Conclusions

I : We did not see any evidence of LENR.

To be specific, we performed a suite of aggressive, yet very different, LENR campaigns trying to detect AHE events. None of them succeeded in doing so.

Loading: Our hardware operated at D_2 pressures up to 500 ksi pressures, allowing us to reach 100% PdD loading in many situations. We used this capability in a wide range of LENR experiments; with targets ranging from slugs to films to chips, stimulations from thermal to electric-field to ultra-short laser pulses, and detection methods from calorimeters to RTDs to magnetic and physical archaeology. No LENR was detected.

Thermal Ignition: We tested highly loaded PdD and PdH targets in two very intense thermal stimulation situations; at temperatures as high as 1200^{o}C (where the palladium hydride melted). In one case, TI-11, the targets were in thermal equilibrium, sacrificing some loading in exchange for long duration. The other case, TI-12 was more dynamic; loadings would start at well over 95% (despite these extreme temperatures) but then rapidly decay over time as the material deloaded. From a material standpoint, these were macroscopic bulk targets (not thin films), and experienced a huge range of lattice deformations, from near perfect crystals to being literally ripped apart. No LENR was detected.

Ultra-Short Pulse: This was used to test a unique, non-thermal, form of stimulation. We loaded Pd targets with D_2 at pressures up to 450 ksi, and irradiated them with very short (~ 35 fsec) laser pulses. This was done both with isolated single pulses, sequences of temporally separated pulses, and with correlated bursts of pulses. We used both pump-probe reflectivity measurements and nanofilm archaeology to analyze results of the stimulation. No LENR was detected.

Staring: This was a two-pronged campaign using laser irradiation as a thermal form of stimulation for 150 ksi-loaded targets. In one effort, we literally stared at the target for long times, determining the temperature evolution of thousands of separate spatial pixels by recording thousands of IR images of the target. In the other effort, we used the laser as a stimulation source, irradiating both Pd and Pd-alloy targets, and using both magnetic and nanopillar/nanofilm archaeology to determine results. No LENR was detected.

Chips: The purpose of the Chips campaign was to test the response of small, lithographically made, targets to electrical stimulation; applied either by resistive heating or by intense electric fields. The smallness of the targets decreased the mass which would have to be heated-up by LENR energy, thereby increasing the detection sensitivity. In some experiments, we used small on-chip RTD thermometers to measure the response of each pulse in multi-thousand-pulse sequences. In other experiments, the chips contained arrays of nanopillars or nanofilms for single-event archaeological detection. No LENR was detected.

High Pressure Electrolysis: We used our high pressure systems in concert with electrolysis to achieve higher and more stable loadings (98%) than achievable in usual electrolytic LENR experiments. With this capability, we ran a number of LENR experiments both in and out of our commercial calorimeters. No LENR was detected.

Replications: We attempted to replicate two of the most influential gas-loaded experiments; those of Arata and Case. We performed these studies both in similar apparatus to that which they had used, as well as in our commercial calorimeters. No LENR was detected.

Calorimetry: Here we used high-sensitivity commercial calorimeters to look for LENR-induced energy from a variety of PdH and PdD targets and situations. We tested nanoparticle and aerogel targets as well as macroscopic foil and wire ones. In most experiments, the targets were gas loaded, but we did perform ones based on high-pressure electrolytic loading. Experiments were run at cryogenic temperatures, ambient ones, and temperatures up to 200^{o}C. Our most sensitive experiments were passive, with no stimulation energy to account for; but, given the probable importance of stimulation, most experiments used monitored amounts of resistive heating. No LENR was detected.

Physical Archaeology: We developed two types of nanostructures, arrays of nanopillars and nanofilms, to serve as LENR sensors with single-event sensitivity. Nanofilms were used as detectors in many different experimental campaigns under a wide range of loading conditions (150-450 ksi D_2 gas, D_2O electrolysis, cryogenic loading) and stimulations (lasers, ultra-short pulse lasers, resistance heating, electric fields), and with materials using Pd as well as several Pd alloys. No LENR was detected.

Magnetic Archaeology: We developed a new type of ultra-fast thermal history detector based on the permanent change, induced in a magnetic material, by the fast thermal pulse from a nearby AHE event. We developed arrays of nanoscale ferromagnetic dots to detect thermal changes in D_2-loaded Pd films. The pre and post experimental state of the targets was measured with nanometric resolution by magnetic force microscopy. No LENR was detected.

Nuclear Detection: We searched for nuclear products in two ways, looking for energetic products emitted during experiments, and for delayed γ-rays generated after them. No LENR was detected.

II : We have concluded that LENRs[101] do not exist

Obviously, this is a belief, not a proven fact. It's very hard to prove a negative, and we haven't done so.

Nonetheless, it's a strong belief, and a conclusion which we're confident in.

