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Other papers by McKubre and Tanzella describe this research program. One listed on page 3-1 is available here:

McKubre, M.C.H., et al. *Isothermal Flow Calorimetric Investigations of the D/Pd System*. in *ICCF2, Second International Conference on Cold Fusion*. 1991. Como, Italy: Societa Italiana di Fisica, Bologna, Italy.

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A review of this report may be found here:

Rothwell, J., *Review of McKubre, M. C. H., et al., Development of Advanced Concepts for Nuclear Processes in Deuterated Metals, EPRI TR-104195*. *Infinite Energy*, 1996(11).

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# Development of Advanced Concepts for Nuclear Processes in Deuterated Metals

**TR-104195**  
**Research Project 3170-01**

Final Report, August 1994

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## Development of Advanced Concepts for Nuclear Processes in Deuterated Metals

The excess heat generated in electrochemical cells with palladium cathodes and heavy water electrolyte appears to be far too large to result from chemical or metallurgical transformation. The evidence implies that the heat source is a nuclear reaction of some as yet undetermined nature.

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### INTEREST CATEGORY

Advanced nuclear systems

### KEYWORDS

Electrochemical power generation  
Palladium  
Heavy water  
Deuterium  
Cold fusion  
Heat source independent

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**BACKGROUND** Since first announced in 1989 by Fleischmann, Pons, and Hawkins, "cold fusion" has been the subject of widespread interest and intense controversy. Palladium (Pd) cathodes electrochemically charged with deuterium (D) to unusually high D/Pd ratios exhibit episodes of heat in excess of measured electrical inputs. Although nuclear reaction products commensurate with the excess heat have not yet been observed, small but definite evidence of nuclear reactions have been detected at levels some 40 orders of magnitude greater than predicted by conventional nuclear theory.

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**OBJECTIVES** To measure, optimize, and control the excess heat produced in highly deuterated palladium cathodes; to measure any signatures of possible nuclear reactions associated with the production of excess heat.

**APPROACH** The project team designed electrochemical cells that allowed precision calorimetry to be conducted while measuring all input heat from electrochemical and calibration resistor currents. The team operated 25 separate cell/calorimeters for periods of several days to several weeks each. Separately, the team operated 80 open cells to test various procedures for obtaining high cathode D/Pd ratios, a key condition for obtaining excess heat.

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**RESULTS** Three conditions were found characteristic of all cells yielding episodes of excess heat: (1) a D/Pd ratio  $>0.9$ , (2) initial appearance times of 8 to 23 days, and (3) cathodic current densities above  $0.1 \text{ A/cm}^2$ . Excess powers ranging between a few percent to  $-350\%$  were observed, measured to an accuracy of  $-0.5\%$ . These excess powers integrated to a total of  $\sim 0.1$  to  $1.1 \text{ MJ}$  for a  $\sim 2.5 \text{ g}$  ( $1/40$  mole) palladium cathode. Thus, the excess heats ranged between 4 to 44 MJ/mole of palladium, which was well above the largest known heats of chemical transformation in this or any other metal. The largest heat of chemical transformation in palladium is to the bromide at  $0.9 \text{ MJ/mole}$ . If the integrated excess powers are diluted by the electrochemically generated heat during the long initiation periods, net positive heat balances of 2 to 4% are obtained.

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**EPRI PERSPECTIVE** This work confirms the claims of Fleischmann, Pons, and Hawkins of the production of excess heat in deuterium-loaded palladium cathodes at levels too large for chemical transformation. However, the phenomena were

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obtained in only about half the cells. From the conditions of loading, initiation time, and current density on the successful observations of excess heat, it is understood why the phenomena are so difficult to attain. The conditions in the successful cells were not entirely under experimental control because the closed cells slowly leach silica and other materials from the anode and its supports as well as from the cell walls. This leached material can deposit on the cathode surface and interfere with the loading process. Also, the palladium purity depended on whatever was available from the manufacturer. Subsequent research has shown a pronounced batch effect on successful loading from different shipments of palladium from the same as well as from different suppliers. It is suspected that metallurgical conditions as well as impurity content may be the source of this batch effect.

