J. Condensed Matter Nucl. Sci. 36 (2022) 1–24

Research Article

Lattice Energy Converter II: Iron Hydrogen Host Material

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Abstract

Continuing development of Lattice Energy Converter (LEC) technology has resulted in both experimental and theoretical advancements. Replicated experimental results and analysis for a LEC wherein a codeposited palladium-hydrogen working electrode produced spontaneous and sustained electrical energy attributed to ionizing radiation have been previously reported. Herein is reported the use of a working electrode comprised of codeposited iron-hydrogen from an aqueous solution of $FeCl_2$ which demonstrated similar capabilities to produce spontaneous and sustained electrical energy as well as ionizing radiation. These results also have been replicated. http://ikkem.com/iccf23/PPT/Invited%20Gordon%20ICCF%2023%20LEC%20T5.MP4. This paper updates the presentation at the workshop in honor of Dr. Srinivasan in January 2021 which is available at: https://www.youtube.com/watch?v=J4dzTWY_aWM This paper provides additional analysis that supports the observed experimental results from both presentations.
 ISSN 2227-3123

Keywords: Direct energy conversion, Electricity generation, Ionizing radiation

1. Introduction

As previously reported, the Lattice Energy Converter (LEC) has demonstrated the capability to convert thermal energy in a codeposited palladium-hydrogen lattice into ionizing radiation [1]. It is well known that hydrogen will diffuse into many metals and alloys to form an interstitial metal hydride [2] but it was not known if other metal hydrides would produce results similar to the LEC palladium-hydrogen system.

H. Mehrer [3] discusses the diffusivity of hydrogen in various metals and includes a plot on page 322 of the diffusivity of iron, palladium, and nickel as a function of inverse Kelvin temperature.

As shown, in Fig. 1, the hydrogen diffusivity of iron is approximately two orders of magnitude greater than that of palladium at room temperature and is approximately equal to the hydrogen diffusivity of palladium at its melting point.

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 ISSN 2227-3123

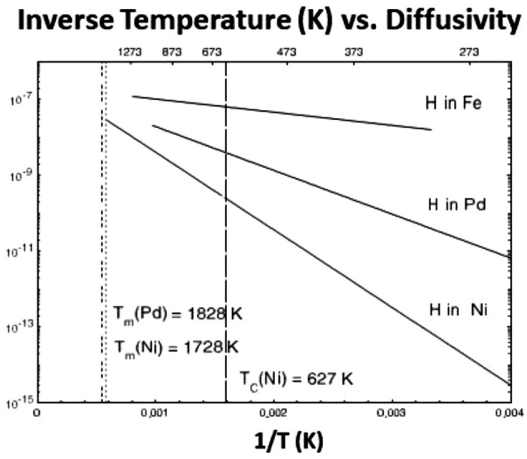

Figure 1. Plot showing hydrogen diffusivity of Fe, Pd, and Ni vs. inverse temperature.

Diffusivity describes the ability of a H atom to circulate through the lattice under a relative H concentration gradient. The reader may be surprised to see that diffusivity in Fe is larger than in Pd because it is well known that palladium is quite permeable to hydrogen. This is because the permeability is given by the product of the diffusivity by the hydrogen solubility in the metal. H solubility is much higher in Pd than in Fe and it is the reason why the permeability is so high in Pd in spite of a lower diffusivity.

Although properties such as permeability and solubility may also contribute to LEC cell performance, diffusivity may be an important parameter. The much lower cost and worldwide availability of iron could be important factors in the future economic feasibility of LEC devices. For these reasons, LEC cells were prepared using working electrodes of codeposited iron hydrogen-host-material (HHM) to evaluate iron-hydrogen performance.

2. Experimental description

As shown in Fig. 2, LEC cells were prepared where the codeposited Pd-H brass working electrode (WE) as previously described [1], was replaced with a 1/8 inch by 4 inch black iron (low carbon steel) pipe nipple. The iron pipe nipple included a protective coating to prevent oxidation which was removed by sanding. The iron pipe nipple was the cathode in a plating solution of 0.1M $FeCl_2{\cdot}4H_2O$ in distilled H_2O and platinum wires were the anode. The initial plating current was approximately 100 μA/cm^2 for 15 minutes and then increased to approximately 1 mA/cm^2 for 15 minutes followed by an increase to approximately 2-3 mA/cm^2, for approximately 4 hours, until the codeposited Fe-H was visible and appeared to be uniform. The codeposited iron HHM WE was removed from the plating solution and placed in a 1/2 inch galvanized pipe nipple counter electrode (CE)while avoiding physical contact between the pipe nipples and connected to a digital voltmeter (DVM) to determine if a voltage was produced. If no voltage is measured, additional codeposition of the HHM may be required. The codeposited iron WE is blotted dry and assembled into a LEC cell. A vacuum ($\sim$50 to 75 Torr) is pulled and the cell is refilled with hydrogen gas. Hydrogen gas pressures ranging from several hundred Torr to a few thousand Torr have been successfully tested and other pressures are expected to work.

Multiple Fe-H LEC cells have demonstrated the ability to spontaneously produce a voltage and current. In addition, there have been multiple successful replications of the Pd-H, and/or the Fe-H LEC by several individuals [4], [5],

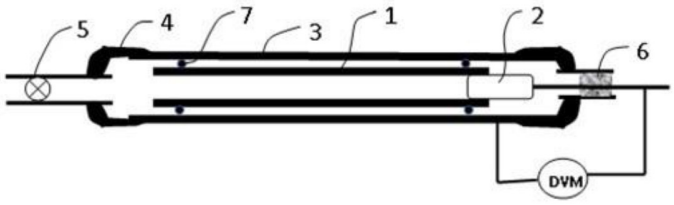

Figure 2. LEC cell using iron pipe nipple codeposited with FeH for the working electrode.
1. 1/2 inch by 4 inch iron pipe nipple with id threaded at one end with $5/16$ 24 tap and then codeposited with $\mathrm{Fe} - \mathrm{H}$
2. $5/16 \times 24$ set screw with Cu wire brazed on one end and screwed into threaded nipple
3. 1/2 inch by 5.5 inch brass or galvanized pipe nipple (provides different work functions between outer pipe and the inner iron pipe nipple.)
4. $3/2$ inch to $1/4$ inch bushings on each end of the $3/2$ inch nipple
5. $1/4$ inch nipple and valve to evacuate and fill LEC with hydrogen or deuterium gas
6. $1/4$ inch nipple with high temperature epoxy fill to provide electrical insulation
7. Small high temperature Orings ora bead of high temperature epoxy to maintain physical separation between items 1 and 3 while allowing gas to pass between. Note-Orings provide separation and do not seal the gas.

[6], [7]. Similar results have been reported using modified cell designs including hydrogen or deuterium, modified codeposition protocols, modified electrode geometries, as well as the inclusion of additional components between the electrodes. [8], [9], [10]. The collective results provide compelling evidence of the existence of these surprising phenomena.

3. Experimental Results

The Fe-H LEC cells have been characterized following the same procedures used for Pd-H LEC cells including tests in air as well as in hydrogen [1]. A typical LEC cell test consists of several steps. The cell is placed in an electric kiln at laboratory temperature that is instrumented with one or more thermocouples. The LEC electrodes are connected to a high input impedance DVM ($\sim$1000 MΩ) with the WE positive and the CE negative. A variable resistance box is connected between the electrodes with a nominal starting resistance of 1 MΩ. The DVM is connected to a digital computer via an optical USB connection and the recording sample rate is set at 2 S/s. The kiln is powered by a variable voltage auto-transformer that is started at a low voltage setting and intermittently raised. LEC voltage and kiln temperature are recorded, and variable resistance load tests are performed occasionally in order to characterize LEC performance, i.e., LEC voltage versus load resistance at selected LEC operating temperatures.

Figure 3 is an example of Fe-H LEC performance in air at approximately 30 °C soon after it was removed from the plating bath. The working electrode was a 1/8 inch by 4-inch black iron pipe nipple that was codeposited with iron from a solution of 0.1 M $FeCl_2$ in H_2O.

A test to measure the LEC voltage under various load conditions was conducted immediately after the working electrode was removed from the plating solution and placed in the counter electrode containing air at approximately 30 °C. The performance of this Fe-H LEC is qualitatively similar to that of a Pd-H LEC in that the load current of the LEC behaves as if it were a current source shunted by a variable voltage conductance. More explanations can be found in [1].

