Chapter 1

Introduction

1.1 The Climate Crisis

The climate crisis refers to the significant changes in global climate patterns, primarily attributed to human activities, particularly the emission of greenhouse gases (GHGs). These changes have led to global warming, extreme weather events, and disruptions in natural ecosystems.

Before the industrial revolution (circa 1750), the average global temperature was relatively stable, with pre-industrial atmospheric CO_2 levels at approximately 280 parts per million (ppm) [1]. As of 2023, CO_2 levels have surpassed 420 ppm, indicating a significant increase due to human activities [2]. In addition to CO_2, methane, nitrous oxide, and various fluorinated gases are critical GHGs that contribute to the climate crisis. Each of these gases has a higher global warming potential than CO_2, making their management essential in efforts to mitigate climate change [3–5].

The consequences of the climate crisis are dire, including substantial economic damage, costs to human life, and destruction of infrastructure and the environment. Over the past 50 years, extreme weather events have caused over two million deaths and resulted in approximately $4.3 trillion in economic losses globally [6–9]. The economic damage from climate-related disasters has grown substantially in recent years, with losses increasing from $184 billion in the 1970s to nearly $1.5 trillion in the decade leading up to 2019 [8]. Human deaths related to extreme weather have also risen dramatically [7]. The climate crisis is an urgent, global-scale emergency. Humanity must act decisively and cohesively.

1.1.1 Global Emissions Contributors

Accurate information about GHG emissions is crucial to identify technical, legislative, and cultural opportunities for change. The top contributors to global GHG emissions span both the developed and developing world, including China (27 %), the United States (11 %), India (6.6 %), the European Union (6.4 %), Russia (4.8 %), Japan (3.1 %), Brazil (2.9 %), Indonesia (2.3 %), Iran (2.1 %), and Canada (1.6 %) [10]. These countries are responsible for a substantial portion of global emissions, driven by their industrial activities, energy consumption, and transportation sectors.

As the quality of life improves in developing countries, factors such as economic development, increased energy consumption, industrial activity, and transportation will influence their GHG emissions. Rapid urbanization can lead to higher energy demand for housing, infrastructure, and services. Changes in agricultural practices and increased food production also contribute to emissions.

Despite a negative forecast, developing countries have significant potential to leapfrog to renewable energy technologies, bypassing the fossil fuel-intensive development pathways of the past. Improvements in energy efficiency in buildings, industry, and transportation can help reduce emissions. Adopting sustainable agricultural practices can also reduce emissions. Financial and technological support from developed countries is crucial in helping developing countries transition to low-carbon economies. It is imperative that we improve the quality of life for more humans while adopting improved energy strategies.

1.1.2 Legislative Action

Global legislative action is one of the critical facets to addressing the climate crisis. However, it was only recently that international efforts to curb the climate crisis have gained momentum. The scientific community first flagged the detriment of increased CO_2 levels well over 100 years ago. In 1896, the noted scientist Svante Arrhenius published a paper 'On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground' [11]. He predicted that doubling the atmospheric CO_2 concentration would result in a 5 to 6°C increase in global temperatures, remarkably close to modern predictions of 2.5 to 4°C given the limited and incomplete data available at the time. This warning was largely ignored until the mid-twentieth century when researchers started to track increasing GHGs. Even still, it would be decades before any notable government action.

The establishment of the Intergovernmental Panel on Climate Change (IPCC) in the late 1980s marked a turning point, providing scientific assessments on climate change and strategies for adaptation and mitigation [12]. The United Nations Framework Convention on Climate Change (UNFCCC), established in 1992, aimed to combat 'dangerous human interference with the climate system' [13]. The Kyoto Protocol (1997) set binding emission reduction targets for developed countries, although notable exceptions included the United States and Canada [14]. The Paris Agreement (2015) was a landmark international treaty where 196 countries committed to limit global warming to well below 2°C compared to pre-industrial levels [15]. Annual Conferences of the Parties (COP), such as COP26 in Glasgow (2021) and COP27 in Sharm El-Sheikh (2022), review progress and negotiate further actions [16]. The Green Climate Fund (GCF) assists developing countries in adaptation and mitigation practices to counter climate change [17].

As of today, 128 years after the first alarm was raised, the global conversation has finally reached a critical point. With increased momentum and progress made on both the legislative and technological fronts, humanity can now say we are taking the climate crisis seriously. Investments in renewable energy sources such as wind, solar, and hydroelectric power have increased, with renewables accounting for about 29 % of global electricity generation as of 2023 [18]. Improvements in energy efficiency across various sectors, including transportation, industry, and residential buildings, have also contributed to emission reductions. Efforts to reduce deforestation and promote reforestation and afforestation, such as the REDD+ program, aim to incentivize forest conservation [19]. Technological innovations in carbon capture and storage (CCS), electric vehicles (EVs), and sustainable agricultural practices are also making a difference. Policy and legislation, including carbon pricing, emissions trading systems, and subsidies for clean energy technologies, are crucial in driving these changes.