The primary objective of further work on this subject will be to demonstrate which nuclear reactions, if any, are generating the excess heat. The only way to do this is to observe in at least roughly quantitative fashion the nuclear reaction products or "ashes." At this time, it is thought that the most likely ashes will be helium of mass 4 observable in the vapor phase of closed cells. The reaction producing helium needs to be known in order to maximize this excess heat phenomena for practical uses in the nuclear power industry.

## **PROJECT**

RP3170-01

Project Managers: Thomas O. Passell; Joseph Santucci

Nuclear Power Group

Contractors: SRI International; Lockheed Missiles and Space Company, Inc.

For further information on EPRI research programs, call EPRI Technical Information Specialists (415) 855-2411.

## **ABSTRACT**

An experimental program sponsored by the Electric Power Research Institute (EPRI) was undertaken at SRI International to explore the central idea proposed by Fleischmann et al. that heat, and possibly nuclear products, could be created in palladium lattices under electrolytic conditions. Three types of experiments were performed to determine the factors that control the extent of deuterium (D) loading in the Pd lattice and to search for unusual calorimetric and nuclear effects.

The overall conclusions of the loading studies are that, by careful control of the electrode pretreatment, the electrolyte composition, and the current density, Pd can be loaded to an atomic ratio  $D/Pd = 1$  and this loading may be sustained for periods of weeks.

Accurate, closed cell, state-of-the-art, mass flow calorimeters were designed, constructed, and calibrated. Extended calorimetric studies have confirmed the presence of a heat source that may be observed when certain criteria are met.

Rigorous attempts have been made to anticipate, exclude and define quantitative upper limits on artifacts and systematic error sources that may give the appearance of excess power. None of the artifactual sources considered can account for the excess power and heat observed. It is therefore concluded, tentatively, that the source of excess energy is an unexpected, and as yet unexplained, property of the D/Pd system. Further, the excess energy observed exceeds that of known chemical processes by two or more orders of magnitude.

Limited nuclear detection capability was included within this first project phase. Low-level detection was not attempted. These observations nevertheless indicate that any nuclear reaction quantitatively associated with the observed power and energy excess can only yield low-energy or stable products. Tritium, neutrons, or gamma rays are not quantitatively correlated with the excess power production observed.

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# ***INTRODUCTION***

An experimental program sponsored by the Electric Power Research Institute (EPRI) was undertaken at SRI International to explore the central idea proposed by Fleischmann et al.<sup>1</sup> that heat, and possibly nuclear products, could be created in palladium lattices under electrolytic conditions. Three types of experiments were performed to determine the factors that control the extent of deuterium (D) loading in the Pd lattice and to search for unusual calorimetric and nuclear effects. We summarize here selected examples of power and energy output observed calorimetrically to be in excess of known sources of input power and energy.

Following the results reported by Fleischmann et al.<sup>1</sup> considerable effort has been expended to test the hypothesis that the electrochemical loading of deuterium into palladium leads to the production of more energy than is predicted to arise from known chemical or electrochemical phenomena. From all the calorimetric results reported to date, it is evident that the ultimate acceptance or rejection of the original hypothesis will not be determined by calorimetry alone but only in addition to the confirmed observation of other products of the energy-producing process, which will ultimately lead to the development of supportable new theories. However, because of the potential importance of the energy-related aspects of the phenomenon, calorimetric studies provide the most appropriate basis from which to undertake a comprehensive investigative program.

Some of the discrepancies in the results of the various calorimetric studies undertaken thus far may be traced to the different experimental approaches adopted; not all of these may be expected to be equally accurate or reliable. More important, perhaps, in accounting for the variety of reported calorimetric results, is the wide range of possible conditions that may be employed (or encountered) in a given experiment, some of which will be difficult to control or reproduce. This consideration, in particular, may hinder attempts to replicate the original experiments of Fleischmann et al. Nonetheless, the calorimetric results reported to



date make it evident that the experimental hypothesis referred to above cannot be supported *as stated*; additional criteria must be satisfied.

