The Material Science Aspects of Low Energy Fusion
Edmund Storms

Notes from Seamus L. @ LF - 15/4/23

General Remarks

Note that I have moved “Nature of the Gap Structure” to after “Discussion,” which I have proposed be renamed. With these two sections next to each other, it feels like there might be some redundancy across the two, though I have not addressed this. I have tried to work by recapitulating sections of the paper that merit comment, and then indenting my comment above / below, with green highlights to represent suggested changes, blue highlights to note strike throughs, and orange highlights to highlight inline comments.

Abstract

The fusion reaction called “cold fusion” is difficult to initiate. This difficulty has hampered research and slowed acceptance of the effect. Progress requires this unique fusion reaction to be produced with greater reliability. This paper describes the treatments found to improve success.

> *I would be inclined to more carefully delineate between the two purposes of the paper. Assuming I understand your work, and intent, correctly (to my abilities, at least), then this paper is really doing two things. It is a literature review, but it is also an explication of your theory. I would be more explicit about this.*
>
> *For example:*
>
> *“The fusion reaction called “cold fusion” is difficult to initiate. This difficulty has hampered research and slowed acceptance of the effect. Progress requires this unique fusion reaction to be produced with greater reliability. This paper describes the treatments found to improve success that are available in the literature, and propounds the author’s theory of the NAE, which can, it is asserted, tie together the disparate and often counterintuitive or contradictory observations made in the literature.”*

Introduction

Thirty-four years ago, Profs. Martin Fleischmann and Stanley Pons(F-P)[1] claimed to produce the fusion of deuterium in PdD using electrolysis of D2O + LiOD. The claim was soon rejected because most efforts failed to reproduce the claim and the claimed fusion process conflicted with the common understanding of how such nuclear reactions are known to behave. The phenomenon was initially called cold fusion. Now the preferred name is Low Energy Nuclear Reaction (LENR) because nuclear reactions in addition to fusion have been found to occur.

> *My instinct is to orient the reader a little more. For example:*
>
> *"Thirty-four years ago, Profs. Martin Fleischmann and Stanley Pons(F-P)[1] claimed to produce the fusion of deuterium in PdD using electrolysis of D2O + LiOD. Despite an initial burst of optimism, the claim was soon rejected. Critical experimental variables were not understood at the time of Fleischmann and Pons' announcement, including the necessity to load to a high level in the classical bulk Pd experiment (McKubre ref), and the then unappreciated materials science challenges associated with bulk Pd electrodes (ref). In part, because of these unappreciated variables, many early experiments failed to replicate the phenomenon. These challenges, in addition to the fact that the claimed fusion process conflicted with the common understanding of how such nuclear reactions are known to behave, precipitated widespread antipathy and hostility towards the field in the months following Fleischmann and Pons' announcement. The phenomenon was initially called cold fusion. Now the preferred name is Low Energy Nuclear Reaction (LENR) because nuclear reactions in addition to fusion have been found to occur."*

Despite the continued rejection over the last thirty-four years, thousands of studies done in at least 12 countries and in dozens of laboratories have demonstrated that the claimed fusion does indeed occur. The resulting publications can be accessed at www.LENR-CANR.org, where the full text of some papers cited here can be found. In addition, the results of these studies are summarized in many books and reviews. The DOE (Department of Energy) is even providing $10M to study the process.

> *I would reword the DOE line. For example:*
>
> *"Encouragingly, the Department of Energy, through ARPA-E, has recently announced $10mm of funding for LENR research. This, in addition to longstanding interest in the field by scientists at NASA, and recent funding for research from the European Union."*

This nuclear process generates heat energy by forming 4He[2] without radioactive products other than occasional tritium[3] or harmful radiation.

> *"This nuclear process generates heat energy by forming 4He[2] without radioactive products (other than occasional tritium[3]) or harmful radiation."*

Such a clean and friendly energy would eliminate the generation of CO2 from the use of fossil fuels and the dangerous radioactive materials when the fission of uranium is used.