Despite these efforts, the pace of change must continue to accelerate to meet the targets set by international agreements and to mitigate the most severe impacts of climate change. Legislation alone will not be enough; new technologies must be deployed.

1.1.3 Industrial Sectors for Innovation

GHG emissions are primarily driven by human infrastructure, energy technologies, and industrial processes. Coal-fired power plants are one of the largest sources of CO_2 emissions globally due to the high carbon content of coal and its widespread use. Internal combustion engine vehicles, powered by gasoline and diesel engines, emit large amounts of CO_2 and other GHGs, with transportation accounting for about 24% of global CO_2 emissions [20]. Natural gas power plants, while cleaner than coal, still produce substantial CO_2 emissions and are a major source of electricity and heating [21].

The collective 'heavy industries,' are another industrial sector ripe for innovation. The chemical process of producing cement releases substantial CO_2, accounting for approximately 8 % of global CO_2 emissions. Steel production involves the reduction of iron ore using carbon, typically in the form of coke, releasing vast amounts of CO_2, and is responsible for about 7-9 % of global emissions [22]. Agricultural practices, including livestock digestion (methane emissions), rice paddies (methane), and soil management practices (nitrous oxide), contribute around 10-12 % of global GHG emissions [23].

Deforestation and land use change, such as clearing forests for agriculture or development, release stored carbon and reduce the planet's capacity to absorb CO_2, contributing about 11% of global GHG emissions [24]. The extraction, refining, and transportation of oil and gas release methane and CO_2, making the oil and gas sector a significant source of methane emissions. Residential and commercial heating, which involves the burning of fossil fuels for heating buildings, also releases GHGs. Waste management practices, including landfills that produce methane as organic waste decomposes anaerobically and incineration of waste, contribute around 3 to 5 % of global GHG emissions [25].

1.1.4 Conclusion

Addressing emissions from these sources involves a combination of technological innovation, policy measures, and changes in consumption patterns. Efforts such as transitioning to renewable energy, improving energy efficiency, adopting sustainable agricultural practices, and enhancing waste management can significantly reduce GHG emissions and mitigate the impacts of climate change. The more our global energy infrastructure (production, distribution, point-of-use, and remediation) depends on renewables and low carbon sources of fuel, the more effective the climate crisis mitigation will be.

1.2 A Brief History of LENR

Cold fusion, a type of nuclear reaction purported to occur at or near room temperature, gained worldwide attention on March 23, 1989, when electrochemists Martin Fleischmann and Stanley Pons announced they had achieved nuclear fusion during an experiment involving electrolysis of lithiated heavy water using a palladium cathode [26]. This announcement sparked widespread excitement and media frenzy due to the potential for a new, clean, and virtually limitless energy source. However, as more scientists attempted to replicate the experiment, many failed to observe the same results, leading to growing skepticism.

The methodology and results of Fleischmann and Pons were heavily scrutinized, and a 1989 U.S. Department of Energy (DOE) panel concluded that the evidence was not convincing, recommending against further funding [27]. In the review conducted by the Energy Research Advisory Board (ERAB), reviewers identified several critical issues with the cold fusion experiments conducted by Fleischmann and Pons. Many laboratories worldwide attempted to replicate the reported results but failed to observe excess heat or fusion products, raising questions about the reliability of the original experiments. Fleischmann and Pons provided limited and inadequate experimental details in their publications, complicating replication efforts. The calorimetric methods used to measure excess heat were criticized for potential errors. Issues such as improper insulation, inaccurate temperature measurements, and heat loss to the surroundings could have led to erroneous conclusions about excess heat generation. The expected nuclear byproducts of fusion, such as neutrons, tritium, and helium-4, were either not detected or observed at levels far below those necessary to account for the reported excess heat. This discrepancy undermined the hypothesis that nuclear fusion was occurring.

In Morrison's 1991 review, he categorized cold fusion as 'pathological science' where initial positive results are not reproducible, leading to a polarized scientific community of 'believers' and 'skeptics.' Morrison concluded that based on overwhelming experimental and theoretical evidence, cold fusion as initially proposed by Fleischmann and Pons cannot exist [28]. By the early 1990s, cold fusion was largely dismissed by mainstream science and became associated with pseudoscience.

Despite the controversy surrounding cold fusion, several major efforts continued to research the rebranded field of Low Energy Nuclear Reactions (LENR) during the 1990s and 2000s. After their initial announcement, Fleischmann and Pons moved their research to France, funded by the Toyota Corporation through the IMRA laboratory in Nice. At their new laboratory, they were unable to produce conclusive results [29]. Japan also invested in LENR research through the New Hydrogen Energy (NHE) program, which aimed to replicate and understand the cold fusion phenomenon but ultimately also did not achieve definitive results [30]. In the 2000s, Energetics Technologies, an Israeli company, claimed to have observed excess heat production in their experiments; however, serious accusations against overclaiming to funders cast seeds of suspicion [31]. Researchers at SPAWAR in San Diego reported evidence of nuclear reactions, such as the detection of energetic particles and transmutation products [32]. Researchers at the Italian National Institute for Nuclear Physics (INFN) continued to investigate LENR, in some cases reporting excess heat and other anomalous effects [33]. Researchers at MIT worked on largely theoretical models [34]. Andrea Rossi, an Italian inventor, claimed to have developed a device called the E-Cat that produced excess heat through LENR, attracting investment from Industrial Heat [35]. However, Andrea Rossi's work on the E-Cat has been highly controversial due to a combination of scientific skepticism, legal disputes, and his troubled history with the Petroldragon scandal.