The central postulate guiding the experimental program was that anomalous effects previously unobserved or currently unexplained in the deuterium-palladium system occur at a very high atomic ratio of D/Pd. Emphasis was placed on studying phenomena that provide a fundamental understanding of the mechanism by which D gains access to the Pd lattice and how very high atomic ratios (near, at, or perhaps beyond unity) can be achieved and maintained.

With appropriate control of the interfacial conditions, we have shown it possible to load both H and D into Pd to molar ratios of approximately unity. Electrode preconditioning apparently plays a significant role in the ability to attain and maintain high loading under electrochemical conditions and in the appearance of unaccounted-for heat in deuterium-loaded systems. Helium implantation provides a suitable means of surface activation to facilitate loading; the presence of such implanted helium is not obviously implicated in the generation of excess power.

At the outset of the experimental program described here, it was postulated that anomalous effects previously unobserved—and presently unexplained—in the deuterium-palladium system will occur at deuterium loadings (D/Pd atomic ratios) approaching or exceeding unity. Thus a central feature of the experiments described here is the (electrochemical) control and continual *in situ* measurement of the deuterium (and hydrogen) loading during the entire calorimetric experiment.

Further, it was decided that the most accurate and sensitive thermal measurements would be obtained using a sealed (thermodynamically closed) electrochemical cell—with knowledge at all times of the composition of the reacting system—in combination with a flow calorimeter. The experimental approach adopted here thus differs significantly from that originally described by Fleischmann et al.<sup>2</sup> and from the majority of subsequent calorimetric studies.

To characterize the electrochemical kinetic and thermodynamic processes that control the absorption of D into Pd, we measured the interfacial impedance and the Pd cathode voltage with respect to a reference electrode. Measurements of the Pd solid phase resistivity were used to monitor on-line the degree of loading atomic

ratios, specifically D/Pd, H/Pd, and H/D. The resistance ratio/atomic ratio functionality was calibrated primarily by reference to the works of Baranowski<sup>2,4</sup> and Smith<sup>5,6</sup> but also by volumetric observation of the displacement of gas during loading in a closed system at constant pressure and temperature and by anodic coulometry.

The overall conclusions of the loading studies are that, by careful control of the electrode pretreatment, the electrolyte composition, and the current density, Pd can be loaded to atomic ratio D/Pd  $\approx$  1 and this loading sustained for periods of weeks.

Calorimetric experiments were performed in palladium rods highly loaded with D and/or H and electrolyzed at substantial current densities (typically 300-600 mA cm<sup>-2</sup>, but up to 6400 mA cm<sup>-2</sup>) for considerable periods (typically 1000-2000 hours).

Our calorimeters were designed with the philosophy that, in precise calorimetry and in the search for unusual reaction products, it is desirable to have a closed system and a knowledge at all times of the composition of the reacting system. All experiments were performed with closed and sealed electrochemical cells operating from 40 to 10,000 psi above atmospheric pressure. Axial resistance measurements were made to monitor the D/Pd or H/Pd ratio.

Approximately 30 experiments have been performed with flow calorimeters operating at constant power input. The calorimeters were designed and constructed with the following features:

- A conceptually simple system based on the first law of thermodynamics.
- Maintenance of complete control of operating parameters (including cell temperature).
- A large working range of power input and output (0.1-100 W).
- On-line monitoring of all important variables.
- Multiple redundancy of measurement of critical variables such as temperature.
- High accuracy (the greater of 50 mW or 0.5%) and precision (10 mW or 0.1%)
- Known sources of potential error to yield conservative estimates of output power. . . .

[Continues]

# 3

## **CALORIMETRIC STUDIES**

### **3.1 Introduction**

Table 3-1 describes the conditions employed and the results obtained in the significant calorimetric experiments carried out in this program. Certain experiments are described in this Section, as outlined below. A comprehensive compilation of the data obtained in one particular experiment, denoted P19, is included in a separate section, Section 3A. Another separate section, Section 3B, reports the details of the one well-characterized observation of temperature excess for the Pd-coated reference cell.

