J. Condensed Matter Nucl. Sci. 4 (2011) 32–44

Research Article

Cold Fusion, LENR, CMNS, FPE: One Perspective on the State of the Science Based on Measurements Made at SRI

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Abstract

Our object is to clarify in non-specialist terms what is known and what is understood in the general field of so called Low-Energy or Lattice Enhanced Nuclear Reactions (LENR). It is also crucial and timely to expose and elaborate what objections or reservations exist with regard to these new understandings. In essence, we are concerned with the answers to the following three questions: What do we think we know? Why do we think we know it? Why do doubts still exist in the broader scientific community? Progress in the LENR field will be reviewed with primary focus on the experimental work performed at SRI by and with its close collaborators with a view to defining experiments based non-traditional understandings of new physical effects in metal deuterides. Particular attention is directed to the Fleischmann–Pons Effect, nuclear level heat from the deuterium-palladium, and the associated nuclear products: ^{4}He, ^{3}He and ^{3}H.

Keywords: Calorimetry, Cold fusion, Excess heat
PACS:

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1. Introduction

After 21 years of continuous study and tens of millions of research dollars spent worldwide it is appropriate to examine the basis for, and confidence in what has been learned since the public announcements of a prospective new effect in March 1989. One fact that seems irrefutable is the existence of a heat effect in the electrolytic deuterium–palladium system that is quantitatively consistent with nuclear, but not chemical heat production. Now established as the Fleischmann–Pons Effect (or FPE) several tasks require further study:

(i) Certain identification of the pathway from reactant (presumed to be D) to primary product (observed in some experiments to be ^{4}He).
(ii) Quantitative or upper bound definition of the products of secondary or tertiary reactions.
(iii) Complete development of a mechanistic and quantitatively predictive physical and mathematical model for the reaction process.

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(iv) Evaluation of potential applications of any new phenomena.

2. Excess Heat

The Fleischmann–Pons Effect is defined as the production of nuclear level heat from the electrochemical stimulation of the D_2O–Pd. This effect has been observed by hundreds of people in dozens of laboratories around the world, and published in hundreds or thousands of papers as recently reviewed [1,2]. In fact, the very breadth of diversity in experiment and calorimeter choice has contributed to a perceived irreproducibility (although the primary cause of apparent irreproducibility is the lack of measurement and control of variables critical to the effect).

The Fleischmann–Pons effect is produced under difficult-to-achieve but (now) relatively well-defined conditions in the cathodic stimulus of Pd (and alloy) electrodes in heavy water electrolytes (see [2]). Early failures to observe the effect can be attributed to inadequacies or deficiencies[1] in electrochemical and/or metallurgical protocols and the failure to anticipate the threshold nature of the phenomenon, particularly the thresholds of high D/Pd loading (>0.9) and long time initiation (>100 h for bulk Pd wire cathodes). Electrochemistry takes place at an electrified interface between two "difficult" material phases (solid and liquid), neither of which are fully under our control.

Stimulation of the excess heat effect is often observed to be prompted by changes in experimental conditions. Fleischmann and Pons [3] noticed in their initial work that the excess heat effect was occasionally initiated or improved with the application of a heat pulse, which can be considered as a transient change in conditions within the present argument. At SRI, one of the techniques used with success to initiate a heat pulse was to alter the current density, either through sudden changes or ramps. In later work a highly modulated current waveform was used to accomplish simultaneously the conditions of high deuterium loading and flux, following the pioneering work of Dardik [4].

Quantitative evidence indicating that deuterium flux plays an important role in determining the excess heat in a Fleischmann–Pons cell was found at SRI [5]. A purely empirical function was found to describe the excess heat observed for 1 mm diameter Pd cathodes. After initiation, excess power was found to be proportional to the product of three terms: (i) the square of the loading above a threshold value $(x - x^{\circ})^2$ (see Fig. 1); (ii) the electrochemical current above a threshold (see Fig. 2) and (iii) the flux of deuterium through the interface, irrespective of direction, measured as the time derivative of the average D loading, $|\delta x/\delta t|$ (see Fig. 3).

Figure 3 presents data showing the correlation of measured excess power with the amplitude of a $\sim$ 2 h near-sinusoidal loading oscillation. Experiments appear to show that deuterium flux plays an important role in excess power production, independent of whether it is incoming, outgoing, axial, or traversing.

