and electrolyte changes are eliminated.

Few of the above experiments used all these optimal techniques although all the techniques have now been used. The calorimetry work is now of high quality with attention paid to uncertainties. Although the results are still not reproducible, they appear to be quite repeatable. It seems no longer reasonable to assume that these results must necessarily be wrong solely because of lack of a nuclear explanation and lack of reproducibility.

However, problems of electrolyte concentration changes, variations in stirring, effects of bubbles, sporadic partial unloading of deuterium gas, O_2/D_2 recombination, and stability issues surrounding constant current or constant voltage operation, continue to cloud the interpretation of many experiments. Such issues will continue to cause the excess heat results to be called into question.

It is not likely that this picture will change significantly until reproducibility is achieved, ie until the many researchers totally unsuccessful in producing excess heat can be given a good hit-rate recipe, or at least until the large power bursts reported by Wadsworth appear in experiments incorporating the above desirable features. It also seems to be the case that these large power excursions reported by several groups last summer have not been repeated, despite continued reports of the lower levels of excess power.

RESEARCH STRATEGY

Reproducibility is the most important current objective. Reasons for its importance are: 1) lacking it wastes resources on fruitless experiments; 2) the time elapsed while "waiting and hoping" for positive results slows down the program; and 3) variability in magnitude of effects, when eventually obtained, prevents discrimination between experiments unless statistically significant numbers of experiments are run for each set of conditions. This increases the size of an experimental program .

Reproducibility may be difficult to achieve because of the large number of variables to be investigated and the possibility that entirely new domains of physics may have to be explored (new particles, states of matter). Without reproducibility, the global scientific community will not turn significant resources to cold fusion. Advances towards reproducibility will thus be severely slowed down.

Even if the effects turn out to be real EPRI cannot expect to solve the reproducibility problems with its own limited resources, unless a way can be found to strongly focus the effort. A "fishing" approach of running very large numbers of cells and continuing to monitor heat, tritium, helium and neutrons is likely to fail unless one of these nuclear products is found to be directly correlated with excess heat, which seems unlikely on present knowledge. Such a fishing approach is likely to fail on three counts: 1) it would not provide further assurance of verification of the Fleischmann/Pons effects beyond the level we currently have, i.e. simply more repeated findings, lacking reproducibility, will not provide 'proof' acceptable to science, 2) it would not uncover the nuclear reactions involved; without this knowledge, there is no rational basis for acceptance of sporadic heat effects, and 3) as described above, it is likely to provide too slow and costly a path to reproducibility.

Since nuclear diagnostics can be sensitive, non-invasive, and more specific than measuring heat (1 W ~ 10^{12} nuclear reactions per second), there should be an emphasis on finding a nuclear product that could be responsible for excess heat. The sensitive detectability of this product could offer an efficient route to reproducibility. Finding the product and success in identifying the reactions involved would automatically account for the levels of heat. Continued failure to find such a product must be viewed as strong evidence against cold fusion. Success in identifying the nuclear products and nuclear reactions will also provide the starting point for theoretical developments. Particularly important is work to discover the energy of the participating species and the energy spectrum of the products for what they can tell of the location of the reactions as well as their origin.

Notwithstanding the main focus on nuclear products other areas must be pursued in parallel. Chief among these is to properly benchmark cathode materials and cell preparations that already show promise of approaching reproducibility of excess power. Ways of triggering the cells into periods of activity should be studied, not only because of achieving faster results but because of what may be learned of the mechanisms involved. In general, it will be wise to look beyond electrochemical cells because several alternate experimental configurations, e.g. pressure loading of titanium, appear to offer faster routes to positive results with fewer problems of surface contamination. Although not covered in the foregoing review, many electrochemical cells have proved to be contaminated with foreign substances that have coated and concealed the entire surface of the cathode with chromium, zirconium, iron, ruthenium, rhodium, carbon, etc. It is essential that cathode surface activation and maintenance of active surfaces be readily achieved and understood before we get drawn into very large experimental matrices using electrochemical cells that may be run for long periods. In the meantime, pressure loading and ion implantation experiments can help alleviate these problems .

To summarize, at EPRI, we believe that we have a well focused, cost-effective program for 1990 that employs the following strategy:

1. Monitor for nuclear products from active cells, e.g. X-rays, protons, tritium, neutrons etc.

2. Benchmark excess power, making promising materials available to other groups.

3. Study triggering methods.

4. Favor short experiments in alternate configurations, e.g. pressure loading, ion implantation.

5. Study maintenance of active surfaces in electrolytic cells.

6. Using promising cathode materials and cell preparation procedures study alternate electrolytes.

7. At an appropriate point, investigate the parameter space of electrolytic cells.

Following this route should lead to progress toward a scientifically sound basis for either rejecting the Fleischmann-Pons phenomena or for establishing a rational explanation for them.

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