The shunt current as a function of load resistance is thus the difference between the load current at low load resistance and the measured load current as a function of resistance. Load power is computed as load voltage squared divided by load resistance or the product of load voltage by load current. Load power is found to be a maximum at intermediate values of load resistance. Figure 4 shows LEC performance for a Pd-H WE comprised in part of a

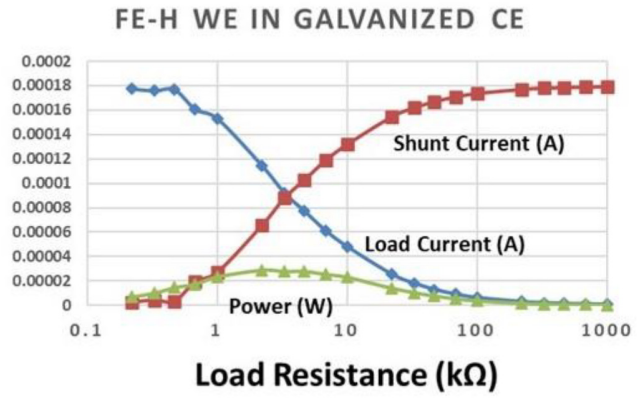

Figure 3. Load current, shunt current, and power as a function of resistance.

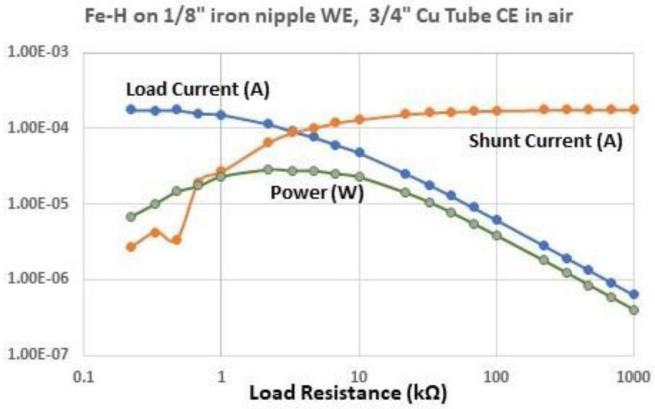

Figure 4. Plots of load current, shunt current, and power as a function of load resistance in kΩ.

stainless-steel screen electrode with codeposited Pd HHM and measured shortly after the electrode was removed from the plating solution.

As experiments have demonstrated, a LEC cell develops a spontaneous voltage between the electrodes with no input other than the energy in the lattice of the hydrogen-host-material including the thermal kinetic energy of the hydrogen that is occluded therein. The current-voltage (I-V) characteristics of a LEC cell is non-ohmic in the sense that the current density and the electric field do not go to zero simultaneously where cell current, I, is the integral of the current density, i, over the surface area of the WE and the cell voltage, V, is the integral of the electric field, E, over the separation distance between the electrodes.

JSE Townsend observed [11].

> "It is difficult to calculate mathematically the equation of the current-electric-force curve in the general case for parallel plate electrodes, when recombination and diffusion are in progress, as the problem becomes very

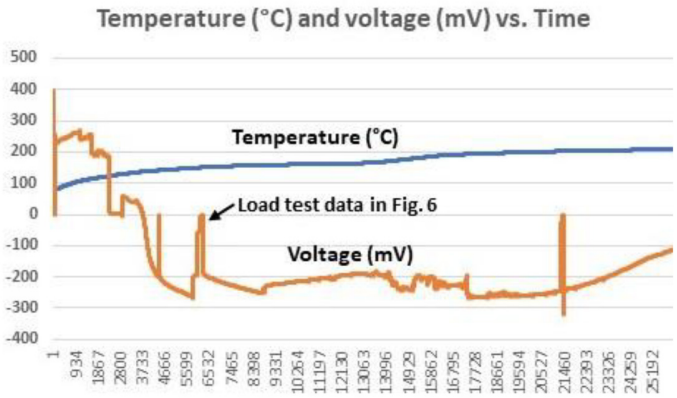

Figure 5. Plots of the voltage (mV) under varying load resistances and temperature (°C) as a function of time. Total time for this test was approximately 13 hours.

complicated owing to the fact that the number of ions per cubic centimetre varies at different points of the gas."

Eduard Riecke reported the full set of equations for the conduction of electricity through an ionized gas containing two types of ions, positive and negative, in a parallel-plate condenser in 1903 [12]. An English translation of Riecke is included as Appendix A. He considered the case where there was a space charge in the gas and included the effect of the electric field on the ions, the diffusion of the ions, as well as their recombination to form neutral molecules and then was able to calculate the approximate distribution of the electric field between the electrodes. Using this electric field distribution approximation, the spatial distribution of the ions between the electrodes now can be estimated by integration assuming the densities of positive and negative ions are equal. Using modern notation, the equation giving the current density in terms of ion drift and diffusion can be rewritten as:

$$i/e = (\mu^+ + \mu^-)\boldsymbol{E}n + (\boldsymbol{D}^- - \boldsymbol{D}^+)dn/dx \tag{1}$$

which has a solution of the form, [Appendix B]:

$$\boldsymbol{n(x)} = (1/\boldsymbol{u}(x))[\int^x u(x')g(x')dx' + C], u(x) = \exp[\int^x p(x')dx'] \tag{2}$$

where $p(x) = (\mu^+ + \mu^-)E(x)/(D^- - D^+)$, $g(x) = (i/e)/(D^- - D^+)$, $D^{\pm} = \mu^{\pm}k_{eV}T$, $E(x)$ is the electric field within the gas, and C is a constant of integration that can be evaluated using boundary conditions.

As shown, the voltage increased initially when the temperature was less than 100 °C. As the temperature increased, the voltage started to decay and ultimately changed polarity. During the initial phase of the test, load resistances were changed from 3.3 k to 2.2 k to 1.0 kΩ which were selected to be approximately the loads that had produce the maximum power in previous tests. Some of the abrupt changes in voltage during this time are due to the changes in load resistance. After the voltage changed sign, the resistance was set to 1 MΩ except for times when load tests were conducted.

Figure 6 is a plot of a load test of an iron pipe nipple, codeposited with iron and placed in a galvanized CE that was filled with hydrogen gas. The test was conducted as indicated on Fig. 5 when the temperature was approximately 160 ^{o}C. Even though the polarity of the voltage has switched, a plot of the absolute values of the variables has the same features as shown in Figs. 3 and 4.

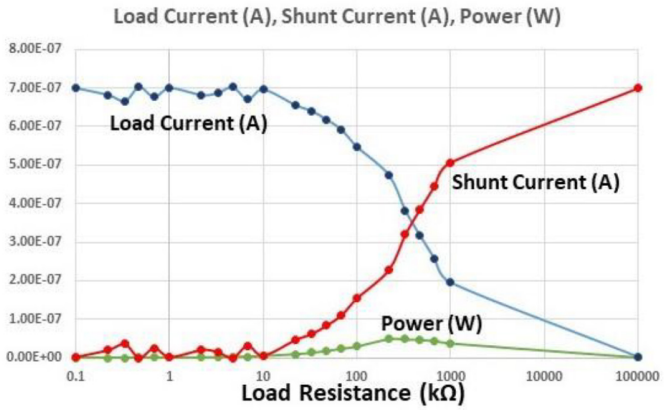

Figure 6. Load current, shunt current, and power as a function of resistance.

Figure 7. Photograph of the working electrode taken after the temperature test shown in figures 5 and 6.

Figure 7 is a photograph of the working electrode that produced the data plotted in Figs. 5 and 6. The WE is a 1/8 inch black iron pipe nipple by 4 inches long that had codeposited with iron from an aqueous solution of 31% HCl using iron wires as the anode. Prior to the test, the Fe codeposition was lumpy but after the test, multiple unusual features are present. As shown these features appear to be the result of ejecta that produced a "cylindrical tower" that is perpendicular to the surface of the WE and are clearly visible to the naked eye, unlike features reported from Pd-D working electrodes that were a few microns in diameter [13]. The color of the inside surfaces of the ejecta is what would be expected if the Fe had oxidized. This is the first WE that we have observed with these features.

4. Possible explanation of LEC voltage generation and its behavior

As currently understood by the authors, LEC voltage generation and the conversion of lattice energy into electrical energy is a multi-step process. Some of these steps are readily explained while others await full explanation. The first step, and perhaps least understood step, is the conversion of the thermal energy in the hydrogen occluded lattice of electrodeposited HHM into some form of radiation. The second step is the conversion of the radiation into ionized gas in fluidic contact with the HHM and heat. The third step, and perhaps better understood step, is the conversion of

the ionized gas into voltage and current in an external resistive load impedance. Throughout this multistep process, total energy, including mechanical, chemical, thermal, and nuclear, must be conserved. No 'excess energy' is being produced.

One possibility is that the radiation generation process might be purely mechanical in origin. Thermally generated phonons in the lattice of the HHM interact linearly or nonlinearly to produce regions of high amplitude atomic motion [14], [15] that interacts either directly with the occluded hydrogen atoms within the lattice; or indirectly with the hydrogen atoms within lattice vacancies, super abundant vacancies, or other crystal defects to emit particulate and/or electromagnetic radiation into the gas. Alternatively, the radiation generation might be due to some form of lattice enabled nuclear reaction (LENR) processes that produces particulate and/or electromagnetic radiation. Whatever process or combination of processes responsible for the production of the radiation itself is difficult to measure and determine its form. That radiation is produced is indicated both by the fogging of film [16], [17], the color change of chemically treated paper exposed to the radiation [18], the production of voltage in semiconductor material exposed to the radiation [19], the development of voltage in combinations of materials in contact with hydrogen and/or deuterium gas [9], and by the conduction of electricity through H_2, D_2, and air exposed to the radiation [20], [21].