#### **3.1.1 Outline**

##### 3.1 Introduction

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##### 3.2 Experiments P1 and P2

Section 3.2 has been published as a manuscript entitled "Calorimetry and Electrochemistry in the D/Pd System" in *Proceedings of the First Annual Conference on Cold Fusion*, National Cold Fusion Institute, Salt Lake City, UT, 1990, p. 20.

##### 3.3 Experiments P12 through P16

This contents of Section 3.3 were originally published as a manuscript entitled "Isothermal Flow Calorimetric Investigations of the D/Pd System" in *The Science of Cold Fusion*, Eds. T. Bressani, E. Del Giudice, and G. Preparata, Conference Proceedings Vol. 33, Italian Physical Society, Bologna, 1992, p. 419. The account included here is an updated version based on a presentation given at the Eighth Australasian Electrochemistry Conference, Auckland, New Zealand (February 1992).

##### 3.4. Description of experiment C1.

Section 3.4 is based on a presentation given at the Third International Conference on Cold Fusion, Nagoya, Japan, 1992. . . .



TABLE 3-1  
CELL CONFIGURATION

Cell #	Electrolyte			Maximum			Duration		Maximum Power			Total Energy			Number of Excess Observations					
	length (cm)	dia. (cm)	A (cm <sup>2</sup> )	Type	Conc. (M)	Addition	Bath Temp (°C)	Pressure (psi)	Current (A/cm <sup>2</sup> )	Loading R/R°	Loading D/Pd	Expt. (hours)	Init. (hours)	Input (W)		Excess (W)	Excess %	Input (MJ)	Excess (MJ)	Excess %
<b>7mm diameter (differential calorimeter)</b>																				
P1a	5	0.7	11.0	LiOD	1.0	None	7	650	682	1.20	1.058	696	369	3.35	1.75	52.2%	3.4	0.07	2.11%	5
P1b	5	0.7	11.0	LiOD	1.0	None	7	650	682	?	9	696	299	3	0.2	6.7%	3.0	0.01	0.47%	2
<b>4mm diameter Johnson Matthey</b>																				
P2	4.5	0.3	4.2	LiOD	1.0	None	4	1000	495	1.65	0.937	1393	504.33	3.8	2	52.6%	50.2	1.07	2.14%	4
<b>3mm diameter Johnson Matthey</b>																				
P3	4.5	0.3	4.2	LiOD	1.0	None	25	1000	354	1.70	0.920	1250					18.0			0
P4	5	0.3	4.7	LiOD	0.1	None	30	100		1.80	0.885	1165					16.8			0
P5	5	0.3	4.7	Li2SO	0.5	None	16	100	849	1.70	0.920	287					4.1			0
P6	5	0.3	4.7	Li2SO	0.5	As2O3	30	100	573	1.70	0.920	649					9.3			0
P7	4.5	0.3	4.2	LiOD	1.0	None	8	1000	259	?	?	145					2.1			0
P8	3	0.3	2.8	LiOD	0.1	None	35	100	637	1.65	0.920	186					2.7			0
P9	3	0.3	2.8	LiOD	1.0	None	35	50	531	1.65	0.920	597					21.5			0
P10	4.5	0.3	4.2	LiOD	1.0	None	35	900	47	9	0.937	18					0.3			0
P11	4.5	0.3	4.2	LiOD	1.0	None	35	1050	1179	1.65	0.937	85					1.2			0
<b>Al additions commenced</b>																				
P12	3	0.3	2.8	LiOD	1.0	4He,Al	30	50	884	1.55	0.937	1631	316	10	0.97	9.7%	58.7	0.80	1.36%	4
P13	3	0.3	2.8	LiOH	1.0	Al	30	50	884	1.1*	0.966	815		15	0	0.0%	11.7	0.00	0.00%	0
P14	3	0.3	2.8	LiOD	1.0	3He,Al	30	50	884	1.60	0.951	692	184	10.5	0.5	4.8%	10.0	0.20	1.96%	2
P15	3	0.3	2.8	LiOD	1.0	Al*	30	40	884	1.58	0.957	1104	684	10	2.4	24.0%	39.7	0.55	1.38%	3
P16	3	0.3	2.8	LiOD	1.0	3He,Al*	30	40	884	1.70	0.920	1104	948	10	0.4	4.0%	39.7	0.10	0.24%	4
P17	3	0.3	2.8	LiOD	1.0	Si	30	40	389	1.29	1.036	1202	1040	10	0.2	2.0%	13.0	0.10	0.75%	2
P18	3	0.3	2.8	LiOD	1.0	Al	35	40	Failed early due to electrical contact						Calorimetry started 677 h					
P19	3	0.3	2.8	LiOD	1.0	B	35	40	672	1.45	0.993	1287	261	0.25	0.85	340%	23.2	0.41	1.79%	4*
P20	3	0.3	2.8	LiOD	1.0	Al	35	40	707	1.55	0.966	954	650	12	0.28	2.3%	17.2	0.16	0.96%	3
P21	3	0.3	2.8	LiOD	1.0	B	30	40	707	1.60	0.951	764	390	10.5	0.6	5.7%	13.8	0.04	0.28%	2
P22	3	0.3	2.8	LiOD	1.0	B	30	40	707	1.30	1.032	1480	378	0.27	0.08	29.6%	21.3	0.27	1.29%	3**
<b>1 mm diameter &amp; 100µm foil (Johnson Matthey)</b>																				
C1	30	0.1	9.4	LiOD	1.0	Al	30	50	764	1.65	0.937	866	390	45	1.35	3.0%	49.1	1.12	2.28%	1
C2	25	µm	60.0	LiOD	1.0	Al	30	50	120	1.60	0.951	356	190	35	3	8.6%	14.4	0.56	3.88%	1

