

Energy balance of pulsed electrical discharges in an aqueous solution

DANIEL FARGUE¹, GAËTAN DE LACHÈZE-MUREL^{1,2}

¹Institut Louis de Broglie, 23 rue Marsoulan, F-75012 Paris

²CEA-DAM

*In memory of our departed friends,
Pierre Clauzon and Michel Karatchentzeff*

RÉSUMÉ. Plasma discharges in electrolytes have long been studied [5], and it has been reported ([6], [8]) that they give rise to energy releases exceeding the associated Joule effect. Here, we report on experiments confirming these excesses using two different calorimetric methods; the measurements were performed in a closed vessel, thereby avoiding the issues associated with heat measurements in open systems. It is important to note that these results depend critically on the discharge settings, which must be very carefully controlled.

ABSTRACT. *Plasma discharges in electrolytes have long been studied [5], and it has been reported ([6], [8]) that they give rise to energy releases exceeding the associated Joule effect. Here, we report on experiments confirming these excesses using two different calorimetric methods; the measurements were performed in a closed vessel, thereby avoiding the issues associated with heat measurements in open systems. It is important to note that these results depend critically on the discharge settings, which must be very carefully controlled.*

1 Introduction

Building on studies of high-voltage discharges in water ([1], [2], [4]), we utilized the available equipment to investigate what are often termed "plasma discharges" or "glow discharges" in electrolytes. These phenomena have long been studied ([5]) and often exhibit distinctive characteristics, including the production of unusual elements or energy ([6], [7], [8], [9], [10]).

However, these discharges—which generally occur under stable, constant voltages—are in reality highly unstable and difficult to characterize

through reproducible measurements (see also [11] regarding discharges in a gaseous medium). This is particularly true for energy measurements, as the current is highly irregular and the required bandwidth exceeds the capabilities of most wattmeters; consequently, one must use oscilloscopes capable of recording long sequences ([9]) with high stability. In this study, we opted for short pulses (a few μs) repeated periodically using IGBTs (Insulated-Gate Bipolar Transistors—power electronic switches from the transistor family) controlled by a function generator (see Appendix 3).

Another difficulty is that, despite all the care and ingenuity applied to these experiments, doubt may still persist regarding the value of the thermal energy released when it is inferred from evaporation measurements ([6], [9], [12]). Indeed, it is known that mists can be generated in cold conditions by ultrasonic waves, and the shock waves associated with discharges could trigger the same phenomenon, leading to the emission of wet steam—which has a lower enthalpy than the dry steam typically used to estimate the energy released.

We therefore sought to address these objections by developing the methods described here; these methods confirm that, under certain circumstances detailed in a patent [13] we have filed, energy releases are indeed observed that exceed what would be expected from the Joule effect alone within the discharge.

2 Experimental setup 1: evaporation calorimeter

2.1 Principle of the experiments

Inside a sealed stainless steel vessel (known as a "firing chamber")—a cylinder 5 cm in diameter and 10 cm high—pulsed electrical discharges (lasting a few tens of microseconds at 500 to 1000 V) are triggered between an electrode (anode) and the solution; the anode typically consists of a short length (1 to 5 mm of exposed wire) of small-diameter wire (typically 0.4 mm, usually copper) immersed in an aqueous sodium hydroxide solution (0.25 to 0.5 mol/L).

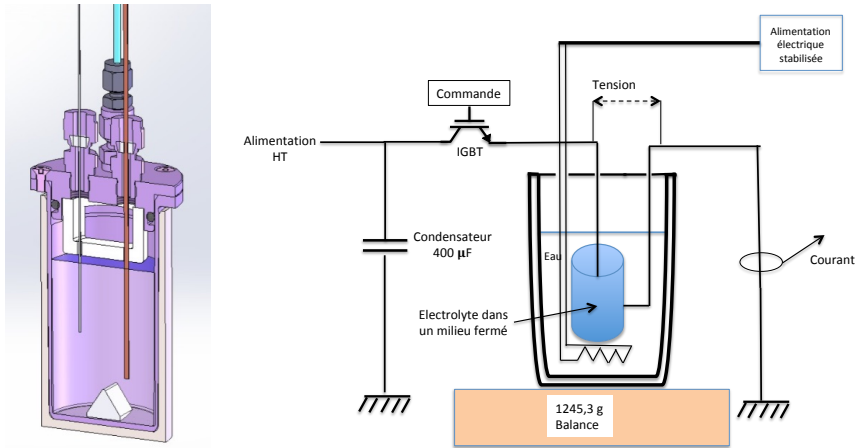


Figure 1. Firing vessel (with bottom agitator) and schematic diagram

The voltage (500 to 1000 V) applied between this wire and the vessel wall, as well as the current, are recorded on an oscilloscope for each pulse (lasting 20 to 100 μs), enabling precise measurement of the electrical energy injected into the vessel.