Here are the reasons why:

1. **The breadth and quality of our search.**

   Our search has thoroughly covered the three main conditions which seem crucial to enable LENR; loading, stimulation, and material. That search, much of which was performed with the ability to detect even single LENR events, did not find any LENRs.

   Loading: High loading is believed by most of the LENR community to be an essential precondition to allow LENRs to occur. It is also a major challenge to LENR researchers, and continues to be despite 35 years of effort; very few can routinely achieve loadings above 90%.

   In contrast, we can always, *every single time*, reach loadings over 95%. And, using two different methods (cryogenic temperatures, or ultra-high pressure gas) we can reliably reach full, 100%, loading.

   Stimulation: It's not clear whether active stimulation is essential for LENR. Certainly, it is simplest to perform experiments without applying any. We have done so, with 95-100% loading, using both perfect and imperfect PdD lattices, and while using very sensitive detection (passive calorimetry and single-event archaeology). None of these experiments detected LENR.

   Because of this, we have considered active stimulation to be important.

   The simplest form of stimulation, and the most commonly used in the field, is thermal. This presents a plausible mechanism both to commence LENR (increased hopping of deuterons out of their individual octahedral sites) and to propagate the occurrence of LENRs across a target. We have run experiments heated up to the melting temperature; which is the maximum amount of thermal stimulation possible in a PdD lattice. We have also done so, holding at these maximum values, over a wide range of time durations, from nanoseconds to seconds. None of these experiments detected LENR.

[101] To be specific, the flavor of LENR we're talking about here, is a nuclear reaction between two deuterons in a (largely) Palladium lattice, producing virtually all of its 24 MeV reaction energy as heat in the nearby lattice, not as the energetic particles seen in conventional D-D fusion.

We have also used a variety of fundamentally different forms of stimulation; from ultrashort-pulse lasers (producing nonthermal excitation), to plasmon excitation, to resonant terahertz radiation (producing optical phonons), and to intense electrical fields. None of these experiments detected LENR.

Material: It is reasonable (and often suggested) that the proper lattice material might be essential for LENR; either due to its composition or its structure. The extreme case here is perfection, both perfect composition, i.e., pure Pd (or at least 99.999%) and perfect structure (single crystal). We learned how to maintain such perfection even with high loading, but saw no LENR.

While there is only one form of a perfect material, there are near-infinite varieties of imperfect ones. We obviously have not tried them all.

We have performed LENR experiments with Pd nanomaterials, both aerogels and nanoparticles, as well as more structured forms such as nanopillars and nanofilms. There is a belief by some researchers that large numbers of dislocations, or other forms of highly strained material are conducive to LENR. Our Thermal Ignition samples literally tear themselves apart after transient heating; in the process, these undergo a full gamut of intense and chaotic deformations. None of this suite of structural variations resulted in detectable LENR.

There are also a huge number of ways to field impure palladium, depending on the type of impurities and their concentrations. We have only explicitly experimented with a few of these, having made and tested nanofilms using several different Pd alloys. Despite the use of nanofilm archaeology, none of these demonstrated LENRs. It should also be pointed out that the single-event sensitivity of nanofilm archaeology provides a strong implicit test of impurities. Each nanofilm contains over 10^{11} palladium atoms and a 9 pad experiment has 10^{14}; no matter how pure the palladium is, it is virtually guaranteed that every possible impurity exists, and that many of the dual impurity combinations do as well. If the presence of impurity atoms within the palladium lattice causes even a single nearby deuteron-deuteron LENR, the nanofilm will reveal it; none were seen.

Detection: Combining the proper loading, stimulation, and material to manage to generate LENRs appears to be quite difficult; doing so, yet failing to detect them would be extremely regrettable.

Accordingly, we have always emphasized high sensitivity detection. This began with commercial differential calorimeters, and then led to high temperature thermocouples, lithographic RTDs, femtosecond pump-probe detectors, and piezoelectric seismology. This effort culminated with our development of archaeological single-event detectors. None of these detected LENR.

Our inability to detect LENR, despite such an extensive and sensitive search over the LENR landscape, strongly contributes to our belief that LENRs simply do not exist.

2. We strongly doubt that other researchers have actually detected LENR

- If other researchers did see LENRs, we would have also.

  Over the past 35 years, many researchers have reported detecting LENRs. Most of these experiments were based on electrolytic loading, not our high-pressure gas loading approach.

  We have not tried to replicate such electrolytic experiments (in multiple cases, the Callisto electrochemical loading project *has* attempted to), and can certainly not *prove* that they failed, nor offer informed commentary as to why they might have failed.

  Nonetheless, we believe they did fail; for the reason given above: If they had seen LENR, we should have also.

  The reason for this, is that their work takes place in the same physical environment (specified by loading, stimulation, material) that we have explored. And, for the most part, they are in "vanilla" portions of this parameter space; ones that our search has *very* thoroughly covered.