An important criterion coupled with excess heat production is the ability of a cathode to *sustain* high D/Pd loading. A variety of evidence supports the notion that the excess heat effect occurs at or very near the electrified electrolyte interface. Nevertheless the maximum *bulk* loading achieved by a cathode tells us something about *whether* (or not) a Pd D_x cathode is going to produce excess. Figure 4 plots the incidence of unsuccessful and successful excess heat producing experiments versus the maximum D/Pd loading achieved by the cathode *at any time* during the experiment. In some experiments the maximum heat was produced at times other than maximum loading; the statistically important feature appears to be *capacity* to obtain high loading. To get more information about when and how much heat is produced[2] we need to have more information about conditions of surface stimulation (current, laser, etc.) and surface dynamics (deuterium flux).

Four important understandings developed from intensive studies at SRI of deuterium loading and calorimetry [6–9]:

(i) Irreproducibility in FPE experiments can be fully or at least sufficiently explained in terms of the electrochemistry of loading D into Pd.

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[1] In most cases early null or unintelligible results were caused more by an artificial sense of urgency than intrinsic core incompetence.

[2] More accurately, heat rate or power.

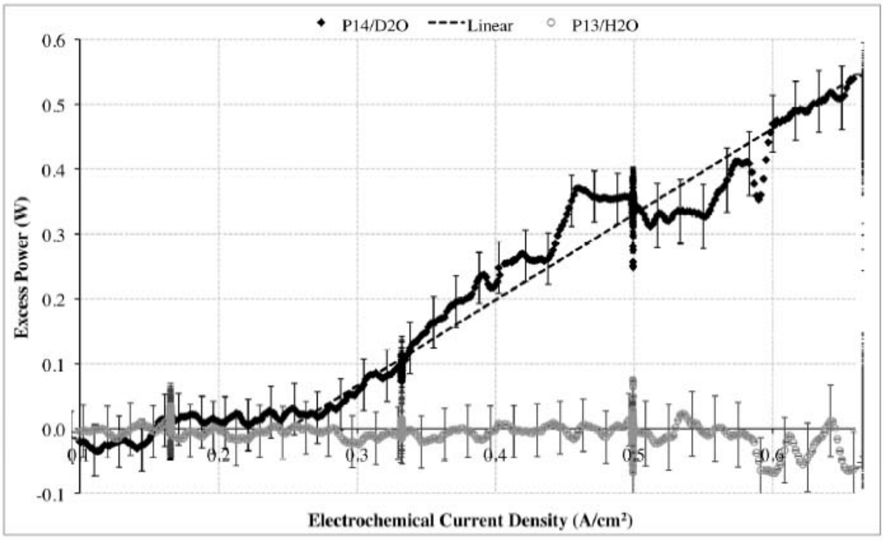

Figure 1. The effect of electrochemical current density on excess heat production in FPE experiments.

(ii) In the absence of a measure or knowledge of the D/Pd loading the experimenter has no basis to judge whether an experiment could or should have produced excess heat.
(iii) After basic precautions are taken the irreproducibility of loading and interfacial kinetics is not largely or even primarily controlled by the electrolyte or the electrochemistry, it is controlled by the bulk palladium metallurgy.

An empirical and near quantitative understanding of the measured magnitude of excess heat effects, and more particularly of the failure to achieve the FPE, can be obtained from measurements made of the controlling variables, and the failure to achieve critical threshold values.

3. Pathway Identification

3.1. Near quantitative

Much effort has been devoted to the search for reaction products that could be associated with the excess heat. It soon became clear that there are insufficient chemical reaction products to account for the excess heat by several orders of magnitude. Attention has been directed to the search for nuclear products in amounts commensurate with the energy measured. The problem is more difficult than in the case of chemical reactions as no similar processes are known.

Searches for neutrons, tritons, and other energetic emissions in quantitative association with the excess heat effect have been uniformly unsuccessful. The primary nuclear reaction pathway identified or hypothesized to be associated with excess heat results is the production of ^{4}He. Observations of this ^{4}He appear to be solid and reproducible although experiment difficulties have reduced the number of successful ^{4}He reports far below the number of reliable excess heat results. Miles and Bush were the first to demonstrate semi-quantitative correlation between the rates of creation of ^{4}He and excess heat [10]. That effect has now been observed in a number of laboratories around the world [10–14] including SRI [9,15].

The simplest imagined nuclear reaction consistent with the thermal signature of the observed effect is the net reaction of two deuterons to produce ^{4}He with overall energy release $\sim$ 23.8 MeV. It is this overall reaction against which Miles and Bush (and subsequent experimentalists) tested their quantitative observations. It has long been widely recognized by those active in FPE research and skeptics alike that this reaction cannot (and need not) proceed at low energies in the lattice by the same mechanism as the elementary process of "hot fusion" in isolation of all other matter.