The vessel itself is immersed in a water bath at 100°C contained within a double-walled stainless steel container (referred to as a "thermostat"), sealed by a plastic lid featuring three holes (0.8 cm in diameter). These holes allow the passage of water vapor as well as the power leads for the discharge and the heating element—the latter ensuring boiling and maintaining the system at 100°C. This heating, kept as constant as possible, is provided by a power-regulated low-voltage supply, thereby ensuring a constant rate of evaporation over time, except during discharge periods.

The entire assembly is placed on the pan of a balance that allows the evaporated mass to be measured and serves as the basis for our energy measurements.

2.2 Measurement principle

We have previously described [12] the method that consists of subtracting the previously measured evaporation rate ($\dot{m}_0$)—observed during the steady state established by heating the thermostat water—from the evaporation rate ($\dot{m}$) observed during the shots. In the present case, where the shots take place within a closed vessel, one simply needs to

formulate the energy balance for the control volume consisting of the thermostat water: first in the absence of shots, and then during the shots (see Appendix 1), noting that without shots, the temperature is uniform throughout the apparatus and there is therefore no energy transfer between the vessel and the thermostat.

From this, we deduce the thermal power absorbed by the thermostat from the vessel during the shots ($L = 2260$ J/g, the latent heat of vaporization of the water in the thermostat—a value we can assume to be constant given the precision of our measurements, which is limited to a few percent).

$$\dot{Q}_1 = (\dot{m}_0 - \dot{m})L$$

and the first law, subsequently applied to the vessel (a closed system), yields the energy potentially released by a reaction inside the vessel:

$$\Delta U_1 = \int (\dot{m} - \dot{m}_0)L dt + W_e = \Delta[m - m_0]L + W_e$$

As with any chemical reaction, if no reaction occurred in conjunction with the firings, the state of the vessel remains the same before and after the firings and $\Delta U_1 = 0$; if an exothermic reaction took place, $\Delta U_1 < 0$, and if it is endothermic, $\Delta U_1 > 0$.

2.3 Validation of the measurement method

This calorimetric method is standard (for similar experiments, see [10]) and has the disadvantage of imposing a fixed temperature—in this case, 100°C—on the experimental setup. However, it offers the advantage of depending solely on the latent heat of vaporization (which is precisely known) and providing an absolute measurement of energy, provided that the heat power exchanged between the thermostat and the surroundings (heating and losses) remains stable; this stability can be ensured by the quality of the heating power supply and the constancy of the temperature, since the latter is simply determined by the boiling of the water in the thermostat.

This stability depends on two factors: the stability of the power supplied to the heating element—maintained to better than 0.2% in our case—and, more importantly, the stability of heat losses from the thermostat, which is more problematic and requires discussion. These losses are significant—on the order of 20 to 25 W for a heating power of 70 W—occurring primarily through the lid, which consists of a single plastic

wall. While better insulation would be preferable, stability is the only essential requirement. Since these losses are, to a first approximation, proportional to the temperature difference relative to the laboratory environment, it is easy to see that the drift—when the ambient temperature rises from 19°C to 22°C (a typical scenario for an experimental session lasting up to 10 hours)—is on the order of 1 W. As each experiment lasts a maximum of 10,000 seconds, we compensate for the corresponding 0.3 W by using a linear approximation of the baseline evaporation (see Appendix 2 for details).

We then validate the method by conducting experiments in which we are certain that only the Joule effect occurs—either by placing a resistor in pure water within the discharge vessel or by performing discharges at a voltage too low to trigger an arc. This confirms that the thermal energy released during these shots (involving energy levels comparable to those of the discharges under study) is indeed equal to the injected electrical energy, as shown in the following figure.

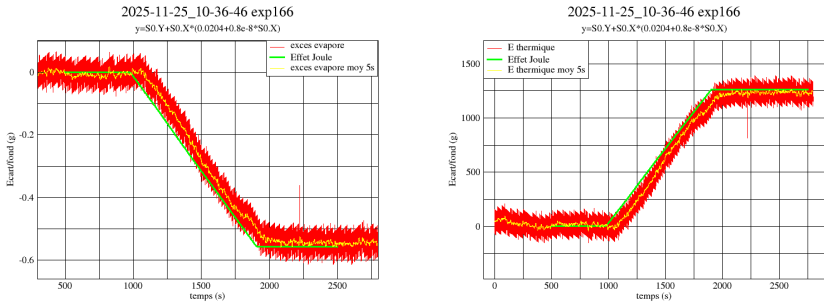


Figure 2. Test discharges; shots into a 2.5-ohm resistor in pure water (a) and their conversion into energy values (b)

In these graphs, as in those presented later, time is plotted on the x-axis, and the difference ($m(t) - m_0(t)$) is plotted on the y-axis as a function of time (mass measured to within 0.1 g). The curve labeled "Joule effect" represents the ideal measurement that would have been obtained if only the electrical energy supplied during the shots had caused an increase in evaporation. It aligns well with the experimental curve, thereby validating the measurement method. It should be noted that, in the case shown, there was a slight change in the evaporation rate before and after the shots (from 0.0204 g/s to 0.02042 g/s, representing a variation of 45 mW); this change is assumed to be sufficiently steady to be accounted for

by a linear approximation of the evaporation rate $\dot{m}_0(t)$ in the absence of shots.

