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Research Article

Characteristics and Energetics of Craters in LENR Experimental Materials

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Abstract

Small craters have been observed frequently in the surfaces of cathodes from electrochemical LENR experiments. They are generally 1–100 μm in size. The craters vary widely in shape and areal distribution. Two methods were used to determine the energies needed to produce such craters. The resulting energies range from nJ to mJ, depending on the crater size. If craters are caused by LENR, then many nearly simultaneous MeV-level energy releases would have to occur in a very small volume. There are numerous open basic questions regarding the formation and characteristics of craters in LENR cathodes. It remains to be seen if craters will be helpful in understanding the origin and nature of LENR. But already, the existence and features of craters seriously challenge theories that seek to understand LENR.

Keywords: Cathode materials, Craters, Low-energy nuclear reactions, LENR, Transmutations

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1. Introduction

The mechanisms and dynamics for the production of energy by Low-energy Nuclear Reactions (LENR) are still not understood. Hence, it seems reasonable to examine all available information from LENR experiments. Small craters are commonly observed in solid cathode materials after electrochemical loading of deuterons into Pd. However, while such craters have frequently been reported, they have not been analyzed significantly. The purpose of this paper is to provide the beginning of such an analysis.

Section 2 presents examples of craters found after LENR experiments. Both their sizes and their areal densities can be obtained from published scanning electron micrographs. Craters larger than those from LENR experiments can be produced in solids by many mechanisms. The scaling of crater sizes with the energies that produced them is discussed in Section 3. That scaling permits estimates of the energies required to produce craters in LENR materials. Those estimates compare favorably with simple computations of crater production energies. Crater energies and densities are used to address the question of what fraction of measured excess energies might be due to events that result in craters. The question of whether or not crater formation might limit the lifetime of electrochemical LENR generators is also

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confronted. Section 4 summarizes what remain as open questions about LENR craters. It is noted that crater formation requires high power, albeit very local releases of energies. The implications of high power production by LENR are noted in Section 4.

2. Crater Characteristics

This section exhibits and discusses a few examples of craters seen after electrochemical LENR experiments. There seems to be no data published on any craters that might be formed during gas loading experiments.

Figure 1 shows the first reported instance of a crater from an LENR experiment, which was presented at ICCF-2 in 1991 [1]. It also contains an image from an experiment reported at ICCF-12 in 2005 [2]. The latter is accompanied by an X-ray analysis of the areas on or near some of the craters. It is seen that the concentrations of three elements, Pd, Pt and Ag, vary widely with location on the cathode. The observation of markedly different chemical compositions from craters and their surroundings has been reported several times. Figure 2 contains another example of such an observation from an experiment in which Pd and D were co-deposited [3]. The encircled elements in Fig. 2 cannot be deposited as elements, so the authors attributed their appearance to transmutations. However, they could have been impurities deposited in electrochemically permissible complexes.

The images in the first two figures show some of the wide variability in the morphology of craters. Their features vary from jagged to smooth. Sometimes they are in and below the original surface plane of the cathode, and occasionally they appear in a raised (blistered) region. The crater diameters in the first two figures range from less than 10 to about 100 μm. Their diameters are similar to the thickness of a human hair.

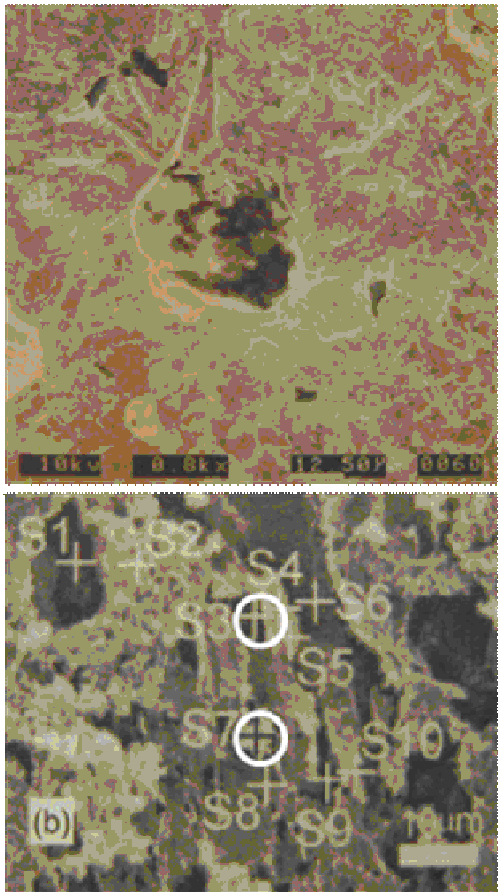
Figure 3 shows another example of craters, this one with very different characteristics. The formation seen by Ohmori and his colleagues has a remarkably intricate structure [4,5]. It appears as if multiple energy releases produced the observed shape. Further, the shapes make it seem that the releases must have been directed, or possibly sequenced, to make the almost-floral structure. The formation extends well above the cathode surface. The complex structure shows no evidence of melting. It is important that the material in Fig. 3 is gold, rather than the Pd used in most electrochemical LENR experiments.