Although measurements have been made of product ^{4}He at close to the 24 MeV Q-value [9,14,15], issues possibly associated with lattice retention always have resulted in larger measured energy values (or correspondingly smaller amounts of ^{4}He). In addition, in no case has it been possible to perform a rigorous D, ^{4}He mass balance to identify the reactant as well as the product. Unless or until the FPE is used on an industrial scale to produce heat it will remain experimentally impossible to measure or even observe the tiny consumption of a very leaky gas (D_2) and isotope that is present ubiquitously in water.

It is also worth noting that several imaginative alternative nuclear reaction schemes have been proposed that produce ^{4}He at approximately the 24 MeV Q-value of dd fusion [2]. A large number of possible nuclear reactions also exist involving the known and expected constituents of the FPE metal/electrolyte system that produce ^{4}He with Q-values different from the $\sim$24 MeV of dd fusion value (typically less). These putative and potential nuclear-reactive elements include: Li, B, C, N, O, Na, Ca, Pd, and all their natural isotopes. While in principle easier to undertake a quantitative mass balance of minority constituents such as Li and B, a rigorous tracking of reactant and product concentrations before, during and following an accurately measured heat release has yet to be performed.

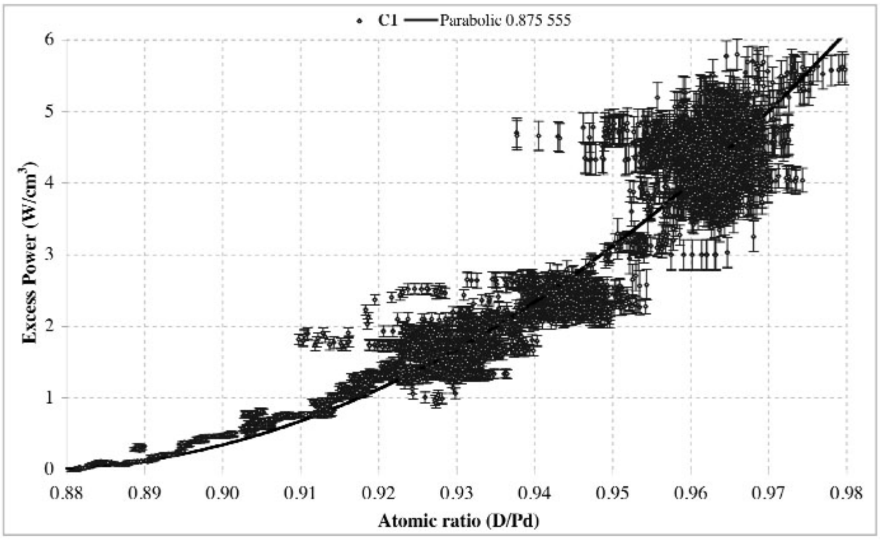

Figure 2. The effect of deuterium loading on excess heat production in FPE experiments.

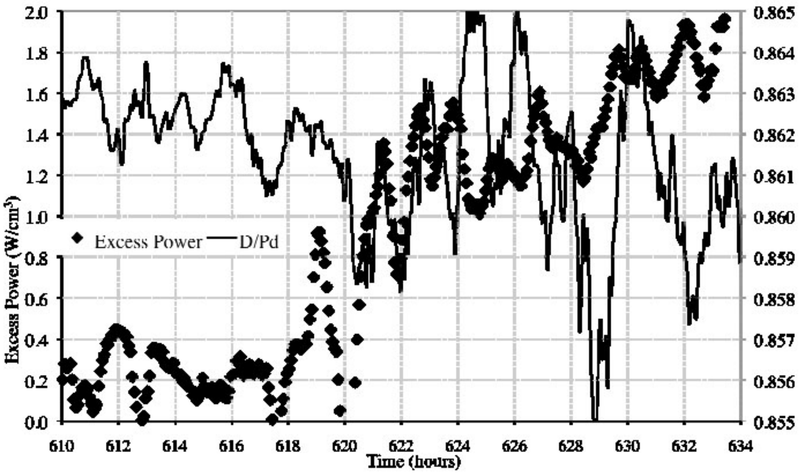

Figure 3. Correlation of excess power and deuterium flux for 1 mm dia. Pd cathode in FPE experiments.

3.2. Associated products (ash)

Additional products have been claimed of secondary reactions such as those that produce ash[3] in chemical combustion. First amongst the secondary reaction products is tritium[4]. This isotope appears both temporally and quantitatively uncorrelated with excess heat production, but is clearly created in a number of experiments. Considerable discussion of this can be found in the excellent review by Storms [2].

Rather than being the dominant observable product (together with neutrons) in a putative dd fusion reaction, tritium is generally created at times when excess heat production is not observed and is not expected. On the rare occasions when heat and tritium production are observed in the same experiment at similar times, the tritium yield is 4–6 orders of magnitude less than that expected for a dd fusion heat effect.