These experiments also allow for an assessment of measurement precision; the difference between electrical energy (which, as we shall see in Appendix 3, is known to within a few percent) and thermal energy (measured via evaporation) generally does not exceed 5% and never exceeds 10%.

3 Experiments triggering an exothermic reaction

Performed without special adjustments, the discharges simply demonstrate—as required by the first law—the conversion of the supplied electrical energy into heat via the Joule effect, and yield curves similar to those in the example shown in Figure 2.

3.1 Experimental results

Although extremely simple in principle, the experiments are quite delicate to perform, and the various parameters must be set to relatively precise values to achieve energy releases exceeding what is simply due to the Joule effect, as previously highlighted by Parkhomov ([9]). Numerous trials were required to ensure the reproducibility of the results reported below.

By way of example, a set of settings conducive to an energy release exceeding the electrical energy supplied—that is, indicating an exothermic reaction within the vessel—is as follows.

Equipment: stainless steel vessel (see above) containing 120 to 140 cm³ of sodium hydroxide solution (0.5 or 0.25 mol/L); sheathed copper electrode (0.4 mm diameter) immersed 20 mm into the solution, with an exposed section of 1 to 5 mm.

Discharges: pulses with a duration of 20 to 50 μ s, voltage of 600 to 800 V, repetition frequency of 0.2 to 1 Hz.

The measurements taken during a typical experiment (exp234 conducted on April 22, 2026) are given below (0.5 mol/L sodium hydroxide solution; 700 V pulses with a duration of 20 μ s every 2 s (0.5 Hz); 0.4 mm copper wire with a 5 mm horizontal stripped section; constant heating stabilized at 70 W).

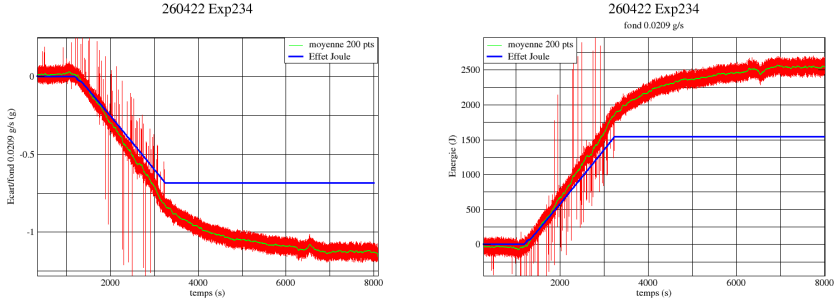


Figure 3. Mass excess due to firing (a) and conversion to energy (b); measured thermal energy (red) and electrical Joule effect (blue). Raw measurement (red) and 40 s smoothing (green).

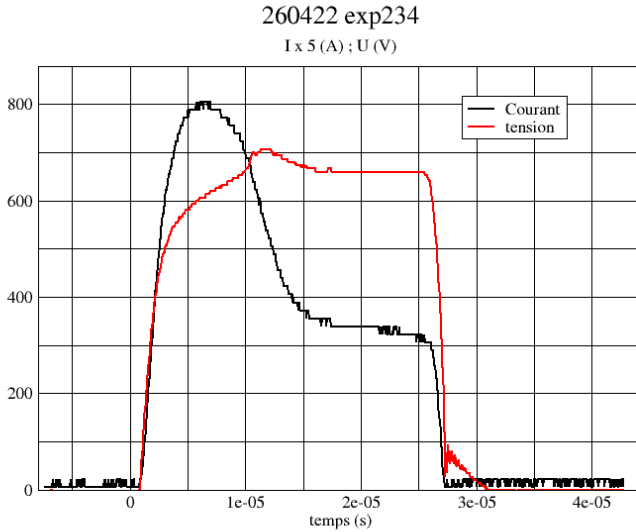


Figure 4. Voltage and current of a pulse at the discharge terminals

Measuring the current and voltage for each pulse (Figure 3b) allows for a highly precise calculation of its energy (see Appendix 3), and the cumulative total of these energies is represented by the blue curve (Figures 3a and 3b) after conversion—by dividing by the latent heat of vaporization of water (2260 J/g)—into an evaporation equivalent. It

can be seen that the excess evaporation measured in red (between the two horizontal plateaus marking the return to the baseline evaporation caused solely by constant heating) is approximately 50% greater than the amount attributable to the Joule effect alone. The figure also shows the time offset resulting from the delay associated with heat transfer between the central electrode, the vessel, and the water in the thermostat.