The conversion of radiation into ionized gas and heat is a well-documented process. The ionization of gas by Röntgen rays (X-rays) was described by JJ Thomson and E Rutherford in 1896 [22] and by uranium rays in 1899 [23] and it is now known that any energetic charged particle can ionize a gas [24] or water vapor [25]. The minimum energy required to remove the first electron from a gas is called the ionization potential and tables of ionization potential are readily available [26]. The ionization potential for H_2 is about 13.6 eV and that for D_2 is about 15.5 eV. However, in the process of ionizing a gas, translational and rotational energy also is imparted to the gas. In the case of polyatomic molecules such as H_2 and D_2, energy also goes into internal bond motion so that the average energy required to ionize gases is greater than their ionization potential. The average energy required to ionize a gas is known as the W-value of the gas and is about 35 to 36 eV for H_2 and D_2 [27]. Thus, the thermal energy, enthalpy, or heat energy, of a gas is increased by ionization and the total heat energy increase of the gas can be estimated by multiplying the W-value of the gas by the ionization rate per unit volume of the gas and integrating over the volume of the gas being ionized. The calculated thermal energy being produced based on the number of ions in the gas and the current produced, is several orders of magnitude below that which calorimetry can detect. This opens the possibility that the occurrence of LENR may be much more pervasive than calorimetry indicates, and when combined with the self-initiation and self-sustaining capabilities demonstrated by the LEC, suggests a possible connection to the reactions and processes leading to biological and nuclear transmutations. [28] [29].

The generation of the LEC voltage can occur in several ways. One possible way is that charged particles are emitted from the WE with sufficient energy to ionize the gas and while ionizing the gas transit through the gas to the CE and deposit their charge on the counter electrode. This mode of voltage generation is analogous to that of a direct charge nuclear battery [30] [31]. Another method of LEC voltage generation is by the photoelectric effect. Electromagnetic energy emitted from the working electrode causes electrons to be emitted from the CE. The emitted electrons then ionize the gas while behaving as free electrons before they attach to neutral molecules to become negative ions. The emission of the electrons from the CE causes a charge to develop on the electrode and thus a voltage to be generated. Another possibility of LEC voltage generation is that the WE and the CE have different work functions thus generating a Volta effect voltage when the gas between the electrodes of different work functions is ionized. LEC voltage generation also may be caused by the different rates of diffusion of positive and negative ion distributions in the gas. These last two methods will be discussed in the following section.

In 1903 JJ Thomson published the first edition of his treatise entitled Conduction of Electricity through Gases, [32] that expanded on his 1899 paper "On the theory of the conduction of electricity through gases by charged ions," where he proposed a method to estimate the electric field distribution in a conducting gas when diffusion of the ions is neglected. In the same year, 1903, Eduard Riecke [12] at the University of Göttingen published in German his method

to estimate by successive approximation the electric field distribution in a conducting gas when the diffusion of the ions is included. An English translation is presented in Appendix A. Measurements of spontaneously conducting LEC cells has shown that LEC cells behave as if they are a current source due to the diffusion of charge concentration within the gas and an internal electric field dependent shunt current caused by the drift of the ions due to the electric field within the gas. Thus, to explain the behavior of LEC cell voltage as a function of both time and temperature, it is necessary to consider both the voltage across the cell and the distribution of charge within the cell.

In 1932 Karl K Darrow explained the spontaneous voltage developed when an ionized gas is contained between two plane-parallel electrodes [33]. A summary of Darrow's and other researchers' contributions are given in [1]. Darrow's insightful contribution explaining the spontaneous voltage produced by a LEC where there are only two types of ions, positive and negative, with different diffusion coefficients is reproduced here with emphasis added.

> "Suppose the ions of the two signs are spread identically through a gas between two walls—by 'identically' I mean that everywhere the concentrations of the two kinds are equal, though their common value varies from place to place—and that this state of affairs is stationary. **Then there must be ionizing rays acting continually on the gas, and also there must be a potential-difference between the walls**. For if there were no field, the negatives would diffuse along the concentration-gradient more rapidly than the positives; there would be a net current; this would result in a depletion of negatives, and an excess of positive charge would arise in the gas, in contradiction with the assumption. But suppose there is a P.D. [Potential Difference] between the walls, in such a sense as to oppose the negatives and pull the positives forward as they stream together down the gradient. A value for this potential-difference can be found, such that the field strength will retard the negatives and encourage the positives just sufficiently to annul the net current aforesaid;"

When a spontaneously conducting LEC is observed over an extended period of time, or when the temperature is slowly changed, the voltage may vary with time or even change sign multiple times. When an externally applied voltage on a LEC is reduced, the current may go to zero before the voltage goes to zero. This behavior is different than that reported in early experiments on the conduction of electricity through gases that were carried out at the Cavendish Laboratory in Cambridge [22], [23], [32] [34] and in later experiments using ionization chambers [35] where the I-V characteristic was observed to be ohmic at low voltage. These unusual electrical phenomena need to be understood in order that they can be either mitigated or exploited in future engineering applications of a LEC.

A cylindrical coaxial LEC with an externally applied voltage is similar to a Gerdien Condenser that is traditionally used to measure the density of ions in a gas. Some Gerdien Condenser applications are to characterize atmospheric pressure plasmas [36] or for atmospheric ion measurements [37]. A plane-parallel electrode LEC with external voltage applied is similar to a plane-parallel ionization chamber [24] while a cylindrical LEC with externally applied voltage is similar to a DC voltage ionization chamber with cylindrical electrodes [38]. Both a Gerdien Condenser and a LEC behave strangely when no voltage is externally applied to the electrodes and although the explanations for the Gerdien Condenser and LEC performance are different, similar phenomena may be responsible for both unusual behaviors.

4.1. Contact potential or work function effect

Two possible causes of LEC voltage change with time and temperature are the variation of the work function of the electrodes or variation in the mobility of the ions in the gas due to changes in the molecular or atomic composition of the gas. With regard to the variation of the work function of the electrodes The Radio Corporation of America (RCA) [39] reports that contact potential difference between electrodes of different material may lead to a measured cell voltage when the gas between the electrodes is ionized. They report that

> "The principle involved here goes back to 1897, when Lord Kelvin[12] only a year after the discovery of radioactivity by [Henri] Becquerel, used the radioactivity from uranium to ionize the air between two plates

of dissimilar metals and reported that he had observed a potential between them of up to 1.9 volts. ⋯
[12] Kelvin, Lord, "Experiments on the Electrical Properties of Uranium", *Edinb. Roy. Soc. Proc.* Vol. 21, p. 417 (1897); also Mattr. and Phy. Papers, Vol. 6, p. 84 (1911). "The Direct Conversion of Radiation into Electrical Energy""

In 1928 *The Electrician* [40] reports "A New Electronic Battery" by Mr. J. Kramer in his presidential address before the Scientific Society of the Birmingham and Midlands Institute.

"This electronic cell would be similar to a voltaic couple, but the electrolyte would be replaced by radio-active material. It might also be described as a "self-charging" condenser. ⋯⋯. Turning to the new development, it is found that if the air gap between the dissimilar plates is occupied by radio-active materials a steady e.m.f. is produced."

In 1951 PE Ohmart [41] reports that

"Experiments have shown that if a cell, made up of two electrochemically dissimilar materials separated by a gas, is connected to a current measuring device, a small continuous current will be caused to flow from the more noble to the more active electrode without an external source of voltage when the separating gas is forcibly ionized by exposure to nuclear radiation. The current thus produced has been found to be dependant upon the nature of the electrodes and their surfaces, the type and flux of the energizing radiation, the type and pressure of the filling gas, and (when excited by gamma radiation) the gamma stopping power of the electrodes."