Tritium is relatively easily observed. It is present at very low-background levels in most laboratories, and can be unambiguously identified by three different commonly employed methods: liquid scintillation in the liquid phase; direct beta observation in the gas using proportional counters or ionization chambers; mass spectrometric measurement of the rate of production of ^{3}He via ^{3}H decay. All three methods have been used in FPE studies, increasing the reliability and confidence in tritium observation. Other isotopic effects also have been reported, proposed and reviewed [2].

3.3. Mechanism and theory

At present there is no consensus among those in the field as to what physical mechanism is responsible for the effect although many propositions are under active discussion and significant progress is being made [16]. Nuclear reactions in the rarified environment of high-energy beams or plasmas are generally understood in terms of local energy and

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[3] The term "nuclear ash" was originally applied not to the parasitic processes of reaction (by analogy with chemical combustion) but to mean the products of heat generating reactions (either observed or absent). This is equivalent to describing the products of chemical combustion, CO_2 and H_2O, as ash. Like helium, both are gases and neither can be considered as ash. The ashes of chemical combustion are the oxidation products of trace metal impurities and the residuum of already oxidized fuel inclusions.

[4] As a gas, tritium cannot be an ash.

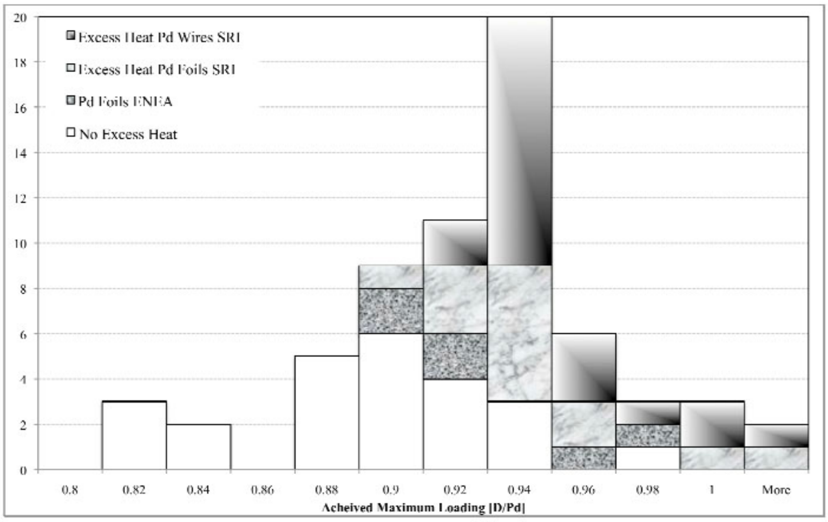

Figure 4. No heat (white) and successful excess heat experiments as a function of maximum D/Pd loading achieved in the FPE experiment.

momentum conservation in an assumed closed system encompassing only the putative reaction volume. It is not clear to what extent such simple considerations will prove to apply to nuclear reactions in solid lattices or in any form of condensed matter where the reactants and products are not isolated from their environment but are integral parts of the extended coherent system, the wave structure of the lattice.

4. Calorimetry: Measurement of Excess Heat

By simple consideration of energy scales and experiment duration the needs of so called “cold fusion” calorimeters are so different from those intended for use studying brief chemical reactions that, while valuable as a guide to basic principles, very little of value can be learned from studying that community, and little reference will be made to them here. The generation of mass flow, or more generically heat balance calorimeters under discussion here, were constructed to achieve confidence and give credence to a result that was not believed. Fleischmann et al. [3], and others had reported results of a nuclear level heat effect resulting from the *extensive electrochemical insertion* of *deuterium into palladium* cathodes over an *extended period of time* by means of electrolysis of heavy water in heavily alkaline conditions.

If true, this result was seen by some as a potential energy source, or at the very least a new potentially interesting physical effect. By others it was viewed as an unwelcome diversion of attention which was criticized as “irreproducible” or the result of unspecified “inaccuracies”. With regard to the second, apparently informed statements were made that “all calorimeters” were “intrinsically inaccurate”, an assertion that early pioneers of chemical thermodynamics in the early 20-th and even late 19-th century would have found puzzling. In this climate, however, the challenges to the second-generation FPE calorimeters were threefold:

(i) To allow reproducible demonstration of the effect -– whether it be real or the consequence of (unidentified) systematic error.
(ii) To exhibit proven levels of accuracy, over sufficient periods to quantify heat generation consistent with the FPE.

(iii) The operating principal must be sufficiently simple to allow an open-minded non-specialist to visualize the full range of potential error.

The SRI calorimeters were designed and constructed [8,9] with 10 requirements.