The electrical pulses generally resemble the one shown in Figure 4, and below—in Figure 5—we present an example in which we also recorded the emitted light (using an optical fiber and a photomultiplier).

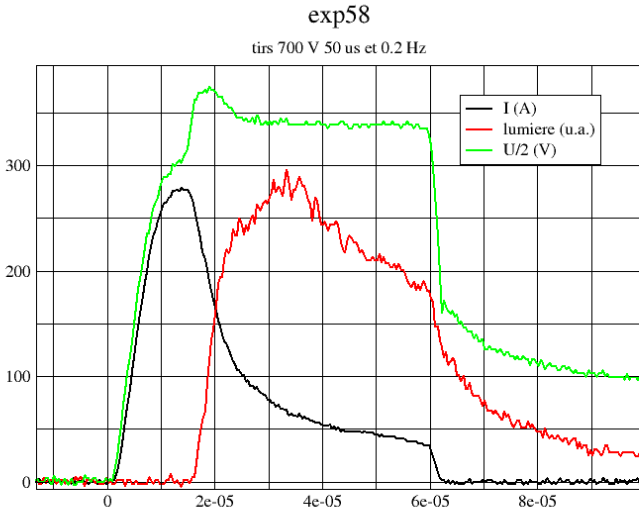


Figure 5. Current, voltage, and light (arbitrary units) for a typical shot. The voltage drop at the end of the discharge arises from the very low parasitic capacitance (between the electrode and the wall), which discharges more slowly but with negligible current.

We believe they should be interpreted as follows (values corresponding to Figure 5).

- From $t=0$ (the moment the IGBT begins to conduct) to $t=10 \mu\text{s}$, the current is due solely to the conductivity of the electrolyte, and it is the circuit inductance (on the order of $5 \mu\text{H}$) that determines the current rise time as it goes from 0 to 270 A. Joule heating

occurs, leading to the formation of a vapor sheath around the electrode.

- Between 10 μs and 20 μs , this vapor sheath breaks the circuit (hence the voltage spike), and the voltage building up between the electrode and the solution surface rises sufficiently for an electric arc to form between the electrode and the liquid, triggering the appearance of a luminous plasma. This effect has been studied since the 1950s [5].
- From 20 μs to 60 μs (the moment the IGBT closes), the discharge continues within the plasma before stopping, and the light gradually fades until the plasma is completely extinguished.

This interpretation is consistent with observations made as early as the 1950s and subsequently confirmed ([5], [9]).

3.2 Remarks

3.2.1 Duration and magnitude of the voltage pulse

A result we consider significant is that the excess evaporation (relative to the Joule effect) appears to vanish when the pulse duration extends too far beyond the time required for plasma formation; 100 μs is an upper limit, while 20 to 50 μs often appear to be optimal.

It should also be noted that for a given physical implementation, there is an optimal voltage, and the effect disappears if the voltage is either too low or too high. For example, it manifests only between 650 V and 750 V if the optimum is 700 V.

3.2.2 Pulse repetition frequency

We have frequently observed that two experiments differing only in the firing frequency—for instance, 3 Hz and 0.8 Hz—could yield vastly different excess values: zero for the first and 50% for the second. This result indicates an interaction between successive discharges, a conclusion supported by the fact that the timing of the emitted light depends on the interval between discharges, all other factors being equal. A possible explanation found in the literature ([14]) attributes this to the persistence of vapor micro-bubbles around the electrode after each discharge. We also observed this phenomenon during test discharges performed in a glass vessel.

3.2.3 *Influence of polarity*

Most of our experiments were conducted using a configuration inspired by the experiments of Bazhutov [8], with the positive high-voltage terminal connected to the electrode; however, we obtained similar results with the negative terminal connected to the electrode, as in Mizuno's initial experiments ([6], [7]). In the latter case, the discharge characteristics differ slightly, and the required voltages are somewhat lower (500 V instead of 700 V); it is likely that hydrogen release around the electrode (acting as the cathode) facilitates the onset of the discharge, given that the breakdown voltage of hydrogen gas is lower than that of water vapor.

3.2.4 *Material conditions, electrode geometry*

Apart from a few trials with other electrolytes—which appear to yield similar results—we have primarily tested discharges in sodium hydroxide solutions (the type most commonly used for water electrolysis) at concentrations ranging from 0.25 to 0.5 mol/L. While the electrode material (W, Ta, Cu) appears to have little influence, its diameter, length, and positioning seem critical, as previously noted ([6], [9]). Below, we present two examples of effective electrode configurations using a simple 0.4 mm diameter copper wire, PVC-insulated and stripped of its coating over a length of 2 mm for vertical positioning or 8 mm for horizontal positioning.