The DOE revisited the topic of cold fusion in 2004, prompted by continued interest and new experimental data from the LENR community [36]. This review reiterated many of the criticisms from the 1989 review. Despite advances in experimental techniques, reproducibility remained a significant challenge. Most experiments still failed to consistently produce the claimed levels of excess heat or fusion byproducts. Ultimately, reviewers found no compelling evidence to support cold fusion. The 2004 review emphasized the need for rigorous, well-documented experiments with clear and reproducible results.

The 2004 review suggested focusing on the material science aspects of deuterated metals and utilizing modern characterization techniques to better understand the conditions under which anomalous effects might occur. It recommended limited, targeted funding for well-designed studies that could clarify these issues. Otherwise, they recommended the US government should not put more funding into LENR research. Among the research efforts that would emerge in the decade following this second DOE review, Google Research is perhaps the most notable.

The 2019 Google-funded review article 'Revisiting the cold case of cold fusion,' published in Nature, critically examined cold fusion claims with rigorous scientific methods [37]. Despite extensive efforts, the researchers did not find evidence supporting the claimed anomalous effects of cold fusion. They highlighted the persistent issue of reproducibility and the technical challenges in achieving the necessary conditions for cold fusion, such as high hydrogen loading in metals like palladium. The review emphasized that while cold fusion itself remains unproven, studying the related phenomena could benefit other scientific areas, including hydrogen-metal interactions relevant to energy storage and catalysis. Their approach advocated continued skepticism but encouraged further exploration of the field's potential scientific value. The Google efforts resulted in a number of peer-reviewed articles in notable archival journals, highlighting their advances in calorimetry under extreme conditions, understanding hydrogen loading in metal hydrides, and investigating the effects of electron screening on increasing conventional fusion yields from low-energy (few keV) deuteron bombardment [38–40, 40–48]. The researchers emphasized the importance of continued open-minded and rigorous scientific inquiry into unconventional energy sources.

Perhaps due to the changing of the guard within government institutions, or perhaps due to the first quality work on LENR performed in decades, the government has become increasingly interested in approaching LENR. In 2016, the U.S. Defense Intelligence Agency (DIA) released a report titled 'Technological Forecast: Worldwide Research on Low-Energy Nuclear Reactions Increasing and Gaining Acceptance,' which highlighted ongoing international research in LENR and suggested that the U.S. should monitor developments in this area [49]. In 2019, the U.S. Senate Armed Services Committee included language in the National Defense Authorization Act (NDAA) encouraging the Department of Defense to explore LENR as a potential energy source, marking a significant shift in the official stance towards LENR research [50]. NASA has also shown intermittent interest, with researchers at NASA's Langley Research Center exploring LENR as a possible energy source for long-duration space missions [51]. Outside of the U.S., the European Union has funded LENR research through projects like the 'Clean Energy from Hydrogen-Metal Systems' (CEHMS) under the Horizon 2020 program, which aimed to investigate LENR for clean energy production [52]. The recent inclusion of LENR in government research agendas and funding programs indicates a softening of previous skepticism and a renewed openness to exploring its potential.

In 2023, the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) announced a $10 million funding initiative for eight projects focused on LENR [53]. This initiative represents a significant shift from previous policy. The ARPA-E funding aims to apply rigorous scientific scrutiny and advanced methodologies to investigate LENR, emphasizing neutron, gamma, and ion emissions in experimental setups. The emphasis on nuclear product detection marks an important shift from the previous focus on calorimetric evidence. Nuclear products are unambiguous, whereas excess heat can be generated from various non-nuclear mechanisms.

With this history in mind, can the scientific community provide robust, reproducible evidence for LENR? To answer this question, Callisto Electrochemical Research ("Callisto") assembled an interdisciplinary team of physicists, chemists, materials scientists, mechanical engineers, electrical engineers, software engineers, and technicians. We committed to high standards of practice and peer review.

This document details our investigations into LENR, which took place between 2017 and 2024. Alongside detailed descriptions of our hardware, software, experimental protocols, and data analysis, we provide constructive criticism of the field and ultimately offer recommendations to future researchers. For those studying LENR with scientific rigor, excess heat appears to have been a red herring. The real opportunities may lie in the exotic bulk and surface properties of metal hydrides, with emergent applications in energy storage and catalysis.