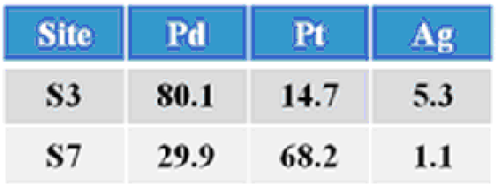
Craters seen in cathodes in Super-wave LENR experiments are shown in Fig. 4 [6]. All of these craters are relatively small, with structures on the order of 10 μm. They obviously exhibit a variety of morphologies. Some show evidence of melting and flow, while others have jagged structures, such as are seen in Figs. 1 and 3. The lower right hand micrograph in Fig. 4 is a crater in which the bottom seems to be influenced by the underlying crystal structure. This could happen two ways. The first, seeming unlikely, is the fracture along low index crystal planes and ejection of a crystallite. It is also possible that the flat interior crater walls formed from recrystallization of molten material. But, that process also seems unlikely because of the very short cooling times of the cathode materials immersed in the electrolyte.

Tsirlin has unpublished images of craters from Super-wave experiments [7]. The morphology of these craters apparently depends on the underlying crystal structure of the cathode. They are shown in Fig. 5. The craters, like those in Fig. 4, are relatively small, all about 2 μm wide. The top two craters exhibit four-fold symmetry, possibly due to (1 0 0) crystal orientations. The bottom two images seem to reflect three-fold symmetry, maybe due to (1 1 1) orientation, and even approximate six-fold symmetry.

The last examples of craters from LENR experiments are in Fig. 6 [8,9]. These images have two valuable features. First, there are enough craters to permit estimates of the areal density of the craters. The values are in the caption of Fig. 6. Second, there is remarkable alignment of many craters with scratches on the surface of the cathodes. Presumably, the scratches existed before electrolysis. The alignment of craters with scratches suggests some experiments, which are discussed in Section 4.

Many more examples of craters from electrolytical LENR experiments could be given. However, those shown above span the range of sizes and morphologies seen in about two dozen papers that have presented or discussed micrographs





Site	Pd	Pt	Ag
S3	80.1	14.7	5.3
S7	29.9	68.2	1.1

Figure 1. Micrographs reported by Numata et al. (*top*) and by Zhang, Dash and Wang (*center*). The concentrations at the two circles are given in the corresponding two lines of the table.

of craters. A summary of observations follows:

- Craters often appear to be due to high power, but very local, energy releases. The high powers are inferred because slower, that is, lower power releases would not produce temperatures high enough to cause the observed effects.
- Part or all of many craters show evidence of melting, i.e., smooth surfaces. But, many craters have sharp

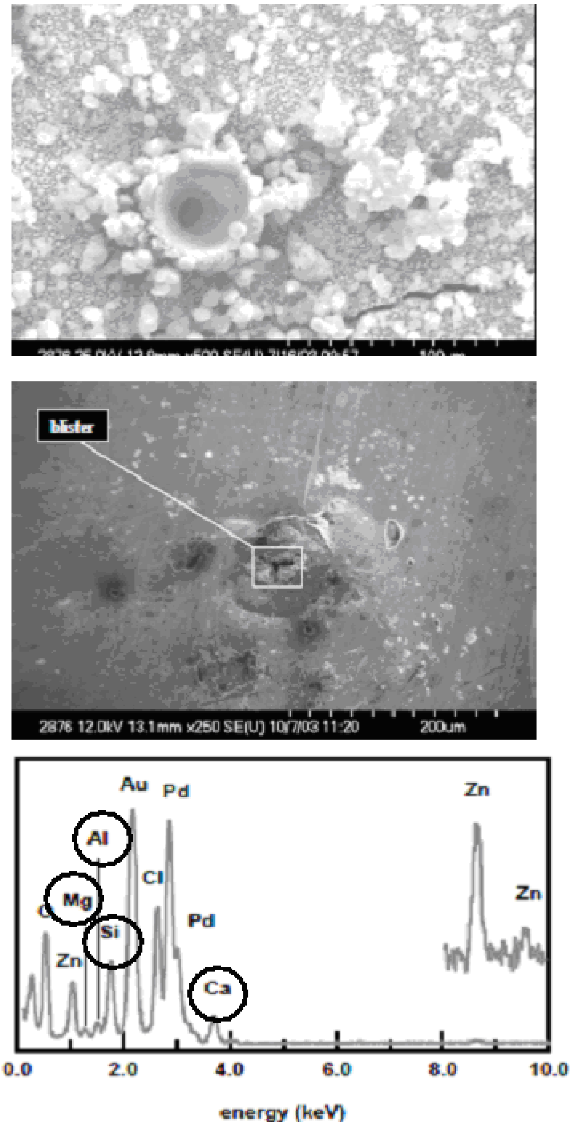


Figure 2. Micrographs showing a crater and a blister from the work of Szpak et al. The X-ray spectrum of elements near the blister is at the bottom. See the text regarding the elements within circles.

features that would not have resulted from melting.