With respect to the role that contact potential could have on the performance of a LEC, KL Alpin [37] reports that for a Gerdien Condenser

"The tube material could be significant for two reasons: firstly that of its durability when used in the field, and secondly that of the effect of contact potential. Wåhlin (1986) discusses the effect of the material of the tube, opining that contact potentials cause offsets in the i-V response. This is credible, as two electrodes touching a fluid containing ions do make an electrochemical cell (e.g. Atkins, 1989), even if the electrolyte (air) is dilute. According to Wåhlin (1986), a Gerdien will measure a non-zero current when the bias voltage is zero, due to electrochemical potential at the surface of the tube. Wåhlin (1986) suggests that a steel tube has to be biased at about 0.4 V and the aluminum at 1 V to counteract this. ⋯
Atkins P.W. (1989), *Physical Chemistry,* 4^{th} edition, Oxford University Press ⋯ Wåhlin L (1986), *Atmospheric electrostatics,* Research Studies Press, Letchworth"

Consider the variation of the work function or contact potential of the electrodes of a LEC. Although there are listings of work function for many different materials, the work function of a given material is sensitive to the surface properties of the material. During prolonged LEC operation the ionizing radiation as well as the gas ions that transit to the electrodes can change the surface condition of the electrodes. Additionally, the fractional atomic loading of the HHM with atomic ($^1H_1$) or molecular ($^1H_2$) hydrogen or a combination of these gases is a function of the density of WE vacancies and other HHM structural defects such as grain boundaries. Fractional atomic loading of the HHM depends on the over-potential of the ionized hydrogen gas as an electrolyte and the current load voltage of the LEC. The number of HHM lattice vacancies varies exponentially with the inverse kelvin temperature of the HHM in accordance with an Arrhenius equation of the form $N_V = N_0 \exp(-E_a/k_{eV}T)$ where N_0 is a constant depending on the lattice material, E_a is an activation energy in electron volts (eV), k_{eV} is Boltzmann's constant expressed in eV/K, and T is the HHM temperature in Kelvin. Additionally, the number of grain boundaries increases with increased stress on the HHM due to changes in lattice dimension due to the occlusion of the hydrogen in the HHM lattice structure.

4.2. Gas ion mobility effect

There is a second phenomenon that in combination with changes in the work function or contact potential of the electrodes of a LEC may explain the unusual voltage variation of a LEC. This is the variation of the composite mobility of the gas ions due to changes in the composition of the gas during operation. A gas that is being ionized either by interaction with energetic particles or by electromagnetic radiation, *e.g.*, UV, X-rays, or gamma rays, may contain several different types of molecules with different masses as well as free electrons that have not yet attached to neutral molecules to form negative ions. Therefore, following Riecke [11], [12], assume that all ions carry a single charge, e, the conduction equation for a LEC can be written for plane-parallel electrodes as

$$i/e = \sum\nolimits_{\mathrm{k}} (v_{\mathrm{dk}}{}^{+} n_{\mathrm{k}}{}^{+} - D_{\mathrm{k}}{}^{+} \mathrm{d}n_{\mathrm{k}}{}^{+}/\mathrm{d}x) + \sum\nolimits_{\ell} (v_{d\ell}{}^{-} n_{\ell}{}^{-} + D_{\ell}{}^{-} \mathrm{d}n_{\ell}{}^{-}/\mathrm{d}x) \tag{3}$$

where i [A·cm^{-2}] is the measured cell current density, $v_d{}^{\pm}$ [cm·s^{-1}] is the magnitude of the drift velocity vector, $\boldsymbol{v}_d{}^{\pm} = \mu^{\pm}\boldsymbol{E}(x)$**,** of the ions, $\mu^{\pm}$ [cm^2·V^{-1}·s^{-1}] is their mobility, $E(x)$ [V·cm^{-1}] is the electric field strength, $n_k{}^{\pm}(x)$ [cm^{-3}] their density, $D^{\pm} = \mu^{\pm} k_{eV} T$ their diffusion coefficient, $k_{eV} = 8.617\text{x}10^{-5}$ eV/K is Boltzmann's constant, T [K] the effective temperature of a gas ion or an electron, x [cm] the distance measured from the anode, k the number of different positive ions, and ℓ the number of different negative ions. Note that the effective temperature of a free electrons can be much greater than the temperature of the gas ions which are approximately the ambient temperature of the gas.

5. Observations and Conclusions

1) The surprising phenomena produced by a LEC is real.
2) Carefully conducted control experiments using blank electrodes do not produce a voltage and current above the extremely small currents and voltages predicted for conduction through air that has not been ionized except for the naturally occurring ions [7].
3) LEC's are easy to replicate and are not very sensitive to codeposition protocols.
4) Both the origin as well as the nature of the LEC radiation that ionizes the gas is unknown.
5) Possible mechanisms that might produce the initial ionizing radiation at the working electrode include:
   (a) thermally induced vibration of the hydrogen host material's lattice enhanced by nonlinear wave-wave mixing in conjunction with the presence of hydrogen occluded in lattice vacancies near the surface of the hydrogen host material;
   (b) thermally induced interaction between multiple occluded hydrogen atoms contained within a vacancy, or super abundant vacancy, or other crystal defects;
   (c) LENR reactions such as when different nuclear spin orientations are present within a vacancy; or
   (d) a combination of mechanisms.
6) Given that the gas between the electrodes is ionized, LEC properties such as spontaneous and self-sustained production of a voltage and current has been explained.

6. Future research and development

Scaling up these experimental results to produce a commercial energy device requires 6-10 orders of magnitude. Possible areas for improvement include:

(1) better metallurgy/materials and plating processes to increase the activity that produces the ionizing radiation;
(2) methods to increase flux such as flowing gas, increased temperature, gas pressure;
(3) cell designs to optimize electrode separation distance and electrode design; and
(4) the application of magnetic and/or electric fields.

7. Conclusions

The conduction of electricity in a LEC is significantly different than that conventionally used to describe the conduction of electricity through gases for several reasons [33], [44], [45]. First and foremost is the fact that the source of the conduction is from some form of radiation produced by or within the hydrogen occluded hydrogen-host-material (HHM) of the cell's working electrode (WE). Secondly, the equivalent gas pressure caused by 'over-potential' in the gas near the HHM of the working electrode [43] appears to cause the conduction to not 'saturate' as the voltage across the cell increases.

Thirdly, diffusion of the ions plays a major role in the generation of the spontaneous voltage of a LEC when there is no electrical input to the LEC. Finally, the electrical work function of the material of the counter electrode (CE) also appears to play a role in the conduction of electricity in a LEC [41].

8. Appendix A

English translation of Eduard Riecke from the news of the K Society of Sciences in Göttingen. Mathematical-physical class. Issue 4. (1903).

8.1. On approximately saturated currents between plane-parallel plates

In two earlier works[1]) I developed the theory of the currents which occur between two concentric spherical surfaces as a result of the ionization of the air contained in the cavity. It was found that the observation of these currents provided a means of determining the reunion [recombination] constant α. In considering this possibility, it seemed to me of interest to also subject the case of an air space enclosed between two plane-parallel plates to a somewhat more precise investigation.

8.1.1. *The general equations of the problem*

Let one of two infinite plates, which are parallel to each other at the distance l, be positively charged, the other connected to the conductive [grounded to earth]. Let the intensity of the electric field enclosed between the plates be $\mathfrak{F}$. The air in the space between the plates is ionized, for example, by X-rays or radium rays. The ionization strength is q, the density of the electric current generated by the force $\mathfrak{F}$ [is] c. The densities of the positive and negative ions are N^+ and N^-, their absolute mobilities U and V, their diffusion coefficients k^+ and k^-. The coefficient of reunification [or recombination] is α, the electrical elementary quantum is denoted by ε, the speed of light by v. We establish the normal at some point on the positive plate. We make its base point the zero point, its two, which crosses over to the negative plate, the positive direction of an axis x.

Then the following equations result:

$$\left\{\begin{aligned} \frac{d\mathfrak{F}}{dx} &= 4\pi\varepsilon(N^+ - N^-), \\ v\varepsilon\left(UN^+ + VN^-\right)\mathfrak{F} - \varepsilon\frac{d}{dx}\left(k^+N^+ - k^-N^-\right) &= c, \\ q = vU\frac{d(N^+\mathfrak{F})}{dx} - k^+\frac{d^2N^+}{dx^2} + \alpha N^+N^-, \\ q = -vV\frac{d(N^-\mathfrak{F})}{dx} - k^-\frac{d^2N^-}{dx^2} + \alpha N^+N^-. \end{aligned}\right. \tag{I}$$

We have four equations and we can consider the quantities $\mathfrak{F}$, q, N^+, N^- as unknowns; it is then assumed that the current density c is determined by observation.