> *"Such a clean and friendly energy source would eliminate the generation of CO2 from the use of fossil fuels, and the production of dangerous radioactive materials from nuclear fission reactors."*

In addition, the damage to the environment caused by conventional energy sources could be eliminated. Besides these practical benefits, the behavior reveals the operation of a mechanism that is in direct conflict with conventional understanding. This conflict opens the door to a new understanding of how nuclear processes might be made to occur in a chemical environment.

> *"Besides these practical benefits, the behavior reveals new science that is in direct conflict with conventional understanding. This conflict opens the door to a new understanding of how nuclear processes might be made to occur in a chemical environment."*

Success in attracting support for further research requires the reasons for rejection to be acknowledged and addressed. Several reasons were used as justification for rejection. As an example, when people tried to replicate the claimed behavior, they failed. They did not realize that most Pd is not able to support the fusion process. Rather than blame their failure on the use of inactive material, they concluded that F–P had made a mistake and the claim was not valid.

> *I find these sentences to be a little difficult. I would consider something like the below in their place:*
>
> *"Myriad reasons were used as justification for rejection of the field. When inadequately prepared palladium was used, it was not able to support the reaction. When the palladium cathode was not loaded to a sufficient degree, likewise, it was not able to support the fusion process. Rather than recognise that the experiment had been conducted incorrectly, many researchers concluded that Fleischmann and Pons were in error, and that their work was not valid."*

This paper focuses on the various ways palladium can be made to support the fusion mechanism, thereby making failure less frequent. A universal condition is proposed to be required, which is identified as physical gaps having a critical dimension, not vacancies[4] or defects[5]. This universal condition can be created in any material using many different treatments with the size of the gap being the critical variable.

> *"This paper reviews the current literature of the field, and advances the author's theory of the various ways palladium can be made to better support the fusion mechanism, thereby making failure less frequent. A universal condition is proposed to be required, which is identified as physical gaps having a critical dimension, rather than vacancies[4] or defects[5], as other authors propose. It is asserted that this universal condition can be created in any material using many different treatments, with the size of the gap being the critical variable."*

Discussion

> I would rename this section something like “The Theory of the Nuclear Active Environment”, rather than calling it “Discussion.” My instinct is, again, to try to delineate as clearly and precisely as possible between what is literature review, what is your theory, and what is your interpretation of the literature in the context of your theory. As it stands, the three sometimes bleed through each other in a way that vitiates the readability of the paper.

The mechanism requires a unique and rare condition to form within the material, which is called the nuclear active environment (NAE). The mechanism operating in the location is still unknown, but clearly unusual. Because PdD is the material on which the main effort to cause LENR has been focused, experience using this material will be used here even though other materials have been found to support the fusion reaction.

> *Some edits I would suggest below. I find your use of the word mechanism a little confusing, and so have tried to work around it.*
>
> *“The author proposes that a critical, and heretofore underappreciated, requirement in the promotion of the LENR reaction is the necessity for the cathode to form what has been called the nuclear active environment (NAE). The LENR reaction requires a unique and rare condition (the NAE) to form within the material. The reaction mechanism operating inside the NAE is still unknown, but clearly unusual. Because PdD is the material on which the main effort to cause LENR has been focused, experience using this material will be referred to herein, even though other materials have been found to support the fusion reaction.”*

Over the last 33 years, a large number of treatments has been explored with only a few showing more than random success. Even agreement about the reason for success is lacking. This paper describes several methods and the reason for their success, with citations to the papers where more detail can be found. The goal is to show the reader where to look for more information.

> *Again, just trying to parse out what is what. Perhaps this is persnickety, but I think it is important.*
>
> *“This paper describes several methods of initiating LENR reactions and the author’s interpretation (using his theory of the NAE) of the reason for their success, with citations to the papers where more detail can be found. The goal is to show the reader where to look for more information.”*

Nature of the Gap Structure

> I don’t know how to interpret your use of the word structure. Here, it seems to refer to the reaction occurring inside the NAE, but below, you suggest that the reaction might be a form of electron screening. The word ‘structure’ feels imprecise, and potentially problematic in this context, given that we are talking about a physical structure (the NAE) and now a reaction structure (the reaction inside the NAE).