1.3 Purported Conditions and Signals

The claims surrounding LENR suggest that nuclear fusion reactions with useful energy outputs can occur at or near room temperature, which contradicts the well-established understanding that nuclear fusion requires extremely high temperatures and pressures. Conventional fusion (or hot fusion) of hydrogen isotopes occurs naturally in the cores of stars where intense gravitational pressures and temperatures around 15 million degrees Celsius create the necessary conditions for the reaction. These extreme pressures and high temperatures allow the positively charged nuclei to overcome the Coulomb barrier, enabling fusion via the strong nuclear force [54]. The reaction energy for deuterium-deuterium (D-D) fusion is around 4 MeV, while deuterium-tritium (D-T) fusion, which is more commonly pursued in experimental fusion reactors owing to its larger reaction cross section, releases about 17.6 MeV [55]. On Earth, achieving a controlled fusion reactor requires synthetic approaches since replicating the extreme gravitational pressures of stellar environments is not feasible. Instead, magnetic or inertial confinement methods are used to create the necessary conditions for fusion, typically at temperatures around 100 million degrees Celsius [56]. These confinement techniques maintain the required plasma density and temperature to provide the kinetic energy necessary for the fusion process. It is somewhat unimaginable that such conditions could be met near ambient conditions.

Despite contradicting classical physics, there are several criteria and signatures that consistently emerge in reports claiming to observe LENR. These commonalities can be categorized into metal hydride formation, stimulation conditions, and thermal and nuclear signatures.

1.3.1 Metal Hydride Formation (Loading)

The premise of LENR lies in the idea that a metal lattice can catalyze the fusion of deuterium atoms, by coordinating their proximity and approach, while simultaneously screening the nuclear barrier. The effect is claimed to occur at or near room temperature, and has been postulated by some to be a collective effect mediated by the lattice. The most studied and reported material used to produce LENR is palladium deuteride, although other metal hydrogen systems like nickel hydride have been reported [57, 58]. In most claimed positive cases, metallic palladium is converted to palladium deuteride using electrolysis of heavy water, although some gas-phase studies are reported as well [59, 60]. Often, a simple electrolytic cell containing a palladium cathode, a platinum counter electrode, and alkaline electrolyte such as LiOD is used to convert the metal into a metal deuteride lattice.

The electrolytic loading of a palladium deuteride cathode is determined by the reaction kinetics of the Hydrogen Evolution Reaction (HER). HER comprises sub-reactions of water splitting and recombination. During alkaline electrolysis, heavy water (D_2O) is split according to the Volmer reaction (Eq. 1.1) and diffuses into the bulk palladium lattice according to the intercalation reaction (Eq. 1.2). In addition to intercalation, deuterium may leave the surface of the palladium through either the Tafel reaction (Eq. 1.3) or the Heyrovsky reaction (Eq. 1.4). For a given set of electrochemical conditions, temperature, and pressure, reactions 1.3 and 1.4 ultimately limit the mass loading of the metal deuteride that is formed.

$$\text{Volmer:} \quad D_2O + 2e^- + 2Pd_{\text{surface}} \rightarrow 2Pd_{\text{surface}}D_{\text{surface}} + 2OD^- \tag{1.1}$$

$$\text{Intercalation:} \quad 2Pd_{\text{surface}}D_{\text{surface}} \leftrightarrow 2Pd_{\text{bulk}}D_{\text{bulk}} \tag{1.2}$$

$$\text{Tafel:} \quad 2Pd_{\text{surface}}D_{\text{surface}} \rightarrow 2Pd_{\text{surface}} + D_{2(g)} \tag{1.3}$$

$$\text{Heyrovsky:} \quad D_2O + Pd_{\text{surface}}D_{\text{surface}} + e^- \rightarrow Pd_{\text{surface}} + OD^- + D_{2(g)} \tag{1.4}$$

In later chapters, we will go into detail about how the Tafel reaction can be suppressed with so-called Tafel poisons, dramatically increasing the fractional deuterium loading beyond what is achievable under standard conditions. In addition to Tafel poisons, ultrahigh pressures can be used to achieve a similar effect, although these methodologies are not covered in this report. This was an intense topic of investigation for our companion high-pressure research group, whose report was submitted separately.

The LENR community mostly agrees that the higher the fractional loading, the higher the probability of fusion. Some researchers, McKubre for example, go so far as to claim there is a threshold near 90% D/Pd which must be obtained before LENR is observed [57].

However, after many attempted studies and replications of positive results, the following belief is generally held by the LENR community: Loading may be necessary but it is not sufficient, i.e., a highly loaded palladium deuteride lattice will not spontaneously result in LENR. This is where the premise of stimulation, the second purported requirement comes into play.

1.3.2 Stimulation Conditions

Stimulation refers to the input of energy into the palladium deuteride system in order to increase the fusion cross-section of the lattice bound deuterons. Although there are theories which try to explain how stimulations might result in LENR, the truth is that given the lack of evidence, there are no solid connections between theory and experiment at this time.