- Craters occur in diverse materials, including some that have not exhibited excess power. Hence, the relationship between craters and excess power is not yet established.
- “New” elements appear near craters, but these may be due to concentration of elements already in the system, which were below instrument thresholds before experiments. More evidence is needed to determine with high confidence that the “new” elements are indeed due to nuclear transmutations.

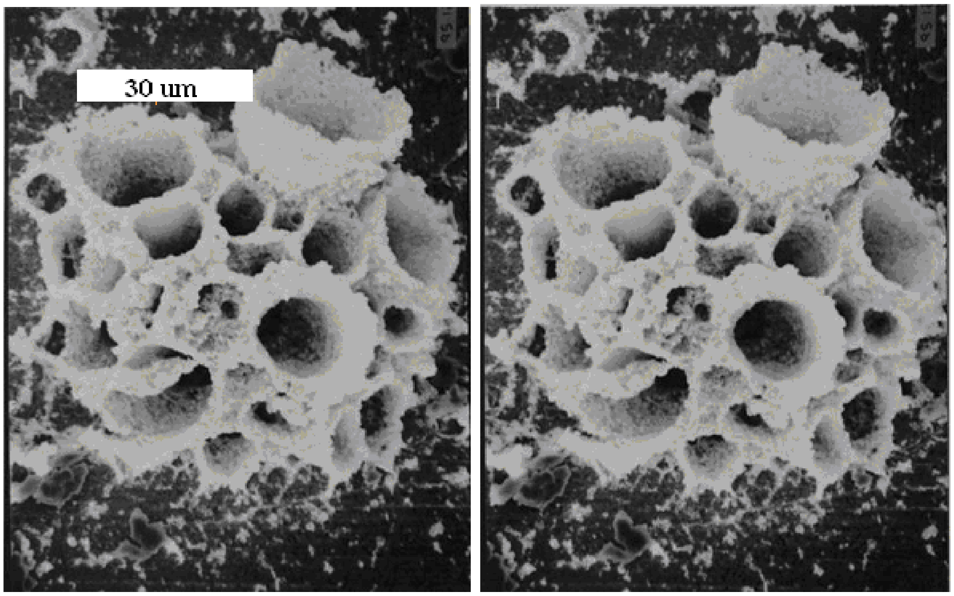


Figure 3. Stereo micrographs of complex craters, which were provided by Mizuno. They occurred on the surface of a gold cathode, which produced excess heat.

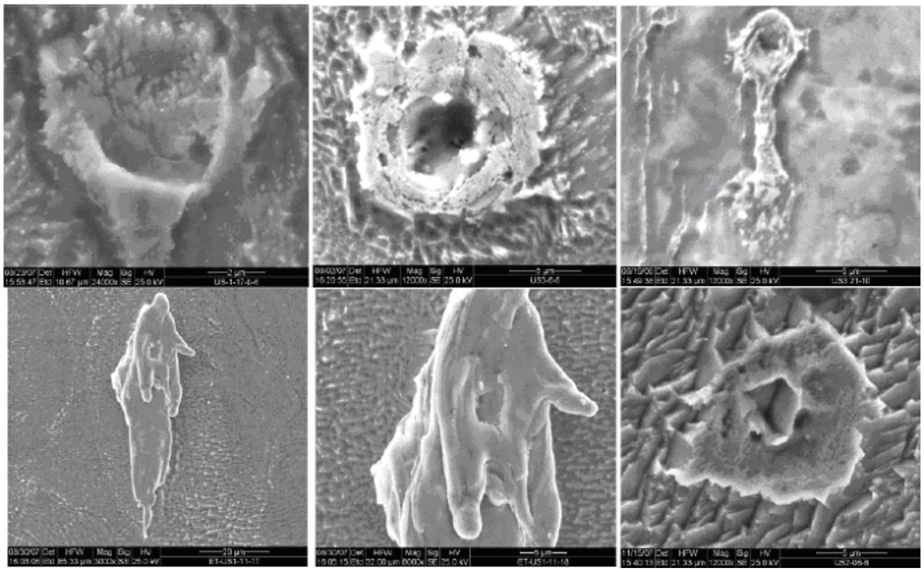


Figure 4. Craters in Pd cathodes from Pd–D Super-wave experiments.