The fusion process is proposed to involve a unique structure that forms in gaps of a critical dimension by a chemical process to which the Laws of Thermodynamics apply. The gap provides the required environment for the unique structure to form and the structure has the ability to initiate nuclear interaction between all isotopes of hydrogen. [9] The mechanism causing this structure to form is presently unknown. Further descriptions of this proposed process is provided in future papers.

Early Experience

Very soon after the discovery of LENR was announced, several people discovered that certain batches of Pd were able to cause it with reliability without additional treatment. For example, Takahashi[6] obtained a sheet of Pd about 1 mm thick from Tanaka Precious Metals, Japan. Most samples he cut from this sheet produced excess power when electrolyzed in D2O. To test this rare ability, he sent samples to various laboratories including to me at Los Alamos National Laboratory (LANL). This sample was the first one I studied after having designed and built a suitable calorimeter[7]. The 9 W of excess power really got people's attention at LANL. Other people who used his material had similar success. Eventually, the sample stopped working, so I requested another sample. Takahashi no longer had any of the original material, so he had another sheet made. Upon testing, this Pd was found to produce no excess energy. Takahashi discovered that Tanaka Metals had not given this batch of Pd the same treatment as before. A third batch was made using the same treatment as was applied to the first sheet. This batch again made excess power.

> *"Very soon after the discovery of LENR was announced, several people discovered that certain batches of Pd were able to reliably initiate the reaction, ~~with reliability,~~ without additional treatment. For example, Takahashi[6] obtained a sheet of Pd about 1 mm thick from Tanaka Precious Metals, Japan. Most samples he cut from this sheet produced excess power when electrolyzed in D2O. To further test this material's rare reliability, he sent samples to various laboratories, including to the author at Los Alamos National Laboratory (LANL). This sample was the first one I studied after having designed and built a suitable calorimeter[7]. These experiments showed 9 watts of excess power. Other people who used Takahashi's material had similar success. Eventually, the sample provided to LANL stopped working, and so I requested another ~~sample~~. Takahashi no longer had any of the original material, and so he had another sheet made. Upon testing, this Pd was found to produce no excess energy. Takahashi discovered that Tanaka Precious Metals had not given this batch of Pd the same treatment as before. A third batch was made using the same treatment as was applied to the first sheet. This batch again made excess power."*

This experience provided two important lessons. Active batches of Pd can make excess energy in various laboratories when different calorimeter designs are used, thereby replicating the F-P claim. In addition, when a special treatment is used, the entire batch of Pd will produce excess power. McKubre reported the same experience when a spool of Pd wire produced excess power when most pieces were electrolyzed in D2O. Fleischman and Pons had the same experience when Johnson Matthey (J-M), the company that supplied their Pd, was able to produce samples that showed significant success in their hands. Other people had similar success when they used this material.[8]

> *Some of these sentences feel clunky to me. I would consider rewriting / reordering some of the sentences as below:*
>
> *"When particular, difficult to identify, treatments are used during the smelting process, it has often been found that the entire batch of Pd will produce excess power. McKubre reported a similar experience to Takahashi's when multiple samples cut from a single spool of Pd wire produced excess power when electrolyzed in D2O. Fleischman and Pons had the same experience when Johnson Matthey (J-M), the company that supplied their Pd, was able to produce samples that showed significant success in their hands. Other people had similar success when they used this Johnson Matthey material.[8] This experience provides two important lessons. Active batches of Pd can make excess energy in various laboratories when different calorimeter designs are used, and that this replicates the F-P claim."*

The treatments used by J-M and Tanaka Metals were never made public. Nevertheless, Fleischmann provided a clue when he revealed that CaB6 was added to molten Pd to remove the oxygen impurity by the formation of B2O3 and CaO, which would float most of the oxygen to the surface as the respective oxides. This purification process would leave small particles of CaO behind as small particles that would be distributed throughout the batch of Pd when the final sheet of metal was fabricated. These particles are proposed to cause a suitable sized gap to form around each particle after the Pd is reacted with a critical amount of deuterium as determined by the particle size.[9] In this way, the success produced by samples from the entire batch, regardless of the physical form, wire or sheet, can be explained. If true, this explanation would identify the critical treatment and eliminate many of the complex treatments now being used to activate a material.