Various forms of stimulation have been studied, including high electrolysis currents, high frequency electrochemical potentials, laser stimulation, THz stimulation, magnetic field stimulation, electric field stimulation, and mechanical stimulation [26, 61–66].

One thread to track throughout this report is how any given stimulation can impact potential thermal and nuclear signatures, and ultimately how essentially all claims of excess heat could be attributed to classically explained phenomena. Without any substantial motivation from known physical theories as to how stimulation might actually trigger LENR, we will leave this commentary on stimulation brief.

1.3.3 Thermal and Nuclear Signatures

The primary criteria and observations claimed for LENR include the production of excess heat that cannot be explained by chemical reactions alone, the detection of helium as a byproduct indicative of nuclear reactions, and claims of elemental transmutation where one element is purportedly converted into another. Unlike traditional nuclear reactions, LENR is claimed to produce minimal or no harmful radiation; although Fleischmann and Pons originally claimed radiation products, they later retracted these observations for insufficient evidence.

These signatures require detection schemes, a major topic of investigation for Callisto. While there is limited theoretical understanding of LENR, experiments have been designed around assumed reaction pathways and relevant detections selected. The two primary reaction pathways suggested are coalescence and transmutation reactions. The former postulates that two deuterium atoms coalesce to form helium-4 and a cascade of phonons with an energy totaling 24 MeV. The latter speculates that the metal lattice transmutes along more traditional pathways with reaction energies on the order of 1 to 100 keV.

Regardless of the claimed reaction pathway, the majority of claimed positive results report excess heat detected using some form of calorimeter. The function of a calorimeter is to create an environment with well-defined heat transfer and measure the energy going into and out of that environment. By accounting for all of the various electrical and chemical energy going into and out of an LENR experiment, one can calculate any apparent excess heat. When the excess heat is greater than zero, researchers have claimed to observe LENR. In section 9.2, we will outline how these claimed results are likely to be erroneous interpretations or incomplete understanding of input energies.

Helium-4 is thought to form as a product of deuterium fusion inside a palladium lattice. Several researchers have reported Helium-4 above background levels [67]. However, helium detection requires very high precision mass-spectrometry, and is fundamentally challenging due to the small mass difference between deuterium gas and helium-4 (Δm = 0.0256 amu = 4.249×10^{-29} kg). While modern equipment is capable of resolving near-equimolar concentrations of deuterium gas and helium-4 (verified by Callisto), without filtration and reaction product concentration techniques, measuring ppb to ppm concentrations of helium-4 in deuterium gas is incredibly challenging.

Finally, some have speculated that LENR results in the transmutation of the metal lattice itself, which can be measured using isotopic analysis. There are several methods for measuring the atomic composition of the metal lattice (energy dispersive spectroscopy, X-ray photoelectron spectroscopy, secondary ion mass spectrometry), however, very few methods offer low detection limits on the order of ppm. One concern over measuring changes to the chemical makeup of a metal cathode is how dirty electrochemical environments can be. Callisto found it incredibly challenging to maintain a highly pure electrochemical environment, even when ultrahigh purity materials were used. Degradation of the electrolyte, corrosion of cell components, dissolution of the counter electrode, among other reactions, can result in contamination build-up on the palladium cathode. The inherent dirtying of the cathode due to electrolysis obfuscates the ability to cleanly track chemical changes to the cathode. Isotopic changes are more easily tracked in gas-phase experiments, although those are not considered in this report.

In summary, high fractional deuterium loadings alongside some form of stimulation are generally claimed to be required to realize LENR. Due to the lack of fundamental understanding of the reaction itself, different detection schemes are required in order to verify a non-classical phenomenon.

1.4 Notable Research Efforts

It should be emphasized that despite the claims among LENR researchers, there has never been incontrovertible proof that LENR is a real, reproducible physical phenomenon. Modern scientific and peer-review standards for a positive result have never been met, in our view. Ultimately, over-claiming, misinterpretation, and in some cases subterfuge, are directly responsible for the stigma and taboo around LENR.

Emphasizing the aforementioned disclaimer, there are exemplary experiments and vocal researchers in the literature which we will highlight. The point in highlighting these experiments will be to illustrate the experimental concepts, datasets, and interpretations that are commonplace. We have limited the extent of our criticism in this section, rather striving to objectively report what the authors have claimed.

In a later chapter, we will highlight the manners in which researchers can produce a false positive. It is Callisto's current belief, based on years of our own research and attempts at replications, that every example of a claimed positive result was most likely due to either incomplete understanding of an experimental apparatus, incorrect data interpretation, cherry-picking of data, or in the worst case, deception. The experiments overviewed will be limited in scope to experiments using electrolysis to form palladium deuteride. Gas-phase experiments are excluded from this overview, although our review of the literature suggests that those experiments were similarly susceptible to false positive results, and the various claims of positive excess heat appear highly suspect.