\* Last event spontaneous, persisted through stripping cycle

\*\* First event spontaneous, persisted through stripping cycle, last event terminated by H2O addition

[Here is another sample of the text in Section 3]

. . . We can conclude from the foregoing discussion that in each instance of excess heat in Table 3A-1, the observed energy exceeds the sum of the enthalpies of known chemical reactions—on average by a factor of ~20, and in total by a factor of more than 100. Energetic radiation and radioactive products have not been detected however. Thus, if a nuclear process gives rise to the heat, the process does not involve easily detected penetrating radiation or energetic charged particles and does not result in qualitatively commensurate radioactive product species.

### **3A.4.3 Power**

Measurement of total integrated excess energy is important in deciding whether one is observing an energy production rather than an energy storage process. However, the existence question, i.e., whether there indeed exists a phenomenon to observe and explain, is more easily and accurately answered by analyzing the instantaneous calorimetric power balance. Therefore, the experiment discussed here was designed to make accurate and stable measurements of the input and output power so that the difference (denoted here as "excess power") can be explained.

One of the more startling observations of excess power is that represented by Event 4 in Table 3A-1. This event is discussed in greater detail here so we can draw conclusions. Figures 3A-6a through 3A-6c highlight the time interval between 650 and 806 hours. Figure 3A-6a shows the cell current, voltage, and reference voltage, together with the excess power averaged from the four pairs of temperature sensors (4-1, 3-2, 6-1 and 5-2), fully corrected for departures from the calorimetric and chemical steady state. Particular attention is drawn to the apparently spontaneous (i.e., not initiated by cell current, reference voltage, or cell power) increase (at 690 hours) and decrease (at 748 hours) in the observed power excess. Note also that the P<sub>xs</sub> increase at 690 hours occurred while the calorimeter was in constant power control at ~14 W, with the heater contributing ~13.7 W, but the P<sub>xs</sub> decrease at 748 hours occurred while the heater was off. Most importantly, the excess power in Figure 3A-6a shows little correlation, or even anti-correlation, with the electrochemical current.

