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Research Article

Reanalysis of an Explosion in a LENR Experiment

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Abstract

An electrolytic cell operated with a hollow Pd cathode exploded in 2004. The violence of the explosion was surprising. We decided to re-analyze this event. The examination of the cell remnants indicate that the explosion occurred in the gas phase, and the electrodes seem unaffected. The stoichiometric H_2–O_2 mix can explode following different mechanisms that are briefly reviewed. A particular phenomenon called Shock Wave Amplification by Coherent Energy Release (SWACER) is able to produce strong detonations. A gas quantity similar to the original cell ignited by a hot spot or a spark produces only weak explosions that do not break the glass tube. Strong detonations are reproducibly obtained with a setup designed to induce the SWACER. The re-analysis of the event shows that the explosion was probably triggered by the SWACER resulting from a reaction in the hollow Pd cathode. In order to avoid accidents in the future during the operation of closed electrolytic cells, it is advised in addition to the conventional safety measures to avoid the presence of hollow, gas-filled metallic pieces in the reactor gas space, like a tube or a folded sheet.
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Keywords: Deflagration, Detonation, Electrolytic cell, Explosion, Pd cathode, SWACER

1. Introduction

In 2004 Jean-Paul Biberian conducted an electrolytic Low Energy Nuclear Reaction (LENR) experiment with a mass flow calorimeter. The purpose of this experiment was to measure the abnormal heat during the electrolysis of heavy water with a palladium cathode. The reactor used has been described in a previous paper [1], see Fig. 1. The experiment ended with a strong explosion. The glass tube was shattered into many small pieces.At that time, the strength of the explosion seemed strange, because the quantity of explosive gas mixture in the reactor was limited. Biberian made some additional tests. An identical reactor was filled with a H_2–O_2 stoichiometric gas mix and ignited by a hot wire. These chemical explosions were relatively weak and unable to break the glass reactor. Therefore, the question was raised about a potential LENR mechanism to explain the explosion.

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Because of the significant implications of this hypothesis, it was considered desirable to further investigate the possibility that the phenomenon is of chemical origin. This is the purpose of the present paper.

The paper is organized as follows:

(1) The experimental setup is briefly presented together with the examination of the pieces recovered after the explosion.
(2) In order to provide a useful discussion of the problem, the basics of the different phenomena that take place during the reaction of H_2 and O_2 are reviewed. The whole series of phenomena ranging for ignition to detonation are briefly described.
(3) Explosions of H_2–O_2 stoichiometric gas mix were tested. They made it possible to demonstrate that the glass tube may be broken or not depending on the conditions of the experiment, in accordance with the theories mentioned in Section 2.
(4) The theoretical and the practical explanations allow the elaboration of a plausible mechanism of the event that occurred in the test reactor.
(5) Some similar events reported in the literature are re-examined under the light of the findings.
(6) Finally, some recommendations are offered in order to avoid accidents in the future.

2. Description of the 2004 Event

Electrolysis was performed in a Dewar to minimize undesirable heat losses. The reactor was built as a mass flow calorimeter. A controlled flow of water in the central condenser removed the heat as illustrated in Fig. 1. The geometrical characteristics are summarized in Fig. 2.

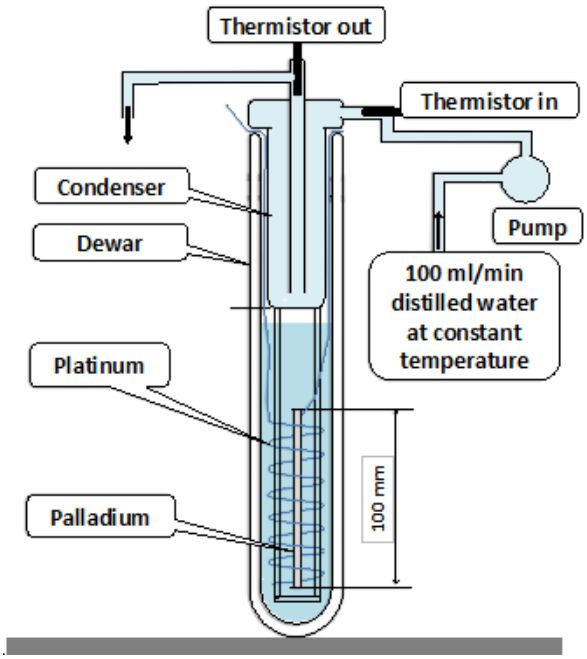


Figure 1. Schematic of the electrolytic cell.