1.4.1 Fleischmann and Pons

In their controversial 1989 paper titled 'Electrochemically Induced Nuclear Fusion of Deuterium', Martin Fleischmann and Stanley Pons investigated the behavior of palladium electrodes during electrolysis of heavy water [68]. Using palladium electrodes (cathodes) of various shapes and sizes, they intercalated deuterium into the metal lattice from a concentrated LiOD solution. The electrodes were placed in Dewar cells to maintain a controlled temperature environment. Large platinum counter-electrodes surrounded the palladium electrodes, and temperatures were monitored with Beckmann thermometers and calibrated thermistors. They reported significant excess enthalpy generation at high current densities, with the observed excess heat reaching up to $10\,W/cm^3$. Additionally, neutron and gamma-ray emissions were claimed, with neutron flux measured at approximately $4{\cdot}10^4$ neutrons per second and gamma-ray spectra suggesting the presence of 2.45 MeV neutrons, which they interpreted as indicative of nuclear fusion reactions. These radiation products were later retracted for lack of compelling evidence.

Following their preliminary findings in 1989, Fleischmann and Pons improved their calorimetric techniques and conducted more detailed experiments. In their 1990 publication, "Calorimetry of the Palladium Deuterium Heavy Water System" they described experiments using Dewar-type calorimeter cells [69]. These calorimeters were designed for uniform heat distribution and effective mixing. Both low and high current density experiments were conducted, with resistance heaters used to calibrate the heat transfer coefficients of the calorimeters. The authors claimed significant excess heat generation, particularly during 'burst' events, defined as short periods where the rate of excess enthalpy generation increased dramatically and unpredictably, often exceeding the energy input by factors up to 40. The magnitude of the observed excess heat led them to hypothesize that non-chemical processes were at play, as the total specific energy output during bursts could reach 50 MJ/cm^3, which is far above what can be attributed to chemical reactions.

In their 1993 study 'Calorimetry of the Pd D_2O System: From Simplicity via Complications to Simplicity' Fleischmann and Pons examined high rates of excess enthalpy generation [70]. They employed a method involving the measurement of time required to boil the cells to dryness, monitored through time-lapse video recordings. The experiments used single-compartment vacuum Dewar open calorimeter cells with a silvered top portion to control heat transfer by radiation. They observed increased generation of excess enthalpy over time, especially near the boiling point of the electrolyte solution. They noted a feedback mechanism where increased temperature led to higher rates of excess enthalpy generation, with some experiments achieving specific rates of enthalpy generation above 1 kW/cm^3.

After the 1993 study, Martin Fleischmann and Stanley Pons continued their research on LENR, albeit with varying degrees of public and scientific support. Fleischmann moved to France with Pons to continue their work at the IMRA laboratory, a part of the Technova Corporation (a subsidiary of Toyota). However, their efforts did not lead to conclusive results, and the laboratory closed in 1998 after significant investment without achieving the desired breakthroughs.

1.4.2 McKubre

Michael C. H. McKubre, a principal scientist at SRI International in Menlo Park, California, extensively researched LENR. McKubre's primary goals were achieving reproducibility, attaining high deuterium loadings in palladium, performing high-quality calorimetry, and exploring various stimulation methods. Colloquially, he established the 'McKubre Threshold', a widely held belief that achieving a high atomic ratio of deuterium to palladium (D/Pd) above 0.85 was crucial for observing the excess heat [71]. He utilized calorimetric techniques to measure excess heat, aiming to attribute heat production to nuclear reactions rather than experimental artifacts. McKubre also explored methods such as electrochemical and gas loading, laser stimulation, and varying current densities and fluxes [72, 73].

Beyond calorimetry, McKubre was known for collaborating with others in the LENR community, evaluating other detection methods to identify and quantify nuclear reaction products. These included mass spectrometry for detecting helium isotopes (^3He and ^4He), tritium, and other nuclear products; nuclear track detectors (CR-39) for energetic charged particles; neutron and gamma-ray detectors for potential emissions; and isotopic analysis for detecting transmutation products. Notably, McKubre claimed that excess heat production correlated strongly with helium production, similar to the observations of Melvin Miles.

McKubre claimed that excess heat production in Pd/D systems, often correlated with high deuterium loading and specific conditions, could not be explained by chemical reactions or known physical processes. However, consistent reproducibility remained a challenge, influenced by material purity, experimental setup, and loading conditions. Over time, SRI funding being directed towards LENR declined and eventually petered out in the 2010s [74].

Callisto has replicated many of the McKubre protocols, which will be described in full detail in section 7.2.

1.4.3 Storms

Edmund Storms is another vocal LENR researcher, primarily known for his experimental, theoretical, and analytical methods [73,75–79]. One significant aspect of his work is the use of a Seebeck calorimeter, which converts a temperature difference into an electrical voltage through the Seebeck effect. This calorimeter features a thermal envelope that surrounds the heat source and thermoelectric (Seebeck) modules that generate voltage proportional to the heat flow. It is calibrated using known heat sources and is highly sensitive, capable of detecting excess power down to the milliwatt range. The calorimeter design ensures uniform heat flow capture and minimizes errors due to heat distribution and temperature fluctuations.