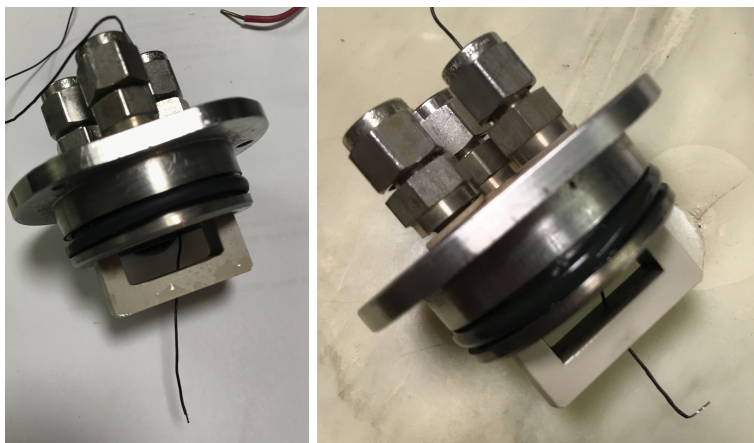


Figure 6. Firing pot sealing cap, with electrode and insulated copper-core wire (0.4 mm); wire stripped by 2 mm for vertical use (exp-by) and by 6 mm for horizontal use (exp220).

Wires of larger diameter or greater length do not trigger any notable exothermic reaction; thinner wires are quite conducive to it but are too fragile. These settings suggest that a strong electric field at the onset of the discharge, or a high temperature, is necessary for an exothermic reaction to occur.

For example, in the case of a short electrode (1 or 2 mm), we can estimate the electric field value at the electrode—using a spherical geometry model—at the moment the vapor bubble (with a typical radius of 0.4 mm) appears. For a potential difference of 200 V between the electrode and the liquid-vapor interface (accounting for the voltage drop in the electrolyte), the calculated field is 2000 V/mm; this is indeed within the same order of magnitude as the dielectric strength of the gases in question.

3.2.5 *In conclusion, what type of plasma?*

It is evident that numerous parameters influence the results—frequency, duration, voltage, polarity, electrode geometry, and sodium hydroxide concentration—and many combinations appear possible. It would certainly be of interest to be able to relate these to the characteristics of the plasma generated during the discharges.

For the moment, we have only preliminary results obtained from a few spectrometric measurements; these are approximate and require refinement. In addition to sodium lines, the measurements reveal lines corresponding to atomic hydrogen—even though the plasma is located at the anode—and a very rough estimate suggests a probable temperature in the range of several thousand Kelvin.

4 Experimental setup 2: heat-flux calorimeter

4.1 Material

Despite all our efforts to eliminate potential artifacts in previous experiments, some doubt may still remain when relying on a single measurement method.

To complement the previous experiments, we therefore employed a completely different method, using a calorimeter to directly measure the heat flux exchanged between the firing vessel and the external environment during constant-temperature discharges. This device was specially designed by the company Calneos. It enabled the use of the exact same electrical circuit as described above.

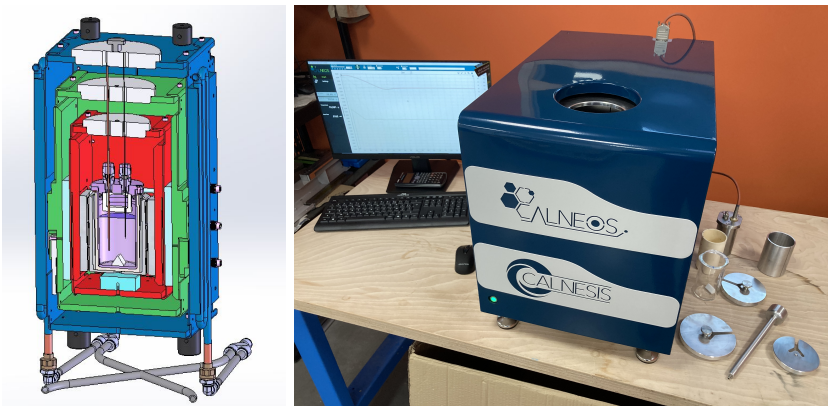


Figure 7. Calneosis calorimeter, cross-section showing the sample vessel inside the various heating and measurement modules (Peltier effect).

This device enables the direct measurement (following manufacturer calibration) of the heat flux exchanged by the outer surface of the firing vessel, as defined in formula (1). In this case, simply applying the first

law of thermodynamics to the closed system consisting of the firing vessel yields

$$dU_1/dt = -\dot{Q}_1 + \dot{W}_e$$

where both terms on the right-hand side are measured.

We used the calorimeter in "power compensation" mode (see Appendix 4) at 100°C to compare the results with those of the evaporation method.