8.1.2. *The saturation current*

If one neglects the influence of reunification and diffusion, one obtains:[1]

$$\begin{cases} \dfrac{d\mathfrak{F}}{dx} = 4\pi\varepsilon(N^+ - N^-), \\ v\varepsilon(UN^+ + VN^-)\mathfrak{F} = c, \\ q = vU\dfrac{d(N^+\mathfrak{F})}{dx} = -vV\dfrac{d(N^-\mathfrak{F})}{dx}. \end{cases} \tag{II}$$

Solving the equations leads to the following formulas:

$$\begin{cases} \mathfrak{F}^2 = \mathfrak{F}_0^2 - \dfrac{8\pi \mathrm{c}}{\nu V}x + \dfrac{4\pi(U+V)}{\nu UV}qx^2, \\ N^+\mathfrak{F} = \dfrac{q}{\nu U}x, \quad N^-\mathfrak{F} = \dfrac{\mathrm{c}}{\nu\varepsilon V} - \dfrac{q}{\nu V}x, \\ \mathrm{c} = \varepsilon q l. \end{cases} \tag{III}$$

For $\mathrm{x} = 0$ it becomes:

$$\mathfrak{F} = \mathfrak{F}_0, \quad N_{\mathrm{o}}^+ = 0, \quad N_{\mathrm{o}}^-\mathfrak{F}_0 = \frac{\mathrm{c}}{\nu\varepsilon V} = \frac{q}{\nu V}l.$$

For $\mathrm{x} = l$:

$$N_\imath^+\mathfrak{F}_\imath = \frac{q}{\nu U}l, \quad N_\imath^-\mathfrak{F}_\imath = 0.$$

So it is:

$$\varepsilon v V N_0^-\mathfrak{F}_0 = \varepsilon v U N_l^+\mathfrak{F}_l = \mathfrak{c}.$$

Using these values, equations (III) can be reduced to the form:

$$\begin{cases} \mathfrak{F}^2 = \mathfrak{F}_0^2 - 8\pi\varepsilon N_0^-\mathfrak{F}_0 x + 4\pi\varepsilon\left(N_0^-\mathfrak{F}_0 + N_l^+\mathfrak{F}_l\right)\dfrac{x^2}{l}, \\ N^+\mathfrak{F} = N_l^+\mathfrak{F}_l\dfrac{x}{l}, N^-\mathfrak{F} = N_0^-\mathfrak{F}_0\left(1 - \dfrac{x}{l}\right), \\ c = \varepsilon q l. \end{cases} \tag{III′}$$

In order to get a more definite idea of the values of the coefficients appearing in these uations, it seems useful to put them as much as possible in numerical form.

We use values for this purpose:

$$U = 1,26 \times 10^{-8}, \quad V = 1,74 \times 10^{-8}, \quad \frac{V}{U} = 1,38.$$

$$\frac{k^+}{U} = \frac{k^-}{V} = 2,33 \times 10^{-6}.$$

$$k^+ = 0,0293, \quad k^- = 0,0405,$$

$$\varepsilon = 4,69 \times 10^{-10}, \quad a = 1,59 \times 10^{-6}.$$

[1] E. Riecke, Nacbr. d. K Gesellsch. d. Wissensch. zu Göttingen, math.-phys. Kl. Heft 1 u. 2. 1903; Ann. d. Phys. 12. P. 52, 1903.

Then it will be:

$$N_0^- \mathfrak{F}_0 = 0,00192 \times ql, \quad N_l^+ \mathfrak{F}_l = 0,00265 \times ql,$$
$$\mathfrak{F}^2 = \mathfrak{F}_0^2 - 0,226 \times 10^{-10} qlx + 0,268 \times 10^{-10} qx^2.$$

It follows from this that the variability of the field strength will in general only be very small.
The theory of the saturation current is only applicable if

$$\alpha N^+ N^-, \quad k^+ \frac{d^2 N^+}{dx^2} \text{ and } k^- \frac{d^2 N^-}{dx^2}$$

are very small with respect to q.

Now is:

$$\alpha N^+ N^- \mathfrak{F}^2 = \alpha N_l^+ \mathfrak{F}_l N_0^- \mathfrak{F}_0 \frac{x(l-x)}{l^2},$$

thus using the given values:

$$\alpha N^+ N^- = 8,10 \times 10^{-12} \frac{q^2 x(l-x)}{\mathfrak{F}^2}.$$

It must therefore be small [relative to] q

$$\frac{\mathfrak{F}^2}{8,10 \times x(l-x)} \times 10^{12}.$$

Also:

$$k^+ N^+ = k^+ N_l^+ \mathfrak{F}_l \frac{x}{\mathfrak{F} l},$$
$$\frac{1}{\mathfrak{F}} = \frac{1}{\mathfrak{F}_0} + 0,113 \times 10^{-10} \frac{qlx}{\mathfrak{F}_0^2} - 0,134 \times 10^{-10} \frac{qx^2}{\mathfrak{F}_0^3}.$$

Consequently:

$$k^+ \frac{d^2 N^+}{dx^2} = \frac{q^2}{\mathfrak{F}_0^3} (1,75l - 6,21x) 10^{-15}.$$

The theory of the saturation current assumes that q is small compared to:

$$\frac{\mathfrak{F}_0^3}{1,75l - 6,21x} \times 10^{15}.$$

From the condition that q should be large compared to $k^- \mathrm{d}^2 N^- / \mathrm{d}x^2$ it also follows:

q small compared to

$$\frac{\mathfrak{F}_0^3}{6,21x - 3,78l} \times 10^{15}.$$

8.2. Unsaturated current, first approximation

From the quantities that we calculated above according to the theory of the saturation current, we distinguish those that apply in a first approximation for the unsaturated current by means of the index 1. The general equations of the problem then come in the following form:

$$\begin{cases} \dfrac{d\mathfrak{F}_1}{dx} = 4\pi\varepsilon\left(N_1^+ - N_1^-\right), \\ v\varepsilon\left(UN_1^+ + VN_1^-\right)\mathfrak{F}_1 = c + \varepsilon\dfrac{d}{dx}\left(k^+N^+ - k^-N^-\right), \\ q_1 = vU\dfrac{d\left(N_1^+\mathfrak{F}_1\right)}{dx} - k^+\dfrac{d^2N^+}{dx^2} + \alpha N^+N^-, \\ q_1 = -vV\dfrac{d\left(N_1^-\mathfrak{F}_1\right)}{dx} - k^-\dfrac{d^2N^-}{dx^2} + \alpha N^+N^-. \end{cases} \tag{IV}$$

Solving the equations leads to the following approaches:

$$\begin{aligned} \mathfrak{F}_1^2 &= \mathfrak{F}_0^2 + c_1x + \frac{4\pi\varepsilon(U+V)}{\nu UV}q_1x^2 + 8\pi\varepsilon\frac{k^+}{\nu U}\left(N^+ + N^- - N_0^-\right) \\ &\quad -\frac{8\pi\varepsilon(U+V)}{\nu UV}\alpha\int_0^x\int_0^x N^+N^-dxdx. \\ N_1^+\mathfrak{F}_1 &= \frac{\mathrm{c}}{\nu\varepsilon(U+V)} + \frac{q_1}{\nu U}x + \frac{k^+}{\nu U}\frac{dN^+}{dx} - \frac{\alpha}{\nu U}\int_0^\infty N^+N^-dx \\ &\quad + \frac{V}{8\pi\varepsilon(U+V)}c_1, \\ N_1^-\mathfrak{F}_1 &= \frac{\mathrm{c}}{\nu\varepsilon(U+V)} - \frac{q_1}{\nu V}x + \frac{k^-}{\nu V}\frac{dN^-}{dx} + \frac{\alpha}{\nu V}\int_0^\infty N^+N^-dx \\ &\quad - \frac{U}{8\pi\varepsilon(U+V)}c_1. \end{aligned}$$

The integration constant c_1 is determined by the conditions that c must [originate] on the electrode plates.

$$\mathrm{c} = \varepsilon\nu V\left(\mathfrak{F}_1N_1^-\right)_0 + \varepsilon k^-\left(\frac{dN^-}{dx}\right)_0 = \varepsilon vU\left(\mathfrak{F}_1N_1^+\right)_1 - \varepsilon k^+\left(\frac{dN_1^+}{dx}\right)_1$$

One finds:

$$c_1 = -\frac{8\pi c}{\nu V};$$

the solution of equations (IV) is then given by the following formulas:

$$\begin{cases} q_1 = \dfrac{c}{\varepsilon l} + \dfrac{\alpha}{l}\displaystyle\int_0^l N^+N^-dx = q + \dfrac{\alpha}{l}\int_0^l N^+N^-dx. \\ \mathfrak{F}_1^2 = \mathfrak{F}^2 + \dfrac{4\pi\epsilon(U+V)}{\nu UV}\alpha\left\{\dfrac{x^2}{l}\displaystyle\int_0^l N^+N^-dx - 2\int_0^x\int_0^x N^+N^-dxdx\right\} \\ \qquad + 8\pi\varepsilon\dfrac{k^+}{\nu U}\left(N^+ + N^- - N_0^-\right), \\ N_1^+\mathfrak{F}_1 = N^+\mathfrak{F} + \dfrac{\alpha}{\nu U}\left\{\dfrac{x}{l}\displaystyle\int_0^l N^+N^-dx - \int_0^x N^+N^-dx\right\} + \dfrac{k^+}{\nu U}\dfrac{dN^+}{dx}, \\ N_1^-\mathfrak{F}_1 = N^-\mathfrak{F} + \dfrac{\alpha}{\nu V}\left\{\dfrac{l-x}{l}\displaystyle\int_0^l N^+N^-dx - \int_x^l N^+N^-dx\right\} - \dfrac{k^-}{\nu V}\dfrac{dN^-}{dx}. \end{cases} \tag{V}$$