# 5

## **SUMMARY AND DISCUSSION**

This section summarizes and discusses some aspects of the experimental results presented in this report. Since there is not yet a detailed mechanistic understanding of the origin of the excess-power-producing phenomenon, the observation of which is the result of central importance reported here, any discussion is necessarily largely phenomenological. However, we present some implications of the phenomenological model developed here in connection with the search for a possible nuclear origin for the excess power production observed.

### **5.1 Experimental Observations**

#### **5.1.1 Degree-of-Loading Experiments**

The central postulate guiding the experimental program was that anomalous effects previously unobserved or currently unexplained in the deuterium-palladium system occur at a very high D/Pd atomic ratio. Emphasis was placed on studying phenomena that provide a fundamental understanding of the mechanism by which D gains access to the Pd lattice and how very high atomic ratios (near, at, or perhaps beyond unity) can be achieved and maintained.

To characterize the electrochemical kinetic and thermodynamic processes that control the absorption of D into Pd, we measured the interfacial impedance and the Pd cathode voltage with respect to a reference electrode. Measurements of the Pd solid-phase resistivity were used to monitor on-line the degree of loading atomic ratios, specifically D/Pd, H/Pd, and H/D.

The overall conclusions of this study are that by careful control of the electrode pretreatment, the electrolyte composition, and the current density, we can load Pd to an atomic ratio D/Pd of approximately unity and sustain this loading for weeks.

#### **5.1.2 Calorimetric Experiments**

Calorimetric experiments were performed in palladium rods highly loaded with D and/or H and electrolyzed at substantial current densities (typically 300-600 mA

$\text{cm}^{-2}$ , but up to  $6400 \text{ mA cm}^{-2}$ ) for considerable periods (typically 1000-2000 hours). Our calorimeters were designed with the philosophy that in precise calorimetry and the search for unusual reaction products make it desirable to have a closed system and a knowledge at all times of the composition of the reacting system. All experiments were performed with closed and sealed electrochemical cells operating from 40 to 10,000 psi above atmospheric pressure. Axial resistance measurements were made to monitor the D/Pd or H/Pd ratio.

Approximately 30 experiments have been performed with flow calorimeters operating at constant power input. The calorimeters were designed and constructed with the following features:

- A conceptually simple system based on the first law of thermodynamics.
- Maintenance of complete control of operating parameters (including cell temperature).
- A large working range of power input and output (0.1-100 W).
- On-line monitoring of all important variables.
- Multiple redundancy of measurement of critical variables such as temperature.
- High accuracy (the greater of 50 mW or 0.5%) and precision (10 mW or 0.1%).
- Known sources of potential error to yield conservative estimates of output power.
- Steady-state operation, leading to simple analysis.

All experiments were performed with thermodynamically closed electrochemical cells. A large area catalyst was provided in the head space of the cells to recombine evolved  $\text{O}_2$  and  $\text{D}_2$  so that the net reaction in all cells after the Pd rod is loaded is  $\text{D}_2\text{O} = \text{D}_2\text{O}$ , for which the thermoneutral voltage is zero. Constant current or slowly



ramped conditions were used in all cases. Commonly, experiments were performed electrically in series to test the effects of different variables.

We have observed unexplained excess power in palladium cathodes when a minimum of three criteria were met:

- (1) The average loading (D/Pd) approached or exceeded unity.
- (2) This high loading was maintained for considerable periods (hundreds of hours for 3-mm-diameter cathodes).
- (3) The interfacial current density exceeded a certain critical value.

For the thermodynamically closed and intentionally isothermal systems described here, output power was observed to be as much as 300% in excess of the electrochemical input power or 24% above the known total input power. When excess power was present, it was more typically in the range 5%-10%, in calorimeters that were accurate to better than approximately 0.5%. The largest observation of excess energy corresponded to 1.08 MJ, or 45.1 MJ/mol, or ~450 eV/atom normalized to the Pd lattice or to the deuterium in the palladium at a loading of ~1.