  Loading: While many LENR reports claim that high loading is important, none of them involve loadings as high as we reach!

  Stimulation: Many LENR reports were from experiments with no active stimulation; just that inherent at normal temperatures (< 100^{o}C), or in the course of electrolysis. Of the active stimulations that have led to reports of LENR, most were one or another form of heating. However, once well above picosecond timescales, all forms of thermal stimulation are fundamentally the same. We have thoroughly covered this landscape, and to the maximum intensity possible!

  There are some reports of LENR in which specialized types of stimulation were used (e.g., terahertz beat frequencies, charged particle impacts, deuterium fluxes) but none of these were involved in the pioneering and primary reports which the LENR field is based on.

  Material: The primary LENR reports use the same basic material that we have, high purity palladium. In terms of structure, there is no consensus as to what form is needed, reports of what "works" are all over the map. However, the given recipes are all global ones (e.g., grain sizes, annealing conditions, surface roughness, nanometric crevices); the local structures are uncontrolled and stochastic. While details of local structures are bound to be unique, all of these types of structural deformations have occurred in our experiments.

LENR, if it exists, is not "hiding". The parameter spaces in which it has been reported to exist are well within those which we have covered. The fact that we have not seen LENR there, is another reason casting doubt on its existence.

- Another reason for doubt, is the failure of the direct replication experiments that we have performed.

  Rather than merely searching in the same basic parameter space as other researchers, we have, in a few cases, tried to search with the identical conditions. This has not been our primary focus, both because relatively few of the LENR reports have utilized gas loading, and because none of these "successful" experiments have been in our high-pressure, high-loading regime. But, as discussed previously in this report, we have tried to replicate two well-known results; low-pressure gas loading experiments by Case and by Arata. In neither case did we see signs of LENR, as they had reported.

  We also attempted to understand the high-energy event seen in the 1989 LLNL experiment. This was an ambient pressure electrolytic experiment, and hence Callisto electrochemical loading has been leading efforts to detect LENR during replication attempts. Our focus was different; we were interested to learn if the experiment could be "mistreated" in ways so as to produce results similar to those originally seen. We found that there were indeed excitation conditions which could produce qualitatively similar behavior (due to its preliminary nature, no quantitative data was obtained in 1989). Whether or not the 1989 behavior resulted from similar mistreatment is, unfortunately, probably unknowable.

- There are no reliable, reproducible, LENR experiments.

  This is clear; if anyone could make LENR succeed, on-demand, the "debate" would be over!

  The fact that, after almost 35 years of research, the sporadic reports of successful LENR are only that, and have not led to reproducible results, is hard to ignore.

3. **We don't theoretically understand how LENRs can occur**

   On the face of it, two aspects of LENRs are implausible; how two deuterons can cross the coulomb barrier between them and get close enough to undergo a nuclear reaction, and, if they do, why the reaction products are just heat and He^4, not the energetic particles produced from conventional deuterium fusion.

   These are not new concerns; they have been major issues since the initial announcement of LENR in 1989. The seeming impossibility of either or both of these results has always been one of the main reasons why LENR research was shunned by the mainstream physics community.

Obviously, we (both our sponsor and the Callisto researchers) were well aware of this problem when we commenced work on Callisto. However, there were (and always have been) a variety of theoretical suggestions as to how these things could take place. And, more fundamentally, there's the fact that in science, experiments trump theory!

However, as time has gone by, our experiments have shown no indication of LENR. Nor have the various approaches proposed to explain LENRs advanced beyond the conceptual stage to become fully developed theories, let alone compelling ones.

Accordingly, this lack of an understandable mechanism continues to nag, and remains a significant reason for us to doubt the existence of LENRs.

Why might our conclusion rejecting LENR be wrong?

We've explained why we do not believe that LENRs exist. However, we've certainly not *proven* this to be the case; our belief might be wrong. Here are some possible reasons why:

Other researchers do claim to have seen LENR: If any of them are correct, our conclusion is clearly wrong!

The burden of proof required for them to demonstrate LENR is not particularly onerous, just deliver convincing and *reproducible* experimental results! To date, 35 years in, no one has managed to do so.

Our search is incomplete: We've searched a very wide swath of the loading, stimulation, and material parameter space underlying LENR. However, we haven't searched it all. In particular, while we've reached a wide range of individual loading, stimulation, and material conditions, we haven't satisfied all the simultaneous combinations of these. So, there are portions of parameter space which we haven't explored; it is certainly possible that LENRs only exist in one of these regions.

We consider our search over loading and over stimulation conditions to be definitive.

No higher loading has been, or can be, achieved; our search here is complete.