> *"Regrettably, the treatments used by J-M and Tanaka Precious Metals were never made public. Nevertheless, Fleischmann provided a clue when he revealed that CaB6 was added to molten Pd during smelting to remove ~~the~~ oxygen impurities by way of the formation of B2O3 and CaO. These would float most of the oxygen to the surface of the molten Pd as the respective oxides. This purification process would leave behind CaO as small particles that would be distributed throughout the batch of Pd, when the final sheet of metal was fabricated."*

> *"These particles of CaO are proposed to cause a suitable sized gap (the NAE) to form around each particle, following the loading of the sample with a critical amount of deuterium. This critical amount being determined by the particle size. Understood this way, the success of entire, specific batches, regardless of the physical form (wire or sheet) can be explained. If true, this explanation would identify the critical treatment and eliminate many of the complex treatments now being used to activate a material."*

To test this idea, particles of CaO were melted with Pd. When a mixture of sizes having a maximum size of 34 µm was added to liquid Pd, the metal produced excess energy after being formed into a flat disc and reacted with D2 gas.[9] A larger collection of sizes failed to activate the Pd. The exact gap size required to cause LENR is still not known.

> *"To test this idea, particles of CaO were melted with Pd [by who? - cite by name in text?]. When a mixture of CaO particle sizes, having a maximum size of 34 µm, was added to liquid Pd, the metal produced excess energy after being formed into a flat disc and reacted with D2 gas.[9] A larger collection of sizes failed to activate the Pd. The exact gap size required to cause LENR is still not known."*

Deposit of Impurities on the Surface

Several successful treatments have been used to activate Pd. In 1996, Storms[10] summarized the available information. At that time, McKubre et al.[11] found that the addition of Al metal to the electrolyte containing LiOD increased success. The metal would slowly dissolve by forming AlO+ in the solution. This ion would be attracted to the cathode where it would deposit and form small islands of Al2O3, which is stable to reaction with large activity of hydrogen present at the cathode surface. The nano-gaps between the resulting islands are proposed to be the NAE. Other stable deposits, such as uneven deposits of gold[12-14] would be expected to cause similar behavior. Such deposits would produce LENR only at the surface of the sample and within the deposited material.

> *"Several successful treatments have been used to create Pd more amenable to the initiation of LENR reactions. In 1996, Storms[10] summarized the available information. At that time, McKubre et al.[11] found that the addition of Al metal to an electrolyte containing LiOD increased success. The metal would slowly dissolve by forming AlO+ in the solution. This ion would be attracted to the cathode where it would deposit and form small islands of Al2O3, which is stable to reaction with the large activity of hydrogen present at the cathode surface. This result, understood in the context of the author's theory, suggests that nano-gaps between the resulting islands are a potential candidate for being the NAE. Other stable deposits, such as uneven deposits of gold[12-14] would be expected to cause similar behavior. Such deposits would produce LENR only at the surface of the sample and within the deposited material."*

Extended Electrolysis

Fleischmann and Pons[17] found that Pd would become active after being electrolyzed for many weeks in an electrolyte containing LiOD. This process would cause Li to react with and dissolve in the PdD forming the alloy Pd-Li-D in which the Li occupies the same lattice locations as Pd. Yamazaki et al.[18] studied this process and found that the amount of dissolved Li increased with increased time and current, as shown in Fig. 1. Asami et al. [19] reported the same behavior. Heating the cell during electrolysis would increase the reaction rate with Li and the activation process.[20]

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Codeposition

The codeposition (Codep)[22, 23] causes small islands of Pd to deposit on the surface of the cathode when an electrolyte containing PdCl2+DCl or LiCl is used. This method is found to produce frequent success. However, the challenge is to keep the 5 poorly bonded particles from being removed from the surface by bubbles of D2 generated at the surface. The use of a very low current (~0.5 mA) while the Pd is being deposited largely solves this problem. Gap formation between these small islands of Pd is proposed to be required for success. The deposited Pd can be removed from the electrolytic cell and made to produce energy when exposed to D2 gas at modest pressures without the formation of chlorine and chlorine oxide adding to the complexity, as is the case when electrolysis is used.