Using the numerical values we get:

$$\begin{aligned} \mathfrak{F}_1^2 &= \mathfrak{F}^2 + 36,3\times10^{-24}\frac{q^2}{\mathfrak{F}_0^2}(l-x)^2x^2 + 0,67\times10^{-15}\times\frac{qx}{\mathfrak{F}_0}, \\ N_1^+\mathfrak{F}_1 &= \overset{+}{N}\,\mathfrak{F} + 3,56\times10^{-15}\frac{q^2}{\mathfrak{F}_0^2}(l-2x)(l-x)x + 0,228\times10^{-6}\frac{q}{\mathfrak{F}_0}, \\ N_1^-\mathfrak{F}_1 &= N^-\mathfrak{F} - 2,55\times10^{-15}\frac{q^2}{\mathfrak{F}_0^2}(l-2x)(l-x)x + 0,149\times10^{-6}\frac{q}{\mathfrak{F}_0}. \end{aligned}$$

8.2.1. *Unsaturated current, second approximation*

In the formulas (I), instead of $N^+$and N in the terms multiplied by α and k, we put the previously calculated quantities ${N_1}^+$ and ${N_1}^-$. We then get the formulas to calculate the second approximation:

$$\begin{aligned} \frac{d\mathfrak{F}_2}{dx} &= 4\pi\varepsilon\left(N_2^+ - N_2^-\right), \\ v\varepsilon\left(UN_2^+ + VN_2^-\right)\mathfrak{F}_2 &= \mathrm{c} + \varepsilon\frac{d}{dx}\left(k^+N_1^+ - k^-N_1^+\right., \\ q_2 &= vU\frac{d\left(N_2^+\mathfrak{F}_2\right)}{dx} - k^+\frac{d^2N_1^+}{dx^2} + \alpha\,\overset{+}{N}_1\,N_1^-, \\ q_2 &= -vV\frac{d\left(N_2^-\mathfrak{F}_2\right)}{dx} - k^-\frac{d^2N_1^-}{dx^2} + \alpha N_1^-N_1^-. \end{aligned}$$

The solution of the equations gives:

$$\begin{cases} q_2 = q + \dfrac{\alpha}{l}\displaystyle\int_0^z N_1^+ N_1^- dx \\ \mathfrak{F}_2^2 = \mathfrak{F}_0^2 - \dfrac{8\pi \mathrm{c}}{\nu V}x + \dfrac{4\pi\varepsilon(U+V)}{\nu UV}q_2 x^2 \\ + 8\pi\varepsilon\dfrac{k^+}{\nu U}\left(N_1^+ + N_1^- - N_{10}^+ - N_{10}^-\right) \\ - \dfrac{8\pi\varepsilon(U+V)}{\nu UV}\alpha\displaystyle\int_0^x\int_0^x N_1^+ N_1^- dxdx \\ N_2^+\mathfrak{F}_2 = \dfrac{q_2}{vU}x + \dfrac{k^+}{\nu U}\dfrac{dN_1^+}{dx} - \dfrac{\alpha}{vU}\displaystyle\int_0^x N_1^+ N_1^- dx. \\ N_2^-\mathfrak{F}_2 = \dfrac{q_2}{vV}(l-x) - \dfrac{k^-}{\nu V}\dfrac{dN_1^-}{dx} - \dfrac{\alpha}{vV}\displaystyle\int_x^l N_1^+ N_1^- dx. \end{cases} \tag{VI}$$

If in these formulas, instead of q_2, N_1^+ and N_1^-, one substitutes the values that follow from the previous one, the result is complicated expressions. We shall only elaborate a little further on the first of the equations, since it is linked to the possibility of determining the value of the constant α of the reunification from observations of unsaturated currents.

To do this, we bring the equation to the form:

$$\varepsilon l_{q_2} - c = \alpha\varepsilon\int_0^l N_1^+ N_1^- dx.$$

Let's use the abbreviation:

$$\frac{x}{l}\int_0^l N^+N^-dx - \int_x^l N^+N^-dx = \mathfrak{X}_1, \quad \frac{l-x}{l}\int_0^l N^+N^-dx - \int_x^l N^+N^-dx = \mathfrak{X}_2,$$
$$\frac{x^2}{l}\int_0^l N^+N^-dx - 2\int_0^x\int_0^x N^+N^-dxdx = \Xi$$

so [this] becomes:

$$N_1^+\mathfrak{F}_1 = N^+\mathfrak{F} + \frac{\alpha}{\nu U}\mathfrak{X}_1 - \frac{k^+}{\nu U}\cdot\frac{dN^+}{dx},$$
$$N_1^-\mathfrak{F}_1 = N^-\mathfrak{F} + \frac{\alpha}{\nu V}\mathfrak{X}_2 - \frac{k^-}{\nu U}\cdot\frac{dN^-}{dx},$$
$$\mathfrak{F}_1^2 = \mathfrak{F}^2 + \frac{4\pi\varepsilon(U+V)}{\nu UV}\alpha\Xi + 8\pi\varepsilon\frac{k^+}{\nu U}\left(N^+ + N^- - N_0^-\right).$$

If you use these values to calculate the integral $\int_0^l N_1^+ N_2^- \mathrm{d}x$, you get the equation for α:

$$\varepsilon l q_2 - c = \alpha\varepsilon \left[\int_0^l N^+ N^- dx + \frac{k^+}{\nu U} \left\{ \int_0^l \frac{1}{\mathfrak{F}} \left(N^- \frac{dN^+}{dx} - N^+ \frac{dN^-}{dx} \right) dx \right.\right.$$
$$\left.\left. - 8\pi\varepsilon \int_0^1 \frac{N^+ N^- \left(N^+ + N^- - N_0^- \right)}{\mathfrak{F}^2} dx \right\} \right]$$
$$+ \alpha^2 \varepsilon \frac{1}{\nu U V} \left[\int_0^l \frac{V N^- \mathfrak{X}_1 + U N^+ \mathfrak{X}_2}{\mathfrak{F}} dx - 4\pi\varepsilon \left(U + V \right) \int_0^l \frac{N^- N^+ \Xi}{\tilde{\mathfrak{F}}^2} dx \right].$$

The numerical calculation gives:

$$\varepsilon l q_2 - \mathrm{c} = \alpha\varepsilon \times 0,85 \times 10^{-6} \frac{q^2 l^3}{\mathfrak{F}_0^2} \left\{ \begin{array}{c} 1 + 4,65 \times 10^{-4} \dfrac{1}{\mathfrak{F}_0 l} \\ -3,34 \times 10^{-16} \dfrac{ql}{\mathfrak{F}_0^3} \end{array} \right\}$$
$$+ \alpha^2 \varepsilon \times 0,143 \times 10^{-12} \frac{q^3 l^5}{\mathfrak{F}_0^4} \left\{ 1 - 0,81 \times 10^{-12} \frac{q l^2}{\mathfrak{F}_0^2} \right\}.$$

You can roughly write:

$$\varepsilon l q_2 - \mathrm{c} = \alpha\varepsilon \times 0,85 \times 10^{-6} \frac{q^2 l^3}{\mathfrak{F}_0^2} + \alpha^2 \varepsilon \times 0,143 \times 10^{-12} \frac{q^3 l^5}{\mathfrak{F}_0^4}.$$

Here is:

$$c = \varepsilon l q.$$

The equation therefore comes in the simpler form:

$$l \left(q_2 - q \right) = \alpha \times 0,85 \times 10^{-6} \times \frac{q^2 l^3}{\mathfrak{F}_0^2} + \alpha^2 \times 0,143 \times 10^{-12} \times \frac{q^3 l^5}{\mathfrak{F}_0^4}.$$

If one uses this equation to calculate α, the result is:

$$\alpha = 1,18 \times 10^6 \times \frac{\mathfrak{F}_0^2 \left(q_2 - q \right)}{l^2 q^2} \left\{ 1 - 0,20 \frac{q_2 - q}{q} \right\}.$$

So the value of α becomes smaller if the quadratic term is also taken into account.

If one introduces instead of q_2 and q the dimensions $\mathfrak{C}$ of the saturation current and c of the actually observed current, then:

$$\alpha = 5,52 \times 10^{-4} \times \frac{(\mathfrak{C} - c)\mathfrak{F}_0^2}{l c^2} \left(1 - 0,20 \frac{\mathfrak{C} - c}{c} \right).$$

(Received 4 August 1903.)

Note: Partial translation prepared by HJ Whitehouse from original text and equations in German using Google Translate and reviewed by Melita Hein, San Diego.