As our experiments are quite specific, we record over very long durations—spanning tens of thousands of seconds—after waiting for stabilization for at least 50,000 seconds.

Under these conditions, after smoothing the measurements (over 200 s, for example), we observed a peak-to-peak noise sensitivity in the range of 10 to 20 mW, as well as good stability—with a potential drift of around 10 mW over 10,000 s, which we account for using a linear approximation.

4.2 Résultats

Using the same firing vessel and under experimental conditions identical to those that led to an exothermic reaction measured by the previous method, we obtained, for example, the following recording:

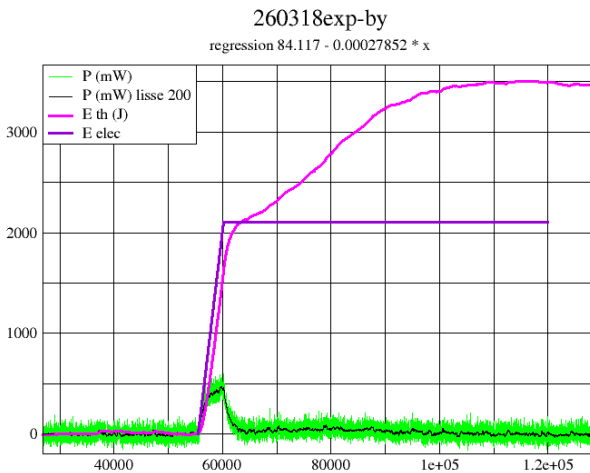


Figure 8. Power (green) and cumulative energy (magenta) curves from an experiment similar to that in Figure 3.

In this experiment, the measured quantity of heat exceeds the Joule effect by more than 50%—as is the case with evaporation measurements— but this result is obtained only after a very long period of 30,000 s, which appears necessary to ensure a return to the steady state. This is a characteristic we have frequently observed, and one that may seem rather unusual in calorimetry. We do not know the exact cause, but one might surmise that if water thermolysis and hydrogen gas accumulation occur, the nickel present in the stainless steel could act as a catalyst for a slow oxidation process following the cessation of the runs, thereby releasing this additional energy.

5 Discussion, interpretation

As we have explained, our experiments appear to show, with a reasonably high degree of precision, that the rather distinctive electrical discharges we employ trigger an exothermic reaction within a closed vessel containing essentially nothing but a copper electrode immersed in an aqueous solution of sodium hydroxide. Several explanations come to mind.

5.1 Chemical reactions

The experimental setup consists of a closed stainless-steel vessel serving as the cathode; a copper wire acting as the anode (which is liable to oxidize); and a sodium hydroxide solution topped by a small volume of gas—a mixture of air and water vapor.

We naturally assume that the first law of thermodynamics applies here. As in any closed system, a change in internal energy between a known initial state and a known final state—such as the one we are measuring—can only stem from a change in state variables. Since the temperature is the same in both states and the volumes of the two phases have changed little, the only possibility is a change in chemical composition linked to a chemical reaction. What are the possibilities?

Since the solution itself remains clear at the end of the experiments, and the sodium certainly remains in solution, a modification of the electrodes must be considered.

For several months, we have verified that the mass of the stainless-steel container has remained constant to within 0.1 g (i.e., 1.8 mmol), which limits the energy potentially released by a chemical reaction involving the vessel to 200 or 300 J —significantly less than the excess energy we measure in a single experiment, which generally exceeds 500 J.

The copper wire serving as the anode shows no significant signs of wear, even though it is slightly oxidized (blackened); given that its mass does not exceed 10 mg (i.e., 0.15 mmol), it can release only 15 to 20 J in a chemical reaction.

The formation of nitrogen oxides must be considered given the high temperatures within the plasma. However, the gas volume upon sealing the vessel does not exceed 20 cm³—containing 7×10^{-4} mol of nitrogen—and the energy released would be, at most, on the order of 60 J.

It cannot be a matter of water dissociation—which is endothermic, like electrolysis (the extent of which is, incidentally, very low, given that in an experiment involving 1,000 shots, the cumulative charge is less than 1 C, or 0.01 mmol). As previously noted by Mizuno ([6], [7]), thermolysis certainly plays a role but can only absorb energy.

We can therefore reasonably rule out an explanation linked solely to a chemical reaction.

5.2 Other types of reactions

We reiterate here the remarks made in a previous article [12], as we have no new information in the absence of additional measurements.

Since the energy released is too great to be explained by a chemical reaction, one is tempted to consider a nuclear reaction—for instance, of the type $\text{H} + \text{H} \rightarrow \text{D}$. Regardless of the specific details of this overall reaction—whether K-capture or a weak interaction involving magnetically excited neutrinos or otherwise—it would yield energy on the order of at least 1 MeV per atom. Under the conditions of our experiments, which release 500 J, this would produce 3×10^{15} deuterium atoms. However, given that we have 120 g of water—representing 4×10^{24} water molecules—the resulting increase in D content would be on the order of 0.75 ppb; compared to the average deuterium content of 150 ppm in water, this is immeasurable.