> *"The deposited Pd can be removed from the electrolytic cell and made to produce energy when exposed to D2 gas at modest pressures (without the formation of chlorine and chlorine oxide adding to the complexity of the experiment, as is the case when electrolysis is used)."*

Nanoparticles

> I find this paragraph to be a bit troublesome. Rather than beginning with an orienting sentence regarding the general nature of nanoparticles, or the experiments conducted with nanoparticles, we get a sentence that hones in on one particular experimental complexity of the usage of nanoparticles – sintering. Moreover, the final sentence does not make sense to me, though I do not know how it might be revised – it feels like it assumes something that is not immediately clear to the uninitiated reader.

Particles having dimensions in the nanometer range are unstable to sintering by which larger particles form. For example, Arata and Zhang[24, 25] placed palladium-black, which consists of Pd with a nanometer size, in a sealed container of Pd. This assembly was reacted with D using electrolysis, during which time heat and helium were detected. When McKubre et al. [26, 27] successfully replicated this study, the palladium-black was found to have formed a solid mass in which the original small particles were no longer present. Nevertheless, small gaps would be present in the structure. In other words, the original claim for the particle size being important is no longer justified because the fusion process is unaffected by the change in particle size.

> *"Arata and Zhang[24, 25] placed palladium-black, which consists of nanometer size Pd ~~with a nanometer size~~, in a sealed container of Pd. This assembly was reacted with D using electrolysis, during which time heat and helium were detected. When McKubre et al. [26, 27] successfully replicated this study, the palladium-black was found to have sintered, forming a solid mass in which the original small particles were no longer present. Particles having dimensions in the nanometer range are unstable to sintering, by which larger particles form. Nevertheless, even in these larger, sintered particles, small gaps [the NAE?] would still be present in the structure. In other words, the original claim for the particle size being important is no longer justified because the fusion process is unaffected by the change in particle size."*

To prevent sintering, Takahashi et al.[28, 29] caused the small particles of a metal to be isolated in ZrO2. This design has been studied with success with many variations, but with the success being attributed to nano-particles being required. The role of nano-gaps cannot be eliminated by their experience.

> *"To prevent sintering, Takahashi et al.[28, 29] caused the small particles of a metal to be isolated in ZrO2. This design has been studied with success with many variations, but with the success being attributed to the use of nano-particles ~~being required~~. Takahashi et al.'s experience with these experiments does not negate the possibility that their results can be explained by way of the formation of nano-gaps (the NAE)."*

Case[30, 31] used coconut charcoal on which small particles of Pd were deposited to produce the fusion reaction. Activation of the wet form of the catalyst required heating to 200° C followed by the sudden release of steam. The resulting small particles of PdCl2 could then be reduced to Pd using D2 gas. This work was replicated by McKubre et al.[26] using the material supplied by Case. The nuclear reaction probably occurred in the charcoal rather than on the nanoparticles of Pd because the use of a different batch of charcoal failed to produce LENR even when the Pd was applied the same way. The particles of Pd probably were only needed to split the D2 gas molecule to make D+ ions available to the gaps in the charcoal.

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Layers of Pd on CaO

Since 1993[13], Iwamura et al.[32, 33] have studied various ways to cause LENR. Methods to cause the production of excess power as well as complex transmutation reactions were explored using sandwiched thin layers of metal on various oxides. These layers are expected to contain suitable gaps formed as a result of stress relief resulting from miss-matched expansion.