Storms claims that his experiments have produced significant amounts of excess energy that cannot be explained by conventional chemical reactions. In his reports, Storms discusses the challenges of achieving reproducible results and the importance of the nuclear-active environment for initiating LENR. His work emphasizes the role of material treatment, temperature, and hydrogen loading in influencing LENR rates and proposed that unique local conditions within the materials are crucial for the observed nuclear reactions. Storms claims that LENR has Arrhenius behavior and advocates for experimenting at higher temperatures to achieve a higher reaction yield. However, similar to his peers, Storms has never provided inarguable evidence for the effect.

Callisto has replicated the protocols described by Storms, which will be described in full detail in section 7.5.

1.4.4 Staker

Michael R. Staker, a materials scientist, has focused on the preparation of the palladium-deuterium cathode used in experiments. He used coupled calorimetry and resistivity measurements to investigate the behavior of deuterium loading in palladium, attempting to elucidate the role of super-abundant vacancy (SAV) phases [80]. It is well established in the metallurgical literature that metal vacancies are stabilized by the presence of hydrogen in most face-centered cubic lattices [81, 82]. In the case of palladium, it is thermodynamically favorable to form six-fold coordinated metal-vacancy hydrogen clusters. Fukai postulated that under certain conditions, the diffusion and accumulation of these lattice defects can coalesce into a new extended phase, which he called the super-abundant vacancy phase [83,84]. Staker, Fukai, and others claim these vacancies can accumulate into ordered structures, creating channels that facilitate rapid transport conditions for deuterons, and which are hypothesized to play a crucial role in LENR. It should be noted that no experimental evidence for the SAV-phase has been provided at room temperature, despite Staker's strong claims of its existence.

Staker monitored the resistivity of palladium-deuterium specimens, hypothesizing the electronic behavior would provide insight into phase transitions. He claimed the SAV phase, or the δ phase as he refers to it, is associated with excess heat production. However, no robust data is provided to support the existence of these phases. Staker does not provide crystallographic evidence, nor do the trends in his resistance data support the existence of the SAV phase.

Using an isoperibolic calorimeter, Staker claimed excess power ranging from 0.10 W to 0.32 W, representing 4.7% to 9.6% of the input power. Additionally, he reported a substantial thermal runaway producing up to 2.4 W of excess power with an input of 1.2 W, among the largest in LENR literature. This claim was later modified by Staker in his published corrigendum to 1.78 W of excess heat on an input power of 2.66 W.

Callisto has investigated Staker's claims and will provide additional details in section 7.3.

1.4.5 Letts and Cravens

Dennis Letts and Dennis Cravens performed experimental work focused on the stimulation of deuterated palladium using laser irradiation [85–87]. Their research is motivated by theoretical considerations suggesting that lattice vibrations, or phonon modes, at certain frequencies might couple with energy states within the palladium-deuterium system, facilitating LENR processes. Letts and Cravens developed methods to fabricate palladium cathodes, involving processes of cold working, polishing, etching, and annealing to prepare the material for electrochemical loading with deuterium. Their experiments often involve dual laser setups producing terahertz beat frequencies rather than true terahertz radiation. Letts and Cravens claimed the application of external magnetic fields and gold co-deposition on cathodes influence the thermal response and reliability of excess power production. However, similar to other researchers, reproducibility and a lack of compelling evidence relegates their work to be considered mediocre at best. We will highlight a meta-analysis later in the document which suggests their data is heavily cherry-picked.

Callisto has extensively replicated the protocols described by Letts and Cravens, which will be described in full detail in section 7.9.

1.4.6 Space and Naval Warfare Systems Center

The Space and Naval Warfare Systems Center (SPAWAR), a division of the U.S. Navy, embarked on Low Energy Nuclear Reactions (LENR) research in the early 2000s. Researchers Dr. Pamela Mosier-Boss, Dr. Stan Szpak, and Dr. Frank Gordon developed what they called a *codeposition* method [88, 89]. During codeposition, palladium (Pd) ions from a palladium chloride ($PdCl_2$) solution are reduced and deposited onto a cathode surface in the presence of heavy water. This protocol aimed to achieve a high deuterium loading within the freshly deposited palladium layer, although no compelling evidence for higher fractional loadings were reported.

Another major feature of SPAWAR experiments was the use of detection techniques to monitor nuclear events and measure excess heat. CR-39 plastic detectors were used to capture high-energy particles emitted during potential nuclear reactions, revealing tracks that were analyzed to determine their nature. Additionally, SPAWAR used isoperibolic calorimeters to measure any excess heat generated during the electrolysis process. Analysis for nuclear byproducts, such as tritium and helium-4, was also conducted.

In various experiments, SPAWAR reported excess heat generation in the range of several hundred mW above the input power. CR-39 detectors consistently recorded tracks suggesting the emission of high-energy particles, pointing to nuclear events at the palladium-deuterium interface. In future sections, we will highlight significant concerns regarding these low-cost nuclear detectors and the plethora of false signals that can arise.