1. As conceptually simple, first-principals devices based on the first law of thermodynamics [5].
2. With a requirement to maintain complete control of the critical chemical and electrochemical operating parameters, including cell temperature.
3. To accommodate a large dynamic range of heat input and output anticipated to be ∼100 mW – 100 W (later extended to 500 W).
4. To permit complete, on-line monitoring of all important physical, chemical, electrochemical and thermal variables.
5. With multiple measurement redundancy of variables critical to calorimetry (e.g. temperature).
6. So that heat was measured accurately, equally and completely, independent of it is source position within the calorimeter.
7. To allow high precision (the greater of 10 mW or 0.1% of power input) and high and stable accuracy for operating times as long as 1000 h.
8. To operate as closely as possible to the (thermal) steady state, thus simplifying calorimetric data analysis.
9. With sufficient time resolution to permit simple non-steady state analysis allowing source reconstruction of possible thermal transients.
10. Such that known sources of potential systematic error yield conservative estimates of “excess” heat.

One means of calorimetry was considered (in 1989) best able to meet the above-listed requirements. Often called mass flow calorimetry because of it’s emphasis on heat convected by a moving fluid mass, Heat Balance Calorimetry is accomplished by monitoring the heat gained or lost by the heat transfer fluid as follows:

$$Q_{\mathrm{o}} = \delta m/\delta t C_{\mathrm{ps}}(T_{\mathrm{o}} - T_{\mathrm{i}}), \tag{1}$$

where Q_{o} is the process heating (output) power (W), $\delta m/\delta t$ the mass flow of heat transfer fluid (kg/s), C_{ps} the specific heat of heat transfer fluid (J/(kg K)), T_{i}, the inlet temperature of heat transfer fluid (K), and T_{o} is the outlet temperature of heat transfer fluid (K).

As written, Eq. (1) has no calorimeter-dependent calibration requirements. Given independent, fundamental calibrated references for mass and time (hence $\delta m/\delta t$) and temperature (or temperature difference), and independent accurately known properties of the mass transport fluid, then the measurement of Q is absolute. This calibration independence is very important. Drifts in calorimeter “calibration constant” are the greatest cause of concern and error potential in FPE experiments that must survive hundreds of hours of intense electrolysis before the effect is seen that may last thousands of years [6].

Input power to an electrochemical cell operating thermodynamically closed is simply the product of the electrochemical current and the voltage measured at the calorimetric boundary (i.e. at a point on the surface that is neither inside nor outside). To meet requirements 2 and 8 above allowing independent control of electrolyte temperature and steady state operation it is necessary to add an input electrical Joule heater to complement the electrochemical power input. In this configuration,

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[5] It is interesting to note that our widespread and deep trust in this law, is based exactly on our confidence in calorimetric accuracy.

[6] The effect of drift was eliminated and turned to advantage in the heat flow calorimeters designed by Fleischmann and Pons by daily, automated Joule calibration pulses. The presence of drift and rather clumsy handling of it essentially invalidated several early null results (sometimes classified as “negative”) as the position of the “baseline” was adjusted daily and arbitrarily.

$$Q_{\mathrm{i}} = I_{\mathrm{EC}} V_{\mathrm{EC}} + I_{\mathrm{J}} V_{\mathrm{J}}, \tag{2}$$

we define as excess power the difference between the calorimetrically determined heating output power and the sum of power input,

$$Q_{\mathrm{XS}} = Q_{\mathrm{o}} - Q_{\mathrm{i}}. \tag{3}$$

Note that Q_{XS} may have either sign. Negative “excess” is possible, although this condition has never been observed in any mass flow calorimetry performed at SRI in studies of the FPE except under transient condition as will be discussed shortly.

4.1. Departures from ideality

To obtain accuracies higher than $\sim 1\%$, two factors affecting calorimeter performance must be taken into account.

4.1.1. *Thermal efficiency*

Equation (1) accounts for heat removed from the calorimeter by convection of the thermal transfer fluid. Heat may also penetrate the calorimeter boundary by conductive exchange with the ambient. Of particular concern are metallic wires and pipes. If the environment is configured in such a way that the ambient is the inlet temperature, then Eq. (1) can be simply rewritten to include a conductive loss term, k,

$$Q_{\mathrm{o}} = ((\delta m/\delta t)C_{\mathrm{ps}} + k)(T_{\mathrm{i}} - T_{\mathrm{o}}). \tag{4}$$

Since k is a calorimeter specific constant that does require calibration, it is important that it be kept small to approach first principals operation. By careful insulation, controlled geometry and selection of the fluid flow rate, k was typically less than 1% of $\delta m/\delta t\ C_{\mathrm{ps}}$ in the SRI mass flow calorimeters. Because k is defined by geometry, it is also very unlikely to change and was observed to be stable.