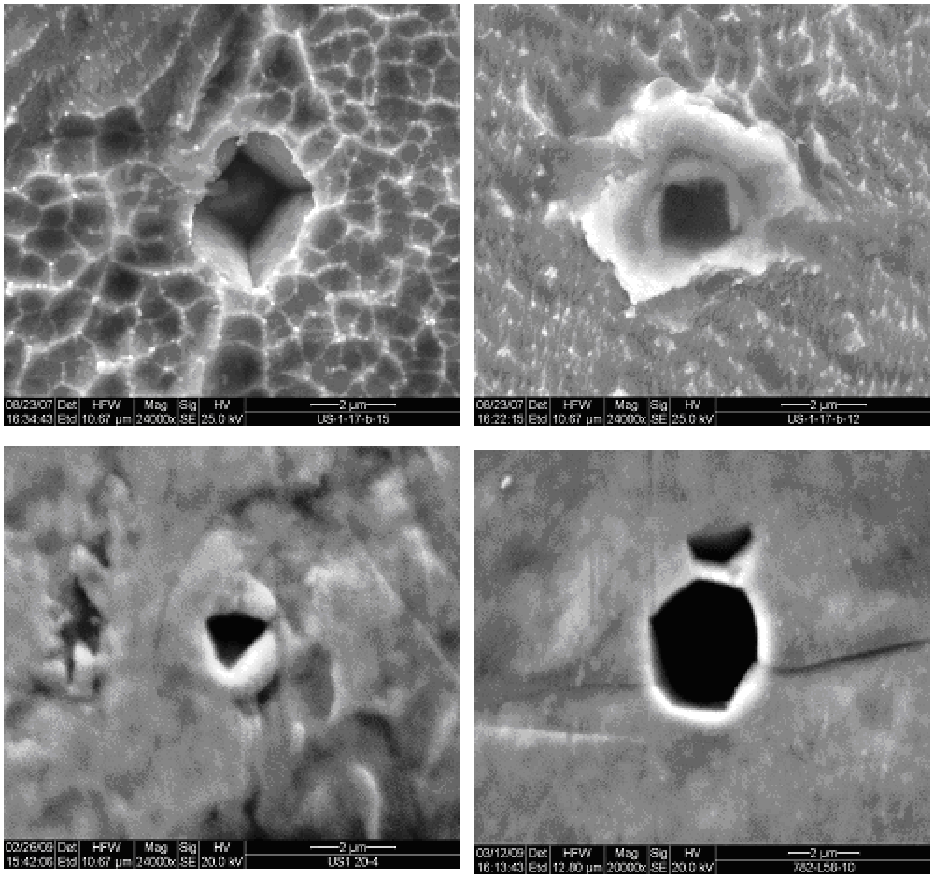


Figure 5. Micrographs of craters from Super-wave experiment that appear to be influenced by the cathode crystal structure. Courtesy of M. Tsirlin (unpublished).

- Crater diameters are generally in the range from about 1 to 100 μm. However, many craters do not have well defined shapes or diameters.
- The ratio of the depth to the diameter for LENR craters appears to be approximately in the range from less than 0.5 to more than 5. More measurements of crater depths are needed.

In summary, both the existence and the variety of craters from LENR experiments are worth attention. Their explanations might assist in the understanding of some of the basic processes occurring during heat generation, and possibly other processes. In particular, can crater formation explain a significant part of the excess energy measured in many LENR experiments?

3. Crater Energetics

There are two approaches to estimating energies required for cratering of solid materials. The first is computation of the energy needed to melt or vaporize a given volume of material. The second is extrapolation of energies from reasonably well-characterized large cratering events. Both of these approaches are employed in this section. They yield similar values for the energy needed to make a small crater on a LENR cathode.

Kim [10,11] used the computational approach shown in Fig. 7. He assumed vapor production during crater formations, and used the heat of vaporization to obtain the cratering energy given in the figure. If a person assumes only melting, and uses the heat of fusion, a smaller energy value for cratering is obtained, again shown in Fig. 7. These values will be compared below with cratering energies obtained by scaling the energetics of big craters to the small sizes of those seen in LENR experiments.

There are several craters of very different energies and sizes in diverse materials that can be used to study the scaling of craters. The physical basis for such scaling is conceptually simple. For very high power input in local events, the energy density can be so large that the type of material and its initial form are irrelevant. The energy density needed for deformation, melting or vaporization of solids is greatly exceeded during the impact or related event. Any solids are essentially fluidized due to energy deposition. The process seems similar for both solid material breakup and ejection, and for melting or vaporization followed by material ejection. In these cases, it does not matter how or where the energy was put into the system, as long as it was on or near the surface of the material that craters.