However, this remains a possibility, as demonstrated by experiments conducted with single discharges of a few kJ in water ([2], [4]).

6 Conclusion

The experiments described above demonstrate unequivocally and with a high degree of reproducibility that brief anodic discharges (pulses of 20 to 50 μs)—carried out in a sodium hydroxide solution at 100°C in a closed system at voltages of approximately 700 V—trigger exothermic

reactions that cannot be solely chemical in origin. The precise conditions under which they occur vary depending on the experimental setup (electrode length and arrangement, and solution concentration). Finally, it should be noted that the thermal energy gain thus produced appears to vanish if the pulse duration is excessive or if the voltage deviates significantly—either upward or downward—from its optimal value.

However, this work should be considered preliminary because, although we believe we have confirmed that the type of discharges studied here gives rise to reactions of a new type, there remain many associated phenomena that warrant further investigation.

Acknowledgments

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Appendix 1

We adopt the standard sign conventions of thermodynamics, taking the perspective of being "inside" the system.

Notations

m	mass of the (liquid in the) thermostat
U	internal energy of the (liquid in the) thermostat
T_e	boiling temperature of water (100 °C)
U_1	internal energy of the vessel
Q_0	heat absorbed by the thermostat from the surroundings
Q_1	heat absorbed by the thermostat from the vessel
Q_c	heat absorbed by the thermostat from the heating cartridge
W_e	electrical energy from the discharges
h_v	specific enthalpy of water vapor at 100 °C
u_l	specific internal energy of water at 100 °C
L	specific latent heat of vaporization of water (2260 J/g)

Let us consider the mass of water in the thermostat (the mass of vapor above it is negligible). The first law of thermodynamics for this open convective system is expressed as follows (the dot denotes the time derivative):

$$dU/dt = d(m u_l)/dt = \dot{m}h_v + \dot{Q}_0 + \dot{Q}_1 + \dot{Q}_c \quad (1)$$

By equating the internal energy of liquid water with its enthalpy (a negligible error at atmospheric pressure), this yields

$$0 = \dot{m}(h_v - u_l) + \dot{Q}_0 + \dot{Q}_1 + \dot{Q}_c = \dot{m}L + \dot{Q}_0 + \dot{Q}_1 + \dot{Q}_c \quad (2)$$

Hence the formula that will allow $\dot{Q}_1$ to be measured based on the evaporation rate ($\dot{m} < 0$)

$$\dot{Q}_1 = (-\dot{m})L - \dot{Q}_0 - \dot{Q}_c \quad (3)$$

In our experiments, under steady-state conditions—excluding the firing phases—we typically have $(-\dot{m})L = 45$ W, $-\dot{Q}_0 = 25$ W, $\dot{Q}_c = 70$ W, and $\dot{Q}_1 = 0$, since we wait for the temperature to become uniform throughout the entire volume of the thermostat—including the vessel—before taking measurements.

If we define the basic evaporation rate $\dot{m}_0$ as that which would be measured in the absence of firing but with the same external conditions, by

$$0 = (-\dot{m}_0)L - \dot{Q}_0 - \dot{Q}_c \quad (4)$$

formula (3) is written as

$$\dot{Q}_1 = [(-\dot{m}) - (-\dot{m}_0)]L = (\dot{m}_0 - \dot{m})L \quad (5)$$

This formula can be used directly when the evaporation rate $\dot{m}_0$ can be assumed constant and known from prior measurement in the absence of shots. This presupposes that $\dot{Q}_c$ is constant—a condition well satisfied if the heating power supply is of high quality (better than 0.2% in our case)—and that external losses $\dot{Q}_0$ are also constant; the latter is not always the case, for instance if there is significant variation in room temperature between the start and end of the experiment.

However, any variation in $\dot{Q}_0$ remains small, and a linear approximation of $\dot{m}_0$ between the values measured before and after the firings is generally sufficient to allow the application of equation (5).

Since the firing vessel is a closed system, the first law simply yields

$$dU_1/dt = -\dot{Q}_1 + \dot{W}_e = (\dot{m} - \dot{m}_0)L + \dot{W}_e \quad (6)$$

If we integrate this equation between a moment before the shots, when the regime was steady, and a moment after the shots, when the regime had returned to the same steady state, we obtain

$$\Delta U_1 = \int (\dot{m} - \dot{m}_0)L dt + W_e \quad (7)$$

This is the formula we use. As with any chemical reaction, if no reaction occurred in conjunction with the firings, the state of the vessel remains the same before and after, and $\Delta U_1 = 0$; if an exothermic reaction took place, $\Delta U_1 < 0$, and if it was endothermic, $\Delta U_1 > 0$.