In high-temperature operation one should expect radiative in addition to conductive transport. No such non-linear tem has been observed or required in the mass flow studies so far performed at SRI or by our close collaborators. In high-temperature studies [4] performed at Energetics reflective surfaces were used to minimize radiative heat transport.

4.1.2. *Thermal time constant*

Input power is measured effectively and instantaneously while the calorimetric output thermal power responds with the thermal time constant(s) of the calorimeter. To make accurate subtraction of $Q_{\mathrm{o}} - Q_{\mathrm{i}}$ in order to calculate Q_{XS} at the same instant and thus improve (instantaneous) accuracy and permit study of thermal transients, it is necessary to apply one or a series of exponential filters to Q_i so that the terms on the right-hand side of Eq. [3] refer to the same time of measurement.

Although other heat transfer processes might be considered, three terms dominate the transfer of electrochemical cell heat out of the calorimeter:

(a) Communication by conduction of electrochemical cell heat to the moving heat transfer fluid.
(b) Convective transport of the heated fluid element to the outlet temperature sensors.

(c) Convective thermal dilution of this heat due to the incoming mass flow at constant rate and constant (cooler) temperature.

Terms (a) and (c) depend exponentially on time. In all calorimeters studied at SRI the time constant for (a) and (b) were substantially less than for (c) and it was found sufficient to adopt a single level of exponential filtering with the following form.

$$\Delta Q = \sum_{\Delta t=0}^{t} \Delta Q_{\mathrm{i},\Delta t}(1 - \mathrm{e}^{-\Delta t/\tau}), \tag{5}$$

where Δt is the time interval of measurement and τ is the composite time constant.

It is important to remember that the form of the non-steady-state correction is such that, while this can significantly improve calorimetric precision, it cannot affect the accuracy of total excess energy generation. The round trip integral effect is zero given the same initial and final conditions.

4.2. Practical implementation

The calorimeter shown in Fig. 5 was designed to accommodate a hermetically sealed quartz (fused silica) cell body. All components structural or otherwise inside the cell in contact with either electrolyte or vapor were manufactured of SiO_2, Al_2O_3, PTFE, Pt or Pd. Internal recombination and thus thermodynamic closure, was provided by either Pt or Pd on Al_2O_3 recombination catalyst suspended above a PTFE conic section designed to prevent electrolyte splash damage and allow the condensed recombinate (either H_2O or D_2O) to wash deposits back into the electrolyte. The working volume was $\sim$30 cm^3. Using this materials selection and design geometry, these cells are capable of sustained operation in 1 M base at currents above 1 A for periods over 1000 h.

The hermetic design of the electrochemical cell allows for full immersion in the mass flow fluid so that the moving mass of calorimetry fluid (in this case air saturated water) can remove heat efficiently from each of five geometrically disperse heat sources:

1. The product of the electrochemical current flow and the cathode interfacial impedance and any excess heat source located at the cathode.
2. The product of the current flow and the electrolyte resistance path located within the electrolyte volume between cathode and anode (or anodes).
3. The product of the current flow and the anode interfacial impedance.
4. The heat of recombination of H_2 and O_2 or D_2 and O_2 at the recombination catalyst located in the volume of recombiner near the top of the cell.
5. The product of the current in a Joule heater used for power compensation and calibration, located in an axially symmetric cylindrical shell immediately outside and intimately contacting the cell wall.

These enumerated terms significantly and differently couple to the calorimeter and outside environment. In a well-stirred electrolyte as exists above relatively modest current densities, the first three terms constitute effectively a single volume source. In the steady state the recombination thermal power is equal to the electrochemical current times the thermoneutral voltage of 1.48 V for H_2O or 1.53 V for D_2O. The Joule heater, while axially symmetric with the electrolyte volumetric heat source, is closer and therefore temporally and thermally better coupled to the convecting mass flow fluid. By enveloping the cell in the flow as shown in Fig. 5 we were able to establish within better than 0.1% (1 ppt) that the measurement of heat (the output power) was independent of its source within the calorimeter. This degree of position insensitivity is very difficult to achieve in calorimeters employing internal heat exchangers to remove calorimetric heat.