Photographs of five craters that are used here to form the basis for extrapolation to the sizes and energies of LENR craters are shown in Fig. 8. The energy needed to form each of these craters was measured or estimated. Hence, it is possible to fit and then extrapolate the energy and size data to estimate the formation energies of individual craters in LENR cathodes. In the case of the Arizona impact crater, the energy was delivered by a meteor. That is mechanistically similar to the explosion of 500 tons of TNT on the surface of an island in Hawaii, and to the hyper velocity projectile impact. The laser-produced crater is also a case of energy arriving on the surface of a solid from the outside of the target. The nuclear explosion was different, because it was buried at a depth of almost 200 m. However, all of these craters involved energy densities that overwhelmed the structural strength of the involved materials. Hence, it is expected that they are "self-similar" and would obey the same scaling law.

The numerical characteristics of the craters shown in Fig. 8 are summarized in Table 1. The parameters for the Chixulub crater are also in Table 1. That crater was due to the meteor impact thought to have caused the mass extinction of dinosaurs about 63 million years ago. The energy estimate for the Arizona crater is available at the indicated web site. The energy released by the nuclear device was probably measured by seismic means. The energy stored in the 500 tons of TNT was computed from known calibrations. The hypervelocity impact energy was calculated from the

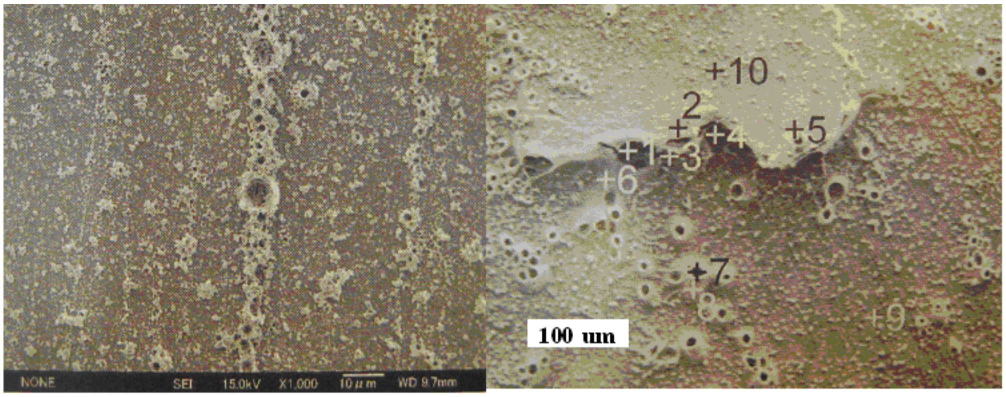


Figure 6. Craters approximately aligned with scratches on Pd cathodes. Left: These data are from Toriyabe et al. at ICCF-12. The crater density in this image is 1.6×10^6 per cm^2. Right: An image due to Zhang and Dash shown at ICCF-13. The crater density is 6.4×10^4 per cm^2. These images enable plotting of distributions (histograms) of crater diameters.

Table 1. Diameters and production energies for craters resulting from six events

Crater origin	Diameter (m)	Energy (J)	Reference
Chixulub meteor	180,000	4.0 exp (23)	[12]
Arizona meteor	1150	1.2 exp (16)	[13]
Nuclear device	390	4.4 exp (14)	[14]
500 tons of TNT	72	2.1 exp (9)	[15]
Hypervelocity Impact	0.033	8.0 exp (3)	[16]
Laser focus	0.00075	4	[17]

known projectile size and its measured velocity. The energy in the laser pulse was measured with a calorimeter.

A plot of the energies known or estimated to produce the six large craters as a function of their measured diameters is given in Fig. 9. It is seen that the expectation of crater size scaling with energy is reasonably well satisfied. The point for the Chixulub event might be high due to uncertainties in the estimate of energy for that event. The point for the half kiloton of TNT might be shifted to the right somewhat due to the explosion occurring near a beach with loose rocks, resulting in a larger crater. However, the plot is sufficient for extrapolation to the size range of craters from LENR experiments. The energies for crater production scale approximately with the crater volume, independent of material or mechanism. That is, a prefactor of 3 rather than 2.67 would show exact scaling of the volume with the input energy. The difference between the value from the fit and 3 might be due to the different crater shapes for the six events. Crater diameters are a measure of crater volumes. They will be used below to estimate erosion rates in LENR experiments and devices.