There are certainly different types of stimulation that can be tried: But, the most common type, thermal stimulation has been fully explored; different implementation details may be tried, but these won't change the fundamental thermal effects. There are still types of nonthermal stimulation which we have not explored, but we don't consider those we know of to be significant; some we don't believe to be physically effective, while others aren't relevant to LENR.

It's our search over materials that is the least complete. While we have experimented with perfect materials, and many types of imperfect ones, there are certainly many other instances of imperfect materials which we have not investigated.

We doubt that these will lead to LENR, but certainly cannot prove this.

LENR may require a "magic" material: One explanation for why, despite our broad search over parameter space, we might not have seen LENR, is that a "magic" material (in composition and/or structure) is required.

This could explain why some researchers are actually correct in claiming to have seen LENR. Given imperfect knowledge of, and control over, microscopic material properties (a particular issue in electrolytic experiments) this could also explain the irreproducibility of LENR results, even in experiments performed by the same researcher and conditions. I.e., sometimes, the proper material exists, and LENR occurs, but usually it does not.

However, why a special form of PdD would be essential, and how it would lead to LENR, is, to be diplomatic, unknown.

That one is required is certainly a possibility, and impossible to discount. But, meaningful support for this proposition will only come if someone actually proffers up such a material.

Electrolysis might be special: Most of Callisto's research has been based on loading palladium via high pressure D_2 gas. In contrast, most of the outside LENR research (and particularly the early pioneering work that initiated the field), uses D_2O electrolysis to load deuterium into palladium. It's possible that there is something fundamentally different in these two processes; LENR may only be possible for electrolysis, and never for gas loading.

If LENRs occur within the interior of the PdD lattice, the difference between gas and electrolytic loading shouldn't matter; the local deuterium ions only "know" their local environment. However, it is possible that LENRs are a purely surface phenomena, occurring only within the first few layers of the lattice. If this is so, then electrolytic loading is fundamentally different from gas loading, and this may well explain why none of our gas-based experiments have detected LENR.

A note, however; Callisto has performed a series of high-pressure electrolytically loaded LENR experiments. These have achieved very high and stable loadings (~ 98%), yet have failed to detect LENR. (And, of course, our sister program, Callisto electrochemical loading, is exclusively focused upon electrolytic loading; they will report on these separately.)

Nanofilms may not work: While nanofilm archaeology is just one of our approaches to detection of LENR, it is our most sensitive one. The fact that it provides the ability to detect even single LENR events, and can be utilized in a broad range of different LENR experiments, has naturally made the failure to detect LENR in any of its applications a very significant component of our belief that LENR does not occur.

This naturally leads to a question; is there any systematic flaw in nanofilm archaeology which makes this an invalid diagnostic tool? Here are two possibilities which could:

We have focused on "heat – helium" LENRs, defining them as deuterium-deuterium reactions in which 24 MeV of reaction energy is transferred as heat to the nearby palladium lattice. However, note that if LENR energy appeared as energetic particles (as in a conventional deuterium-deuterium reaction), these would escape from the thin nanofilms, depositing only a trivial amount of energy in them; nanopillars would not break, and nanofilms would not develop holes. Alternatively, if the reaction energy does indeed appear only as lattice vibrations, but is inherently spread over huge ranges (e.g., thousands of lattice spacings) then it would be too diffuse to damage nanofilms or nanopillars; archaeology would not work.

Another concern would be if the lattice of a nanopillar or nanofilm simply can't support LENRs. For instance, if LENR involves some form of collective behavior, nanostructures may be too thin or have too few atoms to allow LENRs to occur. More conventionally, the palladium lattices of these nanostructures may be too deformed or disordered to host LENRs. Since no one actually knows how LENRs work, neither of these concerns can be dismissed out of hand.

We may have been looking for the wrong type of LENRs: We have focused our search on a specific form of LENRs; the reaction of two deuterons in a palladium lattice, producing heat and He^4. If LENRs instead involve a different reaction, then our search has been misdirected, and may well miss seeing them.

Several possible scenarios illustrate the problems. Obviously, if neither palladium or deuterium are involved, our search would fail. But, involvement of protium as a reactant would also be problematic, since we often use H_2 experiments as a null control.

Even if the LENR reaction involves two deuterons in palladium, it might work fundamentally differently than what we've been assuming. We've mentioned, for instance, the fact that reaction energy will not be retained in thin structures if the energy is delivered as energetic particles; this would affect not just nanofilms and nanopillars, but also magnetothermal detectors or chip-based systems.

Another issue, would be if LENR generation required some form of collective quantum interaction (e.g., Bose-Einstein condensation). Such suggestions have certainly been made in the past, and if correct, would probably require considerably different experimental conditions than we've been using. However, beyond qualitative suggestions, there is no developed theory or experimental evidence supporting this possibility; certainly, none of our cryogenic experiments detected LENRs.