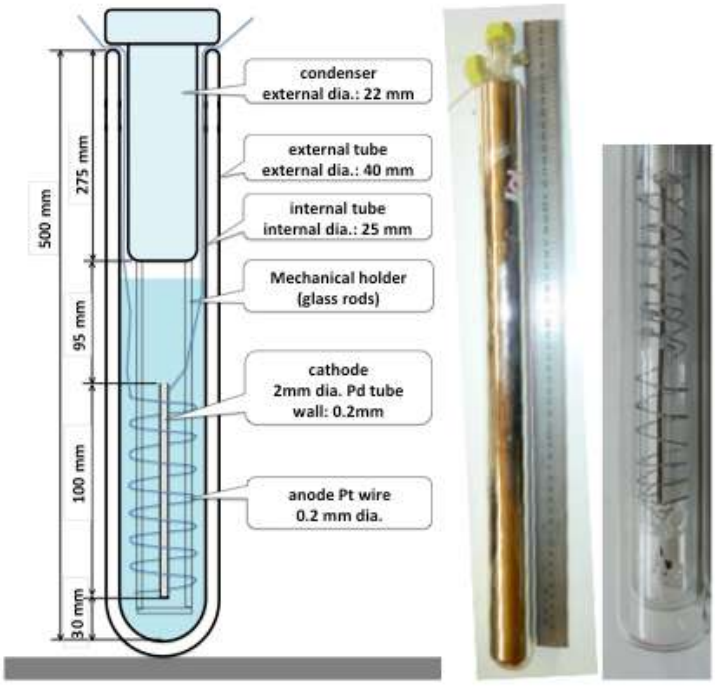


Figure 2. *Left*: Schematic geometry of the reactor used during the test with the precise dimensions as shown – *Middle*: The reactor glass tubes were silver coated on the inner faces. *Right:* The electrodes utilized during the test are shown inserted in a similar non-silver coated reactor.

Figure 3 shows the reactor after the explosion. Figure 4 shows the electrodes after the event. The cathode was a 100 mm Pd tube 2 mm outer diameter and 200 μm wall thickness closed at the bottom and opened at the top. The

Figure 3. Photograph of the reactor after the explosion. The bottom parts remained in place, some liquid was left inside.

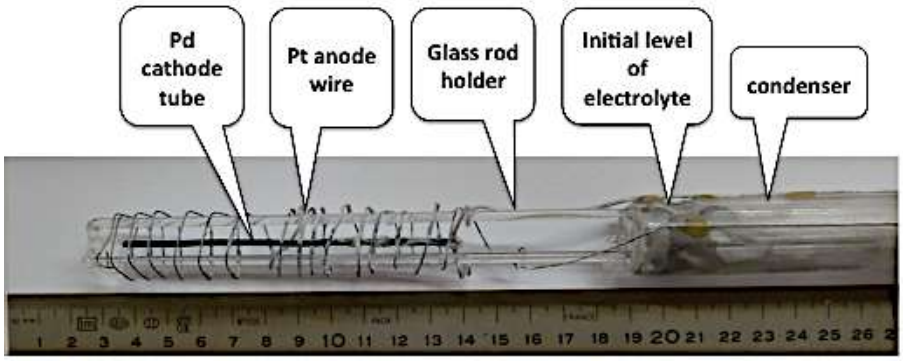


Figure 4. Photograph of the electrodes. The ruler shows the altitude over the bottom of the inner reactor tube. Note the trace at 200 mm probably corresponding to the initial level of the electrolyte.

anode was a platinum wire wrapped around glass rods.

An examination of the electrodes leads to the conclusion that they are relatively unaffected.

The glass reactor was broken into many fragments. Many of them were small pieces in the millimeter size or less. Some others had a size in the centimeter range and were carefully recovered (see Fig. 5).

The bottom part of the outer tube was broken into four pieces that can be fitted together. The bottom part of the inner tube punched the outer tube that was resting on the table. It seems likely that the bottom sections of both tubes were struck nearly simultaneously by the shock wave. The bottom sections were not shattered in small fragments probably because the electrolyte reflected the shock wave.

The elements available for examination lead us to consider that the explosion occurred in the gas phase. This is the hypothesis considered in this paper.

3. Review of the Explosion Mechanisms

The main phenomena are briefly reminded here. The reader interested in more details is invited to refer to the literature.