Figure 10 is an extrapolation of the line in Fig. 9 to smaller crater sizes, those appropriate for LENR. The two computed energies from Fig. 7 for the formation of a conical crater with a diameter of 50 μm nicely bracket the extrapolated line. It is seen that a 1 μm diameter crater can be formed by 1 nJ of energy. A crater with a diameter of 100 μm requires 1 mJ for its formation

The crater densities from Fig. 6 and the energies per crater from Fig. 10 can now be used to estimate two significant quantities, the total energy released during crater formation and the total amount of material removed from a cathode by crater formation. Figure 11 is a parametric plot of these quantities against the areal density of craters. The values of

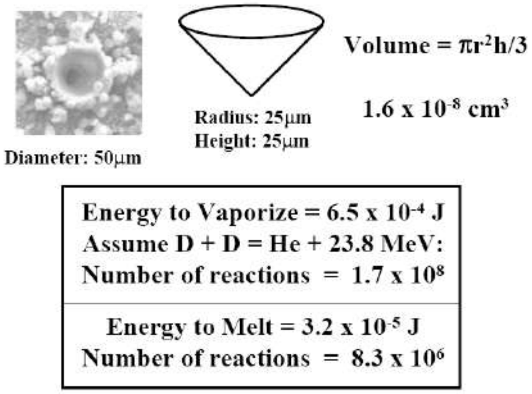


Figure 7. Geometry and results for calculation of crater formation energies.

Figure 8. Craters of widely different size scales: From the left, a meteor impact crater about 1.15 km across in Arizona, a crater 390 m in diameter from a nuclear device test in Nevada, the crater about 72 m across from a TNT explosion in Hawaii, an Al hyper-velocity impact target with a 33 mm diameter crater, and a crater 0.75 mm across at the focus of a high powered laser.

crater density, energy per crater and crater volume, which are relevant to craters from LENR experiments, are spanned in that figure.

Many combinations of parameter can be examined readily by use of Fig. 11. For example, if 1 mJ were released for each crater, and the crater density were 10^6/cm^2, the areal energy would be 1 kJ/cm^2, or 10 kJ for a cathode with a total area of 10 cm^2. For these parameters in an experiment running for 24 h, the average power released by cratering events would be about one quarter of a watt. Hence, the average power generated during cratering events is not large, but it could be a significant fraction of the excess power production in some electrochemical experiments.

The volume of material removed by cratering can also be estimated from Fig. 11. The conical shape shown in Fig. 7 is assumed. For the same 10^6/cm^{2}crater density and an intermediate crater diameter of 10 μm, the total material eroded from the 10 cm^2 cathode would be 0.01 cm^3. That is a small fraction of the volume of a normal rod-shaped cathode with 10 cm^2 surface area. However, long-term operation could lead to removal of a significant fraction of the cathode, and the ejection of a volume approaching 1 cm^3 into the electrolyte. Hence, it can only be said now that erosion due to crater formation might be a practical limitation on the operational duration of electrochemical LENR cells designed to produce energy.

Returning to the energetics of crater formation, one of the most fundamental issues in crater formation by LENR is the number of nuclear reactions needed to produce a crater. We found that 1 nJ is enough energy to produce a 1 μm

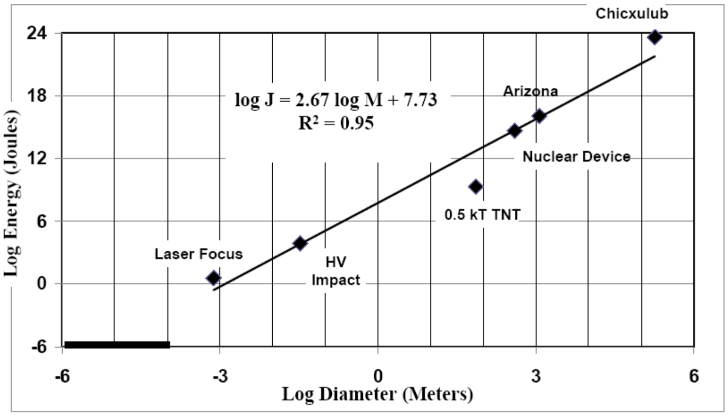


Figure 9. Log-Log plot of the data in Table 1. It is noted that the vertical axis spans 30 orders of magnitude, while the horizontal axis ranges over 12 orders of magnitude. The bar in the lower left-hand corner gives the sizes for craters in LENR cathodes. The straight line was obtained by a least squares fit using EXCEL.