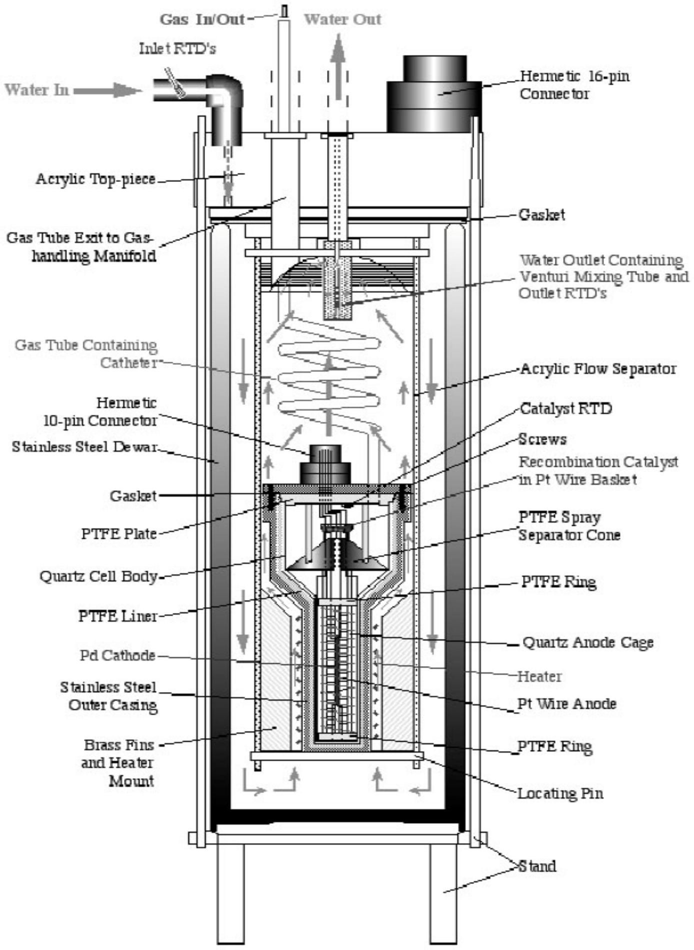

Figure 5. SRI Labyrinth Mass Flow Calorimeter containing hermetically sealed fused silica cell for FPE electrochemical and calorimetric studies. The calorimeter operates immersed in a thermally well-regulated water bath.

Several other features of the calorimeter shown in Fig. 5 merit further discussion. In employing Eq. (4) with a single conductive loss term, *k*, it is necessary to ensure that the calorimeter experiences a single, stable thermal ambient environment. The calorimeter was submerged inside a large ($\sim 1\,\mathrm{m}^3$), water bath that was well stirred and well regulated [7]. This bath was placed in the center of an isolated, temperature controlled room. The mass flow fluid (water) was drawn from the bath past two inlet RTD sensors placed directly in the flow stream. The flow enters the head of the calorimeter through a flow distribution header and channels down through the annular volume between

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[7] Temperature gradients and variability both short and long term were maintained below ±3 mK. A Quartz Crystal reference thermometer [HP Model 2804A] was maintained as a temperature standard in this bath.

the inner wall of a 2-liter stainless steel dewar and a thermally insulating barrier to form a flow labyrinth reversing direction at the bottom to flow past the submersed electrochemical cell. The electrical leads from the cell were dressed in the reverse direction from a hermetic connector at the top of the cell to another at the top of the calorimeter. The purpose of this arrangement is to minimize conductive heat loss radially from the cell and along the electrical leads used for electrochemical control and measurement. Heat leaving by these paths is picked up in the incoming fluid and is delivered to the outlet sensors for measurement.

The final feature of the calorimeter is the hemispherically domed insulating head that houses the outlet temperature sensors. The hemispherical shape was designed to minimize the formation of thermal "pockets" at higher or lower temperature than the average. The mass flow fluid flows through a small hole at the highest accessible point of the hemisphere to enter the outer annulus of a small flow labyrinth containing a venturi (helical) flow mixer. Turning the corner this flow enters a small axial flow channel designed to ensure good mixing at the operating mass flow rate (typically ~1 g/s).

These flow precautions were taken to ensure that the outlet temperatures measured represent an accurate average value in the fluid flow. The outlet temperature sensors were situated within the axial outflow channel, directly in contact with the outgoing fluid. Two RTD sensors were used, identical to the two at the inlet, to provide a redundant measurement of ΔT. In some experiments two additional thermistor sensors were used at the outlet to provide a redundancy of measurement method.

An FMI QV-0SSY constant displacement pump was used to draw water from the top of the calorimeter though a standard heat exchanger to ensure constant mass flow. This flow was then pumped directly into a reservoir placed on a Setra 5000L electronic balance that was polled periodically by the data acquisition system to measure the mass flow rate as $\Delta m/\Delta t$. When the balance reservoir is filled a siphon automatically forms and empties the vessel rapidly [8].