Figure 5. *Left*: Pieces from the outer tube. *Right*: Pieces from the inner tube. The cylinders visible on the left of both pictures are parts of the outer and the inner tubes and give the scale.

3.1. Chemical reaction

The H_2–O_2 stoichiometric gas mix can readily react according to the equation:

$$2H_2 + O_2 \rightarrow 2H_2O + 572\,\text{kJ mol}^{-1}. \quad (1)$$

In standard conditions, this energy equates to 8.5 J/cm^3 of gas mix. The internal volume is 100 cm^3. Therefore, the maximum chemical energy available in the explosive mixture is at most 850 J.

3.2. Reaction initiation

The simplest method to ignite a combustible mixture is to create a hot spot. This may be done with a heated surface. In the case of the H_2–O_2 stoichiometric gas mix, the temperature of the hot surface must be higher than 833 K [2]. Another solution is to trigger an electrical spark with sufficient energy. For the H_2–O_2 stoichiometric gas mix, the critical energy is low: 3 μJ. Such a weak spark may result from an electrostatic discharge. This explains why this stoichiometric mixture can so easily ignite.

There are other ways to ignite the reaction. One important possibility for the present discussion is the presence of chemical radicals on or close to the vessel surface [3]. This has been demonstrated by the initiation of the reaction (and subsequently of the detonation, as will be seen later) by UV irradiation of chemically sensitive gases, like H_2–O_2 with addition of Cl_2 [4]. The Cl radicals resulting from the photo-dissociation of Cl_2 molecules are able to ignite the gas mixture.

It is also well known that a metallic surface like Pt catalyzes the recombination of H_2 with O_2, to the point that an explosion may occur [5]. Therefore, a high temperature spot created by an external energy input is not necessarily required to initiate the H_2–O_2 reaction.

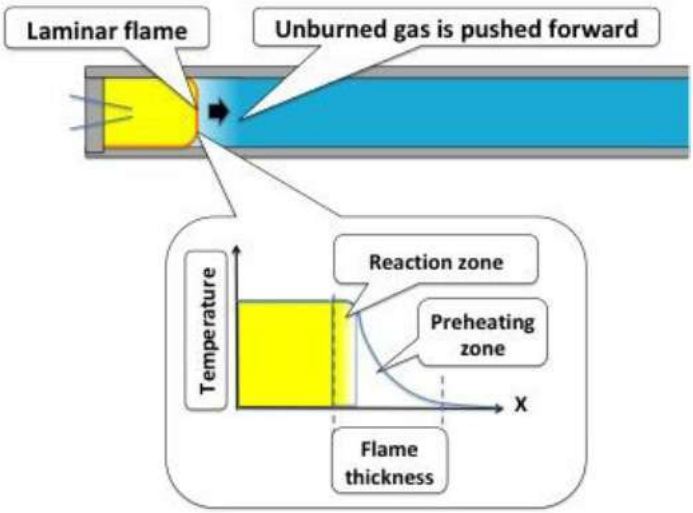


Figure 6. Schematic of the laminar combustion and detail of the flame front.

3.3. Laminar flame

Once combustion is initiated, a flame propagates through the gas mixture [6]. Let us consider Fig. 6. This sketch represents a flame travelling along a tube closed at one end, filled with a combustible gas mixture. The gas is ignited near the closed end. Shortly after the ignition, the flame is laminar. It has typically the shape of a flat front moving at a speed called the laminar flame speed.

Figure 6 also shows a schematic of an enlargement of the flame structure. The reactive zone itself is very thin. The heat released by the combustion diffuses towards the fresh gas adjacent to the front, elevating its temperature to the point that it reacts in turn. The flame moves ahead and the process continues. The flame velocity is governed by heat diffusion. For a stoichiometric H_2–O_2 mix at atmospheric pressure and ambient initial temperature, the flame propagates at a speed of 11 m s^{-1} [6]. This velocity is called the laminar flame speed. The flame thickness for H_2–O_2 is 0.32 mm. Dividing this value by the flame speed, we find that there is an induction time of 30 μs to initiate the reaction locally.

If now we observe the flame propagating along the tube, the hot gas resulting from the combustion creates a movement of the unburned gas ahead of the flame front [7]. The gas movement is sufficiently rapid to induce a turbulent flow of the unburned gas in the tube (Fig. 7).