Some degree of experimental reproducibility between cells was also observed. Five experiments were performed in an attempt to replicate a prototype experiment, with only minor variations in electrode and electrolyte treatment. All the heavy water experiments produced excess heat and reproduced in general form the observation of excess heat in the prototype experiment. However, excess power in these four experiments was *not* produced in exactly the same amounts, or at exactly the same times, in response to the same stimuli. Except for times when the calorimeter was caused to depart significantly from its steady-state condition, "negative excess" was never observed.

Finally, we are unable to account for the observed excess heat by an artifact known to us and are forced to conclude that the source of the excess power is a property of the D/Pd system. Further, we cannot account for the measured excess power and energy by any chemical or mechanical process with which we are familiar.

## 5.2 Phenomenological Model for Excess Power Production

The association of apparent excess power with a set of necessary conditions for the D/Pd system implies a degree of reproducibility. These conditions are not easy to attain, a fact that may explain the irreproducibility of the phenomenon of excess heat. Examined separately, the three criteria may be taken as normal conditions of reacting systems (chemical or nuclear). The criterion of loading is of a thermodynamic driving force, a measure of the activity or chemical potential of a possible reactant species. The need to maintain loading for considerable periods before the onset of excess heat suggests a mass transport constraint, possibly involving nucleation and growth of an active region within the volume of the bulk Pd lattice.

The final requirement, a large interfacial current density, suggests a kinetic criterion. Cathodic current provides the means by which atomic hydrogen or deuterium is discharged onto the palladium electrode surface. The role of current density in producing calorimetric excess power in heavy water systems may be more complex than simply that of initiating adsorption. In our experiments, we observe that the excess heat, when present, increases roughly linearly with current density above some threshold value and achieves a maximum at an upper threshold of current density. Under different experimental conditions, others have observed a second-order or higher dependence of excess power on current density above an initiation threshold, but with no observed upper limit.

In energy-producing experiments, we observe that the loading initially increases monotonically with current density, but this increase is not sustained, and the apparent loading (determined from the resistance ratio) may decrease at moderate and high current densities while the excess power continues to increase. We also observe in repeated experiments that excess power can consistently be reduced to unmeasurably small values by reducing the current density below its lower threshold value. The decrease in excess power generally occurs faster than the time constants of diffusional loading.

These results suggest the potential for using current control as a very effective means of controlling a practical heat producing system. The current appears to act

by many complex mechanisms. Some suggested mechanisms follow:

- Controlling the loading through the electrochemical process of discharge, recombination, and adsorption.
- Providing kinetic impetus to possible interstitial nuclear processes by coupled motion of  $e^-$  and  $D^+$  plasmas in the metal phase.
- Providing optical or acoustic phonon excitation to stimulate lattice neutron transfer reactions.
- Increasing the cathode temperature.

Current perturbation provides the most direct means of probing the electrochemical system and of controlling any practical device. For practical and fundamental reasons, it is critical that we gain a clear understanding of the methods by which it operates to induce excess power.

### **5.3 Influence of Temperature**

The apparent discrepancy between our observation of a roughly linear dependence of excess power on current density and that of Fleischmann and Pons of a roughly second-order dependence may be resolved by understanding the influence of temperature. We have designed our experiments, as closely as possible, to decouple the influences of temperature and current density; calorimetric experiments are performed under constant input power conditions, approaching the steady state. Our calorimeters also have large heat conduction so that, even in the condition of substantial excess power, the cathode temperature is not raised appreciably. Under these conditions, we observe an approximately linear response of excess power with current density.

In the experiments of Pons and Fleischmann, the current density is raised without reducing the power in a compensatory heater, in a calorimeter with very low heat conduction. For this reason, the cell temperature rises markedly with increasing current density, and the temperature increase is exacerbated by the onset of any excess power production. Under these conditions, Fleischmann and Pons observed a second-order or higher power dependence of excess power on current density, with no observed maximum.

Taken together, these results suggest that the rate of excess enthalpy production increases at least transiently, with increasing temperature. Such a degree of autocatalysis would be useful in achieving large power gain; the apparent positive derivative with temperature suggests that it may be possible to produce heat efficiently at a usefully elevated temperature.