4.3. Brief consideration of errors

Excess power is calculated as the difference between the output power and the input power

$$Q_{\mathrm{XS}} = Q_{\mathrm{o}}\text{–}Q_{\mathrm{i}} = (\Delta m/\Delta t C_{\mathrm{ps}} + k)(T_{\mathrm{i}} - T_{\mathrm{o}}) - I_{\mathrm{EC}}V_{\mathrm{EC}} - I_{\mathrm{J}}V_{\mathrm{J}}. \tag{6}$$

Temperatures were measured using 100 Ω platinum resistance temperature devices (RTD's) so that to first order,

$$T = T^{\circ} + (R\text{–}R^{\circ})/\alpha R^{\circ}, \tag{7}$$

where α is the (known) temperature coefficient of resistance for Pt, and R° is the sensor resistance at some known temperature (typically 0°C).

A complete error propagation model has been developed for the calorimeter shown in Fig. 5; the basic elements are reproduced below. Errors propagate from mis-measurement of each of the terms. The constants and variables needed to measure Q_{XS} and its uncertainty may be divided into three classes:

1. Measured variables: Δm, Δt, R, I and V.
2. Predetermined constants: C_{ps}, α and R°.
3. The calorimeter inefficiency: k.

Measurements of mass, time, resistance, current and voltage rely on the calibration accuracy of the instruments being used. At SRI the instruments used for the purposes were periodically calibrated to accuracies better than 1 part

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[8] This normally disrupts only one, and at most determinations of $\Delta m/\Delta t$. In general the flows were very stable but redundant mass flow measurements occasionally were used for added accuracy.

per 1000 (<1 ppt) and typically better than 1 part in 10,000. Measuring R° with the same instrument used to measure R further increases measurement accuracy. Systematic errors in the calorimetry critical temperature difference tend to reduce since this depends on the difference of resistances measured with the same meter at almost identical times.

The heat capacity of air-saturated water and the temperature coefficient of Pt resistance are well measured constants. It should be noted that these are not constant with temperature; for accuracies better than 1 ppt it is necessary to take account of the fact that the outlet temperature may vary over of a considerable range, affecting both C_{ps} and α.

What remains is the conductive loss term or calorimeter thermal inefficiency, k. Three factors contribute to reducing the inaccuracy in this term and increase its long-term stability and thus influence on overall calorimeter accuracy.

(a) By design and selection of mass flow rate k is maintained to be a small fraction of $\Delta m/\Delta t\ C_{\mathrm{ps}}$. Typically this constant was held to contribute ~1% or less of the output power and it can be measured easily with better than ±10% accuracy thus contributing <1 ppt.

(b) The method of calibration using a Joule heater pulse determines k in terms of the other predetermined constants. In this way the cumulative error is reduced and recalibration can be performed at any time (in the absence of excess power) using a Joule heater pulse.

(c) The value of k is determined by the geometry and materials properties of heat conduction pathways. With the calorimeter isolated in the constant temperature bath these are not likely to change, and were not observed to do so.

For the Labyrinth Mass Flow Calorimeter shown in Fig. 5 the maximum error in the typical operating range of input power and mass flow rates (Q_{i} = 5–20 W, $\partial m/\partial t \sim 1$ g/s) was ±0.35% of Q_{i}. The largest source of error in practice is mismeasurement of the average temperature of the outgoing fluid stream due to flow streaming. Care must be taken to ensure good flow mixing and the avoidance of particulates in the flow stream.

5. Conclusions

With some attention to detail heat balance calorimeters based on the mass flow of water are capable and robust instruments that combine the desirable features of simplicity of design and calorimetric analysis, adequate accuracy, high long-term stability and low initial materials and operating costs. By these criteria such devices are well suited to studies of the FPE and have been widely employed with considerable success. Mass flow calorimeters are conceptually simple, first principles devices based on the first law of thermodynamics. They are able to accommodate and operate nearly linearly over a large dynamic range of heat input and output, extending easily to 500 W while maintaining better than 1% accuracy. Designs are available to permit the measurement of heat accurately, equally and completely, independent of its source position within the calorimeter.

The base of experimental support of the FPE is far broader than the interpretation of thermal signatures from mass flow calorimeters. In recent reviews [1,2] and in a full session devoted to the topic at ICCF14, a range of potent calorimetric methods have been reviewed with reference to FPE studies. Although varied in result and quality the (increasing) totality of an observable effect outside of known physics seems unimpeachable based on the heat effects alone, thus supporting the original claims of Fleischmann, Pons and Hawkins [3].

Of perhaps greater significance the support and identified existence of new physical effects does not rely on extreme heat effects alone. Numerous investigators have sought and, in many cases, found ^{4}He in different environments including in the gas phase, dissolved or trapped in the cathode metal, and emitted as charged particles [1]. In 8–10 cases the appearance of ^{4}He correlates to a high degree with the production of excess heat, offering strong support to the idea that the new physical effect is of nuclear origin.

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