The flame front is unstable and distorted by the turbulence eddies. Combustion proceeds over an increased surface that has a larger area than the flat laminar front. The heat release rate in the zone where combustion is taking place is increased. Therefore, the velocity imparted to the fresh mixture is also increased, and this further reinforces the turbulence of the gas flow [7,8]. This process is self-accelerated. The flame velocity increases progressively to supersonic speeds (e.g. 1000 m s^{-1}) [6–14]. This process is called deflagration.

3.4. Deflagration Detonation Transition (DDT)

Once the flame velocity approaches the speed of sound in the unburned gas, a pressure wave is formed ahead of the flame. As the velocity nears the speed of sound, the pressure wave steepens into a primary shock wave. The temperature of the unburned gas is rapidly raised when the primary shock wave passes. In other words, the unburned gas is preheated before the combustion starts. It is clear that because of the preheating, the combustion process is reinforced. The flame becomes supersonic and accelerates further.

At some point, called the detonation kernel, the preheating is such that an explosion arises directly within the combustion front creating a new local detonation shock wave (Fig. 8). The flame and the new shock wave are now coupled. There is a transition of the deflagration into a new phenomenon called detonation [7–14].

If we consider a detonation wave travelling in a stabilized manner along the tube, the flame parameters are well described by the theories of Chapman–Jouguet (CJ) and Zeldovich–von Neuman–Döring (ZND) [7–15].

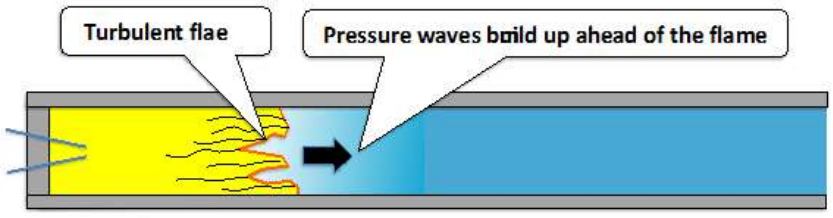


Figure 7. Propagation of a deflagration. The flame front surface is enlarged by the instabilities, this increases the combustion rate.

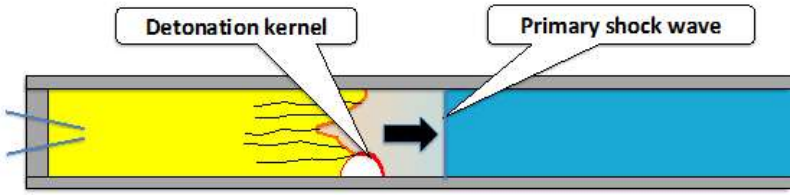


Figure 8. Onset of detonation.With sufficient preheating of the gas by the supersonic primary shock wave, an explosion occurs locally (detonation kernel). The detonation velocity is much larger than the primary shock wave velocity. The detonation propagates rapidly through the unburned gas.

The CJ theory makes it possible to calculate the main characteristics of the detonation. For the stoichiometric H_2–O_2 mix, the pressure in the burned gas is 18.4 bar and the temperature 3400 K. The wave velocity is 2900 ms^{-1}.

The ZND theory takes into account the fact that the reactants cannot be consumed instantly, but that the reaction requires a minimum duration (induction time). Within the wave front, there is a pressure peak P_{ZND} that is typically twice the pressure P_{CJ}, see Fig. 10. The compression results in the instantaneous heating of the gas to a temperature level of roughly $T_{CJ}/2$, sufficient to get the combustion within a short induction time. In the case of H_2–O_2, the reaction time is 80 ns and P_{ZND} is 41 bar [15]. In a 38 mm tube, the time between flame ignition and onset of the detonation is 500 μs for the stoichiometric H_2–O_2 mix [9]. The run-up distance between the point of ignition and the onset of the detonation is 60 mm [15].

The turbulence has a strong influence on the DDT. The run-up distance can be reduced by the introduction of devices able to increase the level of turbulence in the tube. The reader interested in the details of these theories is invited to refer to the relevant literature.