1.4.7 Naval Surface Warfare Center, Indian Head

Building on SPAWAR's research, the Naval Surface Warfare Center (NSWC), Indian Head Division, continued exploring LENR. This program involved researchers from SPAWAR as well as new players, including Carl Gotzmer, Louis F. DeChiaro, Marc Litz, and Oliver Barham. They investigated protocols for more control over loading deuterium into the palladium cathode. A notable accomplishment, the Indian Head team published a peer-reviewed article in Applied Physics Letters Energy, claiming excess heat and nuclear ash under high electrochemical potentials [90]. Despite some concerns over the claims made in the paper which we will fully explore in a later section, the APL-E paper represents a departure from other research endeavors. Fairly complete descriptions of the hardware and protocol are included, positioning other researchers to replicate their results.

Improved CR-39 detectors were used to capture and analyze particle emissions, providing detailed information on the energy and type of particles produced. One notable feature of their nuclear detection was their use of a third party to analyze the detector tracks, mitigating bias from the researchers. A Seebeck calorimeter was used to measure heat output with higher precision than previously.

Similar to SPAWAR, Barham et. al. reported instances of excess heat generation that exceeded the energy input and expectations from chemical reactions. For instance, one experiment claimed an excess power of 5 W, on an input power of 15 W. Additionally, they detected radio frequency (RF) emissions up to 6 dB above the noise floor, which the authors claim are not attributable to background noise or known chemical reactions. Another interesting claim by the authors is that electrodeposited material structure included an unusual Li_2PdD_4 phase, normally synthesized under high-pressure, high-temperature conditions.

Callisto has extensively replicated the protocols described by both SPAWAR and NSWC, which will be described in full detail in section 7.7.

1.4.8 Miles at China Lake

With a background in chemistry and electrochemistry, Melvin Miles conducted electrolysis experiments, focusing on cathode preparation and nuclear byproduct measurements. Miles' primary goal was to achieve reproducible results that demonstrated excess heat production. Notably, Miles provided critical feedback on calorimetry early in the field [91]. Through calorimetric studies, Miles consistently reported excess heat generation. Notably, he was one of the first to correlate this excess heat with the production of helium-4, a potential nuclear byproduct [92]. This correlation provided seemingly compelling, albeit controversial, evidence supporting the nuclear nature of the reactions occurring in LENR systems.

In addition to his work with palladium-deuterium systems, Miles investigated the use of palladium-boron (Pd-B) cathodes. These cathodes, prepared at the US Naval Research Laboratory, demonstrated excess power effects in multiple experiments. Miles identified that the addition of boron improved the mechanical strength of the cathodes, reduced volumetric expansion during deuterium loading, and slowed deuterium escape, factors which potentially contributed to the observed excess heat. This work with Pd-B cathodes further supported the idea that material properties are crucial in achieving reproducible LENR results.

Callisto has replicated the materials and protocols described by Miles, which will be described in full detail in section 7.6.

1.4.9 Google Research

Google's initiative to revisit LENR represents a significant endeavor in scientific research, demonstrating a high standard of scientific rigor and yielding advancements across multiple fields [93]. The effort began in 2015. Google's program aimed to re-evaluate LENR with modern scientific techniques and a stringent peer-review process, involving around dozens of researchers from various prestigious institutions including the University of British Columbia, Massachusetts Institute of Technology, University of Maryland, and Lawrence Berkeley National Laboratory.

Despite thorough investigations, the team did not find any evidence to support the existence of cold fusion. However, the research provided valuable insights into hydrogen-loaded metals and extreme environment calorimetry. One of the significant achievements was the development of a high-temperature, high-pressure calorimeter designed for studying gram-scale heterogeneous reactions, capable of operating up to 1000°C and 100 bar. This calorimeter was validated using standard reactions and provided precise measurements, highlighting its utility in studying LENR and other high-energy chemical reactions [94, 95].

The project also focused on the accurate quantification of hydrogen absorption in palladium (Pd) nanoparticles and thin films using coulometric techniques. This method allowed for precise measurements of the H/Pd ratio, revealing that the hydrogen absorption varied with the size and surface structure of the Pd nanoparticles [96]. Another significant advancement was the development of an apparatus for *operando* X-ray diffraction (XRD) measurements on fuel electrodes of high-temperature solid oxide electrochemical cells. This apparatus, capable of operating at temperatures up to 745°C, enabled the study of structural changes in Pd electrodes under real operating conditions, providing insights into degradation mechanisms and enhancing the understanding of highly hydrided metals [97]. Although no evidence of cold fusion was found, the program advanced the understanding of metal hydrides, calorimetry under extreme conditions, and measurement techniques. This endeavor exemplifies the importance of revisiting controversial scientific claims with modern tools and methodologies.

While Callisto did not explicitly replicate the Google experiments, in evaluating similar hydrogen loading measurements, Callisto has levied a critique of their loading calculations by both coulometry and X-ray diffraction, which may have overestimated the fractional loading by as much as 10 %.