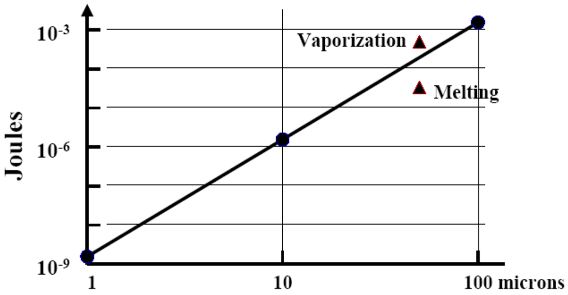


Figure 10. Plot of energies for cratering against crater diameter. The line is the extrapolation of the equation in Fig. 9. The two triangles give the energies for production of a 50 μm diameter crater by melting or vaporization, as given in Fig. 7.

diameter crater and 1 mJ is needed for a crater 100 μm in diameter. An intermediate value of 1 μJ is the energy associated with a 10 μm diameter crater. That energy of 1 μJ is equivalent to 6.2×10^5 10 MeV energy releases. Hence crater formation apparently requires the nearly simultaneous occurrence of many LENR reactions. One million atoms can fit into a cube approximately 100 mm on an edge. That is the minimum nuclear reaction volume could be much smaller than the crater size.

The time interval over which energy releases can occur and still make craters is important. If a region of 1 μm^3 is heated to above vaporization or melting temperatures, how long does it take to fall to below the melting point? This question can be answered by use of software for thermal transport, such as ANSYS [18].

A summary of the energetics and removed volumes due to crater formation follows.

- The energy releases associated with crater formation are in the range of 1 nJ to 1 mJ.
- Many nuclear reactions occurring within a small fraction of a second would be needed to explain the formation of craters due to LENR.

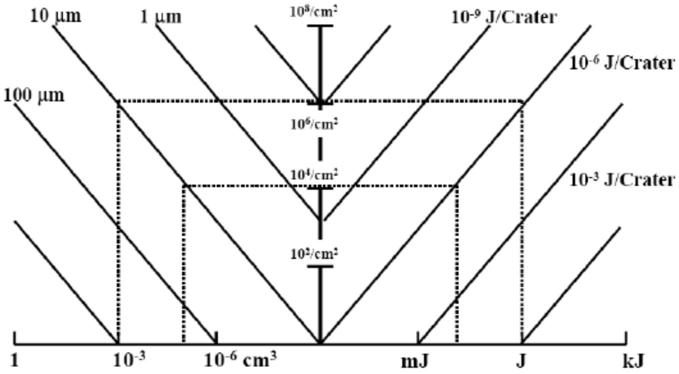


Figure 11. Erosion volumes (*left*) and energy releases (*right*) from crater formation.

- The fraction of total excess energy measured in past LENR experiments, which is associated with crater formation, could be significant, depending on the crater density and size, and on the total excess energy.
- The fraction of the volume of the cathode removed during crater formation might be a practical problem in long-duration experiments, but has not been seen to be that in experiments to date.

4. Conclusion

Important early experimental studies by Srinivasan and his colleagues produced data relevant to the basic questions of how crater formation requires energy release localized in both space and time [19,20]. They performed long-exposure autoradiography of Ti targets from plasma focus experiments with deuterium gas. The resulting images, due to low-intensity decay of tritium, a nuclear reaction product, showed long-lasting activity in generally linear local regions of the anodes, possibly along grain boundaries. The widths of those regions were less than 200 μm in some areas of the target. The researchers at the Bhabba Atomic Research Center (BARC) also observed bursts of neutrons, and report "a rapid cascade of up to 10^{12} tritium producing nuclear reactions takes place in quick succession in this local site, in a sort of micro-nuclear explosion". The BARC data are very important because they indicate the occurrence of nuclear reactions. The researchers there recognized that craters, as well as their radiographs and neutron bursts, are signatures of small, fast energy producing phenomena.

In this study, we have advanced the knowledge and understanding of LENR craters somewhat, but many more basic questions about crater formation remain. They are now presented and discussed:

- The most fundamental question about observed craters from LENR experiments is whether, indeed, they are due to energy released by nuclear reactions. Hard evidence for such craters appearing only in LENR experiments, or only in LENR experiments that produce excess energy, is not yet available. It will be necessary to be able to run identical cells in which there is no excess energy and in which there is energy production at various levels, and then examine the cathodes from all cells, in order to quantitatively correlate the appearance, number and size of craters with the measured excess energy. The reproducibility and control needed to perform the experiments and correlations are still very challenging to achieve.
- The diversity of observed craters raises different questions. Can variations in the amount, timing and depth of energy releases account for all the different topologies, as shown above in Section 2? Why are some craters very irregular and rough in shape, while others are quite round and often smooth, similar to those shown in Fig. 8? Can localized and simultaneous gas evolution and electrochemical deposition, sometimes along scratches, account for any of the observed crater morphologies without energetic releases?
- Another foundational question is whether or not all craters are due to energy releases, whatever the origin of the energy. It might be that some craters with shapes apparently reflecting the orientation of the crystal in which a crater occurs are due to strains or other energy concentrations having no association with LENR.
- Do the energy releases that cause craters occur exclusively on the surface of materials or also at various depths within the cathode? It is not known if the observed variations in crater size, such as in Fig. 6, are due to (a) variations in the amount of energy released per event, (b) variations in the depth of release, or (c) both of these possibilities. If energy releases, which are sufficiently close in space and time to form craters when they are near the surface, actually occur deep in a cathode material, they will lead to heating, but no surface craters. So, it is asked if there are any post-experimental artifacts within a cathode material that might be observed by use of metallurgical techniques of sectioning and polishing. If so, could such artifacts be related to rapid energy releases, such as those which produce craters, when they are near or on the surface?
- Of the energy that is released during crater formation, what fraction of it goes into electromagnetic and acoustic emissions? Diagnostics of co-deposition experiments have shown the emission of both infrared radiation [21] and of sound [22] during LENR experiments. It is possible that those observations have nothing to do with

crater formation. But, it is also possible that the emissions occurred during crater formation. If the latter is the case, might infrared or acoustic time radiations be diagnostically useful? Could the time history of events be correlated with observed areal densities of craters on cathode materials? Might infrared or acoustic spectral information shed light on the mechanisms and dynamics of rapid energy releases? Could the amplitudes of sonic pulses indicate the relative size of energy releases and associated crater sizes, or even energy releases without crater formation?

- Because a large number of nuclear reactions in nearby locations and short times appear to be needed for crater formation, there is the question of whether they happen coincidentally by accident, or else is there some kind of a sequence in which reactions quickly lead to other reactions? The appearance of craters during some, but maybe not all energy release events, might constitute evidence of something resembling a chain reaction in LENR experiments. Experiments at modestly elevated temperatures have shown that higher temperatures favor production of excess energy. The temperatures that occur during the earliest times of a crater forming event might be very high, far in excess of vaporization temperatures. Otherwise, they would not lead to the observed effects shown in Section 2.
- There follow questions about the purposeful production of craters. For example, since surface scratches lead to craters forming in lines along the scratches, as in Fig. 6, would scoring the surface of LENR cathodes prior to experiments lead to more crater production. Might the production of excess energy, or the emission of infrared radiation, or the occurrence of shorts bursts of sound, correlate with the density of scratches in cm/cm^2? Would the frequency of crater production in space and time relate to the shape and size of the surface structures? If the energy releases due to crater formation constitute a significant fraction of the excess energy, could the willful introduction of surface morphology improve the reproducibility or output of LENR experiments? Would it matter if the surface scratches intersected each other? If so, would the angle between scratches be a significant parameter?
- Many LENR experiments are driven much harder and with unusual time profiles compared to more usual electrochemical experiments. McKubre wondered if the appearance of craters might correlate with the input power to electrochemical experiments. Violante similarly asked if craters might correlate with the protocol used to load a cathode or the use of applied voltage modulations in an experiment.

Finally, we speculate on the potential relationship between small craters on cathode surfaces and a singular event described in a paper by Fleishchmann and Pons in 1989 [23]. They were conducting an electrolytic LENR experiment in which the cathode was a cube of Pd 1 cm on a side. During the night, the experiment suffered a thermal runaway, which lead to the following statement in their paper: “WARNING! IGNTION! We have to report here that under the conditions of the last experiment, even using D_2O alone, a substantial portion of the cathode fused (melting point 1554^oC), part of it vaporized, and the cell and contents and a part of the fume cupboard housing the experiment were destroyed.” There are two remarkable aspects of the event. First, it was not documented in detail after the occurrence. And, reportedly, it caused Fleischmann and Pons subsequently to use much smaller cathode volumes, generally in cylindrical geometries. Apparently, they were concerned about safety and the danger of large high-power events.

The point is that both the small craters on cathode surfaces and the extraordinary event observed by Fleishmann and Pons have in common the achievement of very high LENR power densities. Could it be that the conditions, which occur with significant frequency on cathode surfaces in some LENR experiments, also happened in a much larger volume within the big cubic cathode? Might large-scale and high-power releases be produced willfully, maybe on demand? Could their power levels be controlled? If so, what are the implications? Could they be used beneficially in practical LENR power devices? Might they be used to augment existing weapons, or even enable new weapons? Historically, new sources of energy were commonly used for military purposes.

There are certainly many basic scientific and practical questions about craters and high-power releases due to

LENR, whatever their size. Clearly, what is already known experimentally, and the many open questions, both serve to challenge theoreticians to provide needed understanding of the diverse phenomena related to craters and high-power releases in LENR materials.

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