The detonation is in fact a very complicated process. Many shock waves are created, travel back and forth, and interact with each other (Fig. 9). Reflection of the detonation wave on a closed wall may double or triple the pressure shock [16–18]. Values exceeding 80–100 bar are reported [17–19]. Once the detonation front is established, the unburned gas remains unaffected until the arrival of the supersonic front. At the onset of the detonation, the unburned gas ahead of the flame front is already preheated by the shock waves that were running ahead of the flame while the

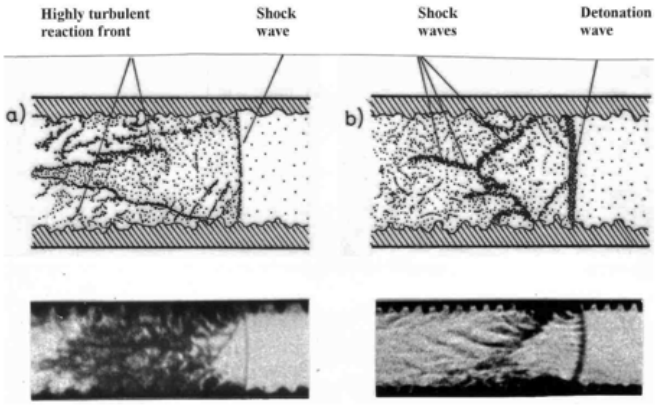


Figure 9. Shadowgraphs after [7]. (a) Before the onset of the detonation, the turbulent distorted reaction front and the supersonic primary shock wave are visible. (b) After the onset of detonation, the detonation front is clearly visible, as well as several secondary shock waves.

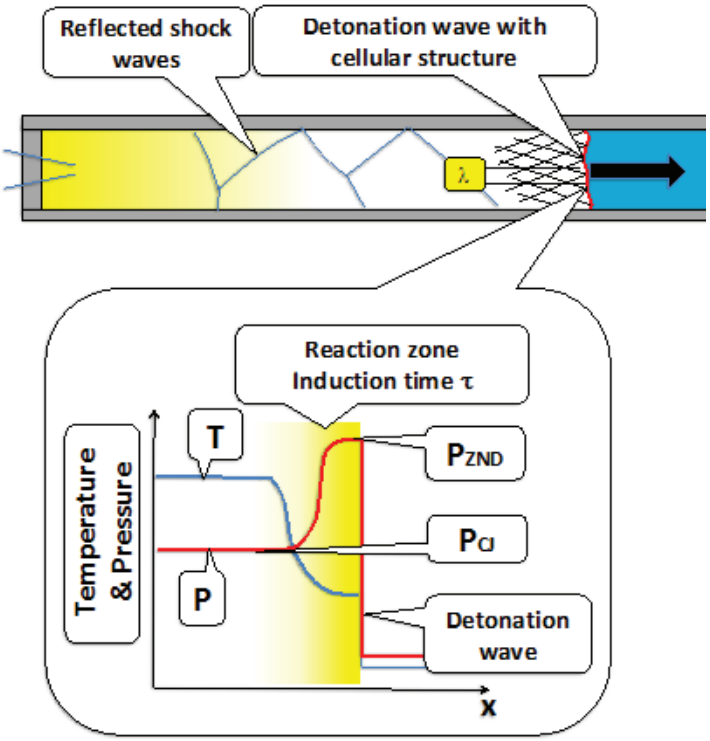


Figure 10. Detonation. The front has a cellular structure. The peak pressure within the front is about twice the pressure of the reacted gas.

flame was still subsonic. Therefore, the reaction is more violent than at a later moment, once the detonation wave is fully established. This is called overdriven detonation and the pressure is temporarily much higher than P_{CJ} [20].

Another fact to be mentioned here is that the reaction front is not a stable uniform structure, but exhibits a cellular structure (Fig. 10). The reader may refer to the literature for details. It is sufficient to mention here that in the case of H_2–O_2 the cell size λg is about 2.4 mm [8,15,21].

3.5. Direct initiation of a detonation

If the ignition energy is large, the shock can directly trigger the detonation without the intermediate deflagration phase (Shock Detonation Transition or SDT). In the case of the H_2–O_2 mix, an energy amount of about 6 J (e.g. a strong spark) is able to directly induce the detonation [8,21].

3.6. Combustion in a small diameter tubes and gaps

In large diameter tubes, the turbulence that can be fully developed is often considered as an important factor to accelerate the flame leading to the DDT. Conversely, in small diameter tubes the role of the turbulence is reduced. The flame is stretched along the boundary layers, and the elongation of the flame accelerates the local combustion, in a similar manner as the turbulence in large tubes. It is generally accepted that no detonation can propagate itself in a tube with a diameter smaller than λ/π [9,21]. However, experience shows that detonation is readily obtained when the reaction

takes place in small dimension tubes [22–25]. Detonation is obtained in tubes as small as 0.5 mm. It is also observed when the gases react between two parallel plates (Fig. 11). A gap of 0.26 mm is sufficient for the ethylene–oxygen mix [23]. Computations make it possible to simulate the phenomena at play. The run-up distance between ignition and DDT is three times shorter in a 3D tube than in a 2D gap [24].