9. Appendix B: LEC Current Behavior and Ion Distribution

9.1. Introduction

Much helpful information to understand the behavior of LEC cells can be learned from the work on the conduction of electricity through gases by the late Sir JJ Thomson and other researchers at the Cavendish Laboratory at Cambridge University near the turn of the 19^{th} century [22], [23], [34]. However, the various different configurations and uses of LEC cells result in fundamental differences in performance than those reported by early authors. One of their primary interests was to understand the processes that take place when gas is ionized. Thomson makes the following assumptions [34] using the CGS-ESU system of units (emphasis added):

"Let n_1, n_2 be respectively the number of positive and negative ions per unit volume at a place fixed by the coordinate x, let q be the number of positive or negative ions produced in unit time per unit volume at this point by the ionizing agent; let X be the electric intensity at this point, k_1, k_2 the velocities of the positive and negative ions under unit electric intensity, so that the velocities of those ions at this point are respectively k_1X, k_2X; let e be the charge on an ion. The volume density of the electrification, supposed due entirely to the presence of the ions, is $(n_1 - n_2)\, e$; hence we have

$$\mathrm{d}X/\mathrm{d}x = 4\pi\,(n_1 - n_2)\, e \tag{1}$$

If i is the current through unit area of the gas, **and if we neglect any motion of the ions except that caused by the electric field**, we have

$$n_1 e k_1 X + n_2 e k_2 X = i \tag{2}$$

Thomson continues by combining equations (1) and (2) and solving for $n_1\mathrm{e}$ and $n_2 e$. Then he observes that in a steady ionization state, ion losses by recombination must be balanced by ionization (emphasis added):

"We shall suppose that the number of positive or negative ions which recombine in unit volume in unit time is $\alpha n_1 n_2$: this is the rate at which unit volume is losing positive and negative ions in consequence of recombination; in consequence of ionization it is gaining them at the rate q, and in consequence of the motion of the ions under the electric force it is losing positive ions at the rate $\mathrm{d}\,(n_1 k_1 X)\,/dx$ and negative ones at the rate $-\mathrm{d}\,(n_2 k_2 X)\,/\mathrm{d}x$. The diffusion of the ions causes unit volume to lose positive and negative ions at the rates $D_1\ \mathrm{d}^2\mathrm{n}_1/\mathrm{d}x^2, -D_2\ \mathrm{d}^2\mathrm{n}_2/\mathrm{d}x^2$, where D_1 and D_2 are the coefficients of diffusion of the positive and negative ions. **Unless the electric field is very weak the motion of the ions by diffusion is, except in quite exceptional cases, insignificant in comparison with that under the electric field.**"

The authors believe that it is the diffusion of the ions that is the primary source of the spontaneous 'open circuit' voltage of a LEC as well as the spontaneous 'short circuit' current measured at low values of load resistance and thus 'very weak' electric fields. Although diffusion is most evident for the spontaneous conduction mode of LEC operation it nevertheless still plays a role in determining the I-V characteristics of LECs with multiple counter electrodes (CE) as well as two-electrode LECs operated in the impressed voltage or current mode.

9.2. Current Saturation during Impressed Conduction

An important characteristic of the conduction of electricity through gases is the rate of gas ionization q. This is traditionally accomplished by measuring the current density, i, at voltages sufficiently high that the magnitude of the drift velocities, v_{d}, of the ions, i.e., k_1X, k_2X in CGS ESU or $\mu_1 E, \mu_2 E$ in CGSA units, are sufficiently high that the ions drift to the electrodes in a time short enough so that there is a minimum loss of ion charge by ion-ion recombination. JJ Thomson and E Rutherford [22] report that:

"for a given intensity of radiation the current through the gas does not exceed a certain maximum value whatever the electromotive force may be, the current gets, as it were, 'saturated.'"

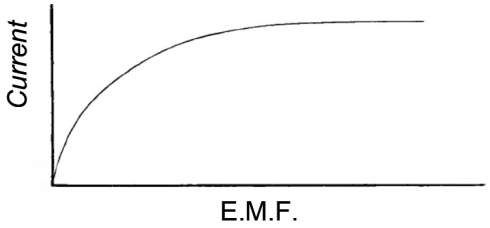

Figure B.1. Current saturation curve adapted from JJ Thomson [34].

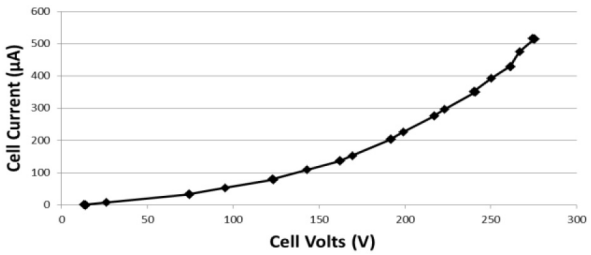

Figure B.2. Impressed current-voltage (I-V) curve for a $\mathrm{Pd-D}$ cell with $6\ \mathrm{mm}$ electrode separation.

An example current voltage (I-V) saturation curve similar to that in [22] is shown in Fig. B.1. This curve clearly shows an 'ohmic' behavior at low voltage, i.e., current goes to zero linearly as the electromotive force (EMF) goes to zero.

However, when a two-electrode LEC cell, i.e., one working electrode (WE) and one counter electrode (CE), is operated in the impressed current/voltage mode the measured I-V curve is remarkably different. Figure B.2 shows the measured (I-V) curve for a Pd-D LEC cell reported in [1],

Note, that the current instead of saturating as the voltage is increased, the current increases rapidly and shows no indication of saturation at a voltage across the cell of approximately $250\ \mathrm{V}$ for a cell with an electrode separation of approximately $6\ \mathrm{mm}$. Analysis of the conduction data for this cell showed that the measured current increased as a cubic polynomial in cell voltage. This difference in performance is thought to be caused by the significant differences in the way that the gas is being ionized. When the cube root polynomial of the cell current is plotted versus the cell voltage the result is an approximately straight line that upon extrapolation to zero voltage does not pass through the origin of the graph. This is due to the presence of ion diffusion in addition to ion drift and ion-ion recombination. In fact, it was this observation that lead to the discovery of spontaneous LEC conduction that was reported in [1].

Only when the full set of equations that include the diffusion term are examined, such as those published by Eduard Riecke in 1903, is it seen that a LEC can have 'non-ohmic' behavior at low voltage. It is the diffusion term that introduces the 'non-ohmic' behavior, i.e., current does not necessarily go to zero when the electric field goes to zero. An English translation of Riecke's University of Göttingen is presented in Appendix A. This German language paper includes the complete set of 1-dimensional equations, including diffusion, for a gas composed of both positive and negative ions.

A potential explanation of the difference in the behavior of the ionized-gas conduction experiments by early researchers at the Cavendish Laboratory and experiments performed by the authors is in the structure and preparation of the working electrode (WE) of the LEC. In all Inovl experiments the WE is comprised in part of hydrogen-host-

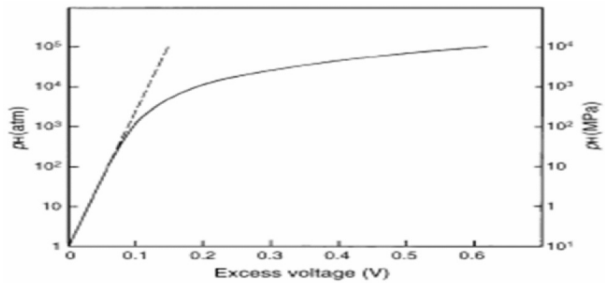

Figure B.3. Equivalent gas pressure versus excess voltage during electrolysis.

material (HHM), i.e., black Pd or black Fe, occluded with atomic hydrogen during electrochemical HHM codeposition performed in light water (H_2O). In addition to occluding hydrogen in the HHM during electrodeposition, Fukai [2] also has shown that a large number of super-abundant vacancies (SAV) are introduced in the electrodeposited metal. In most 2-electrode impressed conduction experiments the gas in fluidic contact with both the WE and the counter electrode (CE) is hydrogen $\left({}^1H_2\right)$ although for the experiment described in Fig. B.2. the gas was deuterium $\left({}^2H_2\right)$. Since ionized gas acts as electrolyte during conduction there is a potential difference developed in the gas which increases as the voltage across the cell increases. This causes an increase in the excess or 'over-potential' near the surface of the WE as a function of the voltage across the cell. Fukai [43] has shown that a small increase of 'over-potential' causes a large equivalent gas pressure, e.g., several thousand atm, due to fugacity at the cathode during aqueous electrodeposition or electrolysis. Figure B.3 is a plot of equivalent gas pressure versus excess or over-potential from Fukai [43]. Thus, the presence of numerous SAV that can receive atomic hydrogen and the large equivalent hydrogen gas pressure to fill the SAV may account to the remarkably different I-V characteristics, e.g., convex for Inovl versus concave for Cavendish, as well as the lack of saturation for the Inovl impressed conduction experiments.

9.3. Current Saturation during Spontaneous Conduction

When a 2-electrode LEC is operating in the spontaneous voltage mode then diffusion and ion-ion recombination are the dominant conduction controlling factors rather than excess or 'overpotential' since the voltage across the cell and thus the electric field strength within the gas are low relative to their values during impressed current/voltage LEC operation. Figures B.4 and B.5 show the I-V (Note: V is not shown) curve for a freshly prepared Fe-H LEC operating in air at NTP. In addition to the I-V curve calculated shunt current and power in the load resistance also are shown.