Appendix 2: Mass measurements

The thermostat and firing vessel assembly is placed on a Sartorius Secura balance (12 kg maximum capacity, 0.1 g resolution, set to 5 readings per second); the power supply cables for the heater and high-voltage (HV) system are sufficiently flexible to minimize measurement interference and, crucially, to ensure their influence remains constant. The boiling of the water in the thermostat is ensured by a sheathed heating element powered by an Elektro-Automatik PS5200-04 A low-voltage power supply—regulated to a constant power output (e.g., 70 W) with stability better than 0.05%. Consequently, the bulk of the drift in background

evaporation (excluding the firing events) stems from thermal leakage in the thermostat—leakage that cannot be significantly reduced, as openings must be maintained to allow the steam flow to escape freely—and depends on the room temperature. However, this effect is minor, and a simple linear approximation of the base evaporation rate—for example, $m_0 = 0.0209 - 0.5 \times 10^{-8}t$ g/s—allows it to be accounted for.

Appendix 3: Electrical measurements

Discharge pulses are generated by the switching of an IGBT (Infineon FZ400R12KS4 with a 22-ohm gate resistor for turn-off protection) connected to the high-voltage supply and controlled—via an optocoupler—by a function generator (AimTTi TG5012A) that allows for the adjustment of pulse width and frequency.

Given the long time interval between pulses, we verified that the IGBT leakage current was low enough not to affect the measurement: indeed, no change in the steady-state evaporation is detected regardless of whether the high-voltage power supply is active or not.

The return-to-ground current (star connections on a 100 g copper plate) is measured using a Rogowski-type loop—specifically, a Pearson model 101 probe with a sensitivity of 0.01 V/A. The voltage is measured as close as possible to the discharge using a Teledyne-LeCroy differential high-voltage probe. Both quantities are recorded for each discharge on Wavesurfer oscilloscopes with a bandwidth of 200 MHz or higher, using a time resolution of 0.1 or 0.2 μ s—sufficient to ensure an overall measurement accuracy of a few percent.

We present below the analysis of shot 101 from the experiment shown in Figure 8, using the calorimeter.

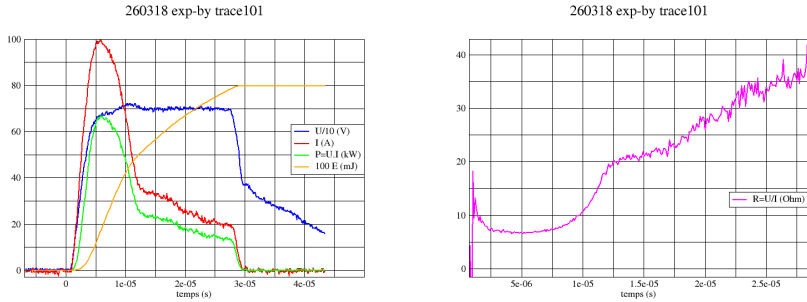


Figure 9. Shot 101 from the exp-by experiment shown in Figure 8. Current and voltage represent measured values, while the other quantities are calculated. On the right, the total resistance clearly shows the two phases: preheating via ionic conduction in the liquid solution, followed by arc ignition and the formation of a more resistive plasma sheath.

Appendix 4: Calorimeter

The calorimeter used is a heat-flow calorimeter manufactured by Calneos at the request of the CEA.

This prototype calorimeter measures thermal effects generated within a cell (sample vessel). It is a non-differential calorimeter featuring a single measurement cell. It operates in isothermal mode, with temperature regulated between ambient and 100°C (to within 0.001°C). The cell is held within a calorimetric block that is in thermal equilibrium with a calorimetric furnace. Heat transfer between the calorimetric block and the furnace is measured using heat-flow sensors. The calorimeter's furnace is maintained at the measurement temperature by a multi-stage control system. The setup enables isothermal temperature control based on a water-thermostated cold source (thermostatic bath). The cell incorporates a magnetic stirrer to optimize heat transfer within it. The calorimeter's sensitivity allows for energy determination with 5% accuracy across the measurement range (1 to 50 W).

This calorimeter can operate in two modes:

- a conventional mode measuring heat flux via Peltier elements surrounding the cell, where the measurement time depends on the time constant characterized by the thermal resistance of the sensors and the heat capacity of the cell;

- a "power compensation" mode, which maintains a fixed heat flux (suited to the desired measurement—here, approximately 1 to 25 W) through the measurement Peltier elements using Joule heating for compensation (PID control to maintain a stable heat flux). This mode makes it possible to bypass the thermal resistance of the sensors and achieve faster calorimeter response. The measurement time thus depends solely on the time constant of the reaction being measured and the thermal resistance within the cell (e.g., the thermal resistance of the solution inside the cell).

We used it in "power compensation" mode at 25 W because the power recording is more stable, albeit noisier.