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Large D/Pd Ratio

McKubre et al.[11] emphasize the need to achieve a large D/Pd ratio, which cannot be achieved by most Pd. However, when the Pd was able to reach a D/Pd ratio greater than 0.85 at 20° C, they found that the amount of power increased when the D/Pd ratio was further increased, as shown in Fig. 3. Kamimura et al.[34] reported similar behavior. Storms found that a large D/Pd ratio was not always required when certain samples of Pd were reacted with D2 gas.[35]

> *"McKubre et al.[11] emphasize the need to achieve a large D/Pd ratio in conventional electrolysis. This cannot be achieved by most Pd, owing to the fact that high loading causes palladium cathodes to warp, crack and deload. However, when McKubre et al. were able to reach a D/Pd ratio greater than 0.85 at 20° C, they found that the amount of excess power increased when the D/Pd ratio was further increased, as shown in Fig. 3. Kamimura et al. [34] reported similar behavior. In contradistinction, Storms found that a large D/Pd ratio was not always required when certain samples of Pd were reacted with D2 gas.[35]"*

Effect of Temperature

The increased temperature was known since 1990 to increase power production.[36] Since then, this effect has been studied in greater detail.[35, 37-40] Of importance, most of the samples I have studied made no detectable power at room temperature yet would produce significant power when heated. Perhaps more success would have been reported if the samples had been simply heated.

> *"It has been known since 1990 that there is a relationship between increased temperature and increased excess power production.[36] Since then, this effect has been studied in greater detail.[35, 37-40] Of importance, most of the samples the author has studied made no detectable power at room temperature yet would produce significant power when heated. Perhaps more success would have been reported by other scientists if their experiments had included the heating of their samples."*

Reaction with D or H

Unless the cell is designed to hold the pressure, some gas would be released when the pressure limit is reached, causing a loss of D2 and a change in the D/Pd ratio. I have found that this loss of D does not effect on the ability of the material to support the fusion reaction after the fusion reaction starts.

> *"Unless the cell is designed to hold the pressure, some gas would be released when the pressure limit is reached, causing a loss of D2 and a change in the D/Pd ratio. The author has found that this loss of D does not affect ~~on~~ the ability of the material to support the fusion reaction after the fusion reaction starts."*

Summary

> The second sentence in the below paragraph should be much earlier in the piece. Preferably, I would submit, in the "Discussion" or "Nature of the Gap Structure" sections. Above, you say "[t]he mechanism operating in the location is still unknown," and yet here, you offer a plausible explanation for what that mechanism might be. Is it worth citing the recent preprint from Metzler et al., which provides a review of electron screening in the lattice?

The behavior obtained from many treatments points to gaps having dimensions in the nanometer range being required to support the cold fusion reaction. The gaps are proposed to provide a chemical environment in which nuclei and electrons can assemble so that the Coulomb barrier can be overcome by a novel screening mechanism.[60]

> *"The behavior of the LENR reaction across many different experimental protocols, featuring many different treatments of Pd, points to gaps having dimensions in the nanometer range as being required to support the cold fusion reaction. These gaps are proposed to provide a chemical environment in which nuclei and electrons can assemble so that the Coulomb barrier can be overcome by a novel screening mechanism.[60]"*

Such gaps can be produced in several different ways in Pd and perhaps in other materials as well. They can form as a result of expansion when the material reacts with D or H, they can form as the result of stress relief when impurities are added to Pd, or they can form as gaps between small particles of an inert material deposited on the surface of any material. This description provides a path to improve the ability to cause cold fusion. For example, such gaps might also be created in high concentration with reproducibility by nano-machining the required gap size in a suitable metal. This technique would avoid the many uncontrolled variables that frustrate efforts to cause active sites to form in a chemical environment using a chemical process.

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It's important to realize that the fusion reaction takes place only in a few isolated sites in an active material and the measured energy results from the total power produced by these individual sites. Therefore, the measured power would be sensitive to the number of active sites. These sites can be located anywhere in the material, depending on the treatment, and can come and go at random times. This behavior makes a study unpredictable and difficult to interpret.

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The use of high temperature and perhaps other stimulations need to be encouraged. These include the application of laser radiation of certain frequencies[61], the use of magnetic fields[62, 63], and the passing of high current through the material.[64]

> Is it appropriate to mention the above for the first time in the summary, or are these techniques worthy of inclusion in the body of the paper?