9.4. Ion Distribution Equations

Consider first analyzing the performance of a LEC under the condition of an impressed voltage. To simplify the analysis, assume that the electrical properties of the electrodes are the same, i.e., their work functions are the same, Also assume that the current density through the gas, i, is the same everywhere over the surface of the electrodes, that the density of ions, $n^+$and n^-, only depends on the electrode separation variable, x or r, that the positive and negative ion mobilities are effective measured values, i.e., the weighted harmonic means of the different ion-type mobilities, and that the electric field can be estimated everywhere throughout the gas. Additionally, following the practice of early authors, let the equations be written in CGS-ESU, i.e., current density is in statAmps, voltage is in statVolts, the unit charge, e, is approximately 4.8032×10^{-10} statCoulombs or esu, and the ions carry only one charge per ion.

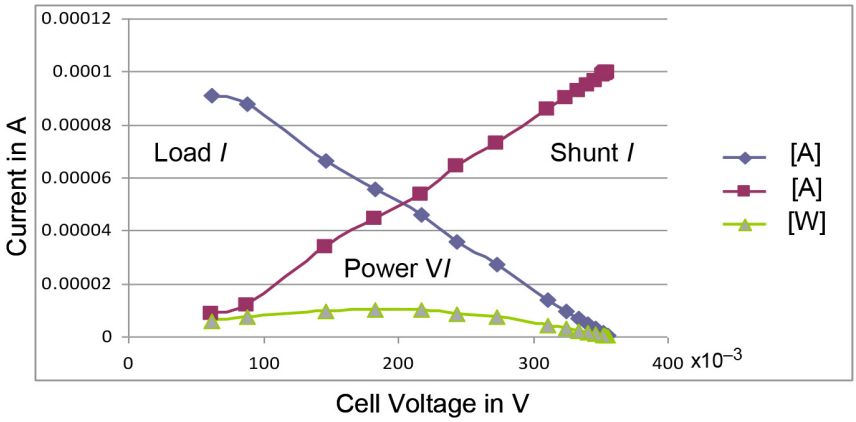

Figure B.4. Fe-H $1\frac{1}{4}$ "black Fe WE and $3/4$" Cu CE using Air at NTP.

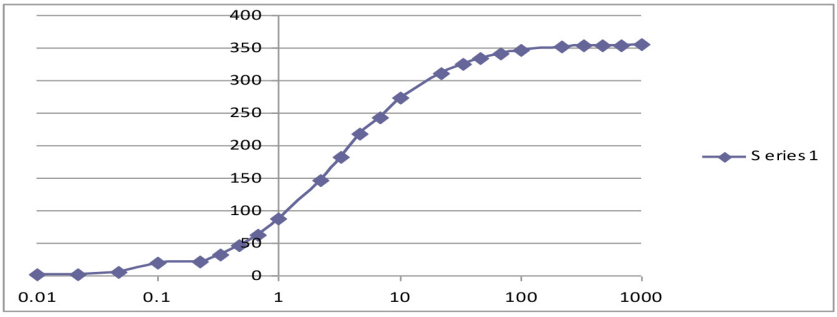

Figure B.5. Cell voltage (mV) versus load resistance in $\mathrm{k}\Omega$ for Fe-H cell using air.

Making these assumptions, the general equations describing the conduction can be written, following Riecke but using modern notation, as:

$$\mathrm{d}E/\mathrm{d}x = 4\pi e\left(n^{+} - n^{-}\right), \tag{B1a}$$

$$e\left(\mu^{+}n^{+} + \mu^{-}n^{-}\right)E - ed\left(D^{+}n^{+} - D^{-}n^{-}\right)/\mathrm{d}x = i, \tag{B1b}$$

$$q = \mu^{+}\mathrm{d}\left(n^{+}E\right)/\mathrm{d}x - D^{+}\mathrm{d}^{2}n^{+}/\mathrm{d}x^{2} + \alpha n^{+}n^{-}, \tag{B1c}$$

$$q = -\mu^{-}\mathrm{d}\left(n^{-}E\right)/\mathrm{d}x - D^{-}\mathrm{d}^{2}n^{-}/\mathrm{d}x^{2} + \alpha n^{+}n^{-}. \tag{B1d}$$

Using CGSA, MKSA or the SI system of units published in 1960 and used in [36], [37], and [38] equation (B1a) becomes equation (B1a′)

$$\mathrm{d}E/\mathrm{d}x = e(n_{+} - n_{-})/\varepsilon \tag{B1a′}$$

where ε is the permittivity of the gas and the value of the elementary charge is $e \coloneqq 1.602176634 \times 10^{-19}\mathrm{C}$ since 2019.

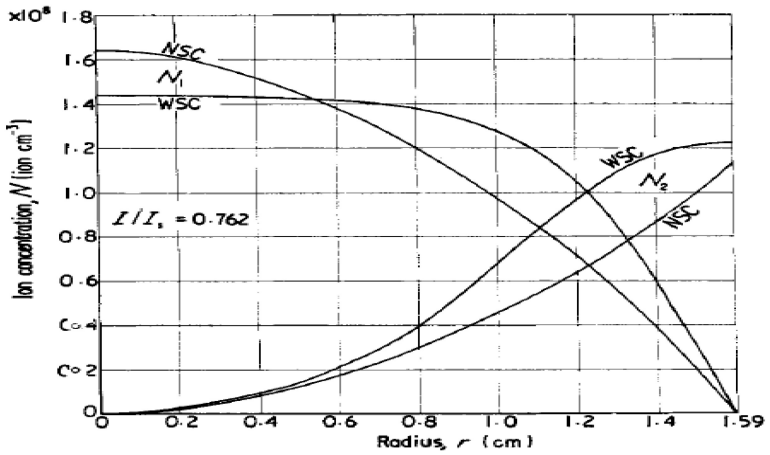

Figure B.6. Ion distribution in a cylindrical chamber with radii $a = 0.0159$ cm and $b = 1.59$ cm for air at 1 atm at a current saturation of 0.762 for no space-charge (NSC) and space charge (WSC) [46].

Further, it should be noted that the measured variables of a LEC are the total current, I, and the voltage, V, between the electrodes. These quantities are related to the corresponding variables, i, and E as integrals, i.e., $I = \int_S i \, \mathrm{d}S$ and $V = \int E(x) \, \mathrm{d}x$ where dS is an element of electrode surface area and x is the variable representing the separation distance between the electrodes, *e.g.*, for coaxial cylindrical electrodes of radius $r_a \leq r \leq r_b$ then $V = \int_{ra}^{rb} E(r) \, \mathrm{d}r$. Also, is important to observe that even if the electric field were identically zero everywhere within the gas, $E(x) = 0$, the current density i would not be zero unless $d(D_+n_+ - D_-n_-)/\mathrm{d}x$ vanishes also. This means that the conductivity of the gas is not necessarily ohmic in the sense that $I \neq GV$ were G is the conductance of the gas.

Darrow assumes that there is only one type of positive ion and one type of negative ion at that these ions are present in equal numbers [33]. Then equation (B1b) can be rewritten as

$$i/e = (\mu_+ + \mu_-) \, En + (D_- - D_+) \, \mathrm{d}n/\mathrm{d}x \tag{B2}$$

which has a solution of the form [42]:

$$n(x) = (1/u(x)) \left[\int^x u\,(x') \, g\,(x') \, \mathrm{d}x' + \mathrm{C} \right], u(x) = \exp \left[\int^x p\,(x') \, \mathrm{d}x' \right] \tag{B3}$$

where $p(x) = (\mu_+ + \mu_-) \, E(\mathrm{x}) / \, (D_- - D_+) \, , g(\mathrm{x}) = (i/e) / \, (D_- - D_+) \, , D_\pm = \mu_\pm k_{\mathrm{eV}} T, E(x)$ is the electric field within the gas, and C is a constant of integration.

The equations for the distribution of charge, neglecting diffusion but including recombination,have been developed by Townsend in 1915 for the case of plane-parallel electrode geometry on page 72 [11]. However,the equations are not evaluated to produce a graph of the ion charge-density as a function of position between the electrodes. R Rosen and EP George in 1975, also neglecting diffusion but including recombination, have evaluated the equations for the distribution of charge for both the cases of plane-parallel and cylindrical electrode geometry.Theirevaluation for cylindrical geometry is reproduced as Fig. B.6 for the case of electrode radii $a = 0.059$ cm and $b = 1.59$ cm and air at 1 atm.

10. Conclusions

For several reasons the conduction of electricity in a LEC is significantly different than that conventionally used to describe the conduction of electricity through gases [33], [44], [45]. First and foremost is the fact that the source of the conduction is from some form of radiation produced by or within the hydrogen occluded hydrogen-host-material (HHM) of the cell'sworking electrode (WE). Second, the equivalent gas pressure caused by 'over-potential' in thegas near the HHM of theworking electrode [43] appears to cause the conduction to not 'saturate' as the voltage across the cell increases. Third, diffusion of the ions plays a major role in the generation of the spontaneous voltage of a LEC when there is no electrical input to the LEC. Finally, the electrical work function of the material of the counter electrode (CE) also appears to play a role in the conduction of electricity in a LEC [41].

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