When a small tube opens into a larger one, the detonation is transmitted in the large one only if some conditions are satisfied [9,15,19,23,24]. In particular, the diameter of the small tube must be larger than 13λ. Otherwise, the expansion of the flame decouples the shock wave from the reaction front and the detonation is changed into a deflagration, or even extinguished. However, the deflagration exiting from a small tube or gap may trigger a large explosion in some cases, as explained in the next paragraph.

3.7. Shock wave amplification by coherent energy release

When certain conditions are present in the explosive gas, initially weak shocks can amplify extremely rapidly to form detonations. There is a universal initiation mechanism called SWACER. The general requirement is the existence of a gradient of induction time in the explosive gas [3,4,10,20]. Of particular interest in the present discussion is the possibility to create the induction time gradient via a temperature gradient [3,25,26]. Consider Fig. 12a. A pre-chamber filled with an explosive mixture is connected through an orifice to a large volume of explosive gas. A deflagration is initiated in the pre-chamber. The temperature rise pushes a hot gas brush into the large volume. The hot jet is mixed with the initially quiescent gas by turbulent eddies. This shows that several outcomes are possible depending on the degree of turbulence:

- If the hot jet velocity is low because the orifice is large, the degree of turbulence is limited and the deflagration flame is transmitted to the gas in the large volume. No detonation occurs immediately (it may later, because of a DDT in the large volume).
- If the orifice is too small, the hot jet velocity is very large. The hot gas is strongly mixed with the cold gas. The temperature of the gas particles falls below the ignition temperature and the flame is extinguished.
- If the orifice section has an appropriate size, the turbulent mixing results in the buildup of a temperature gradient, see Fig. 12b. The hottest gas is located just at the tube orifice, and the temperature decreases as the distance increases. When the temperature at the orifice reaches the gas ignition temperature, the reaction starts in the large volume. The heat released reinforces the flame. Part of this heat is transmitted to the next gas layer that was at a slightly lower temperature but at the verge of ignition (Fig. 12c). If the heat imparted by the previous layer more than compensates for the temperature gradient, this layer reacts as well and amplifies further the flame energy (Figs. 12d and 12e). This process continues until a shock wave is formed (Fig. 12f). If the conditions are correct a detonation occurs (Fig. 12g).

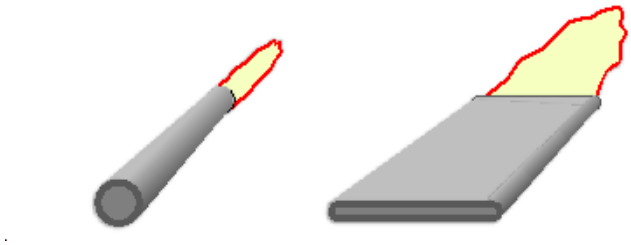
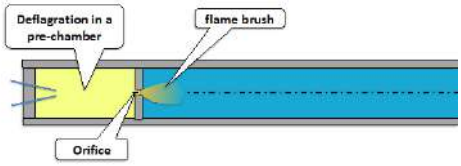
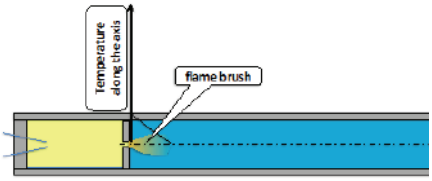


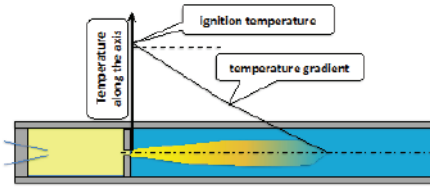
Figure 11. Combustion in small diameter tubes or gaps may transit into deflagration or detonation.



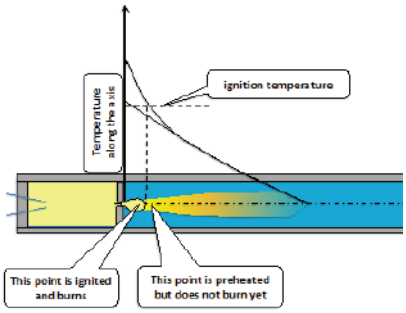
(a) Pre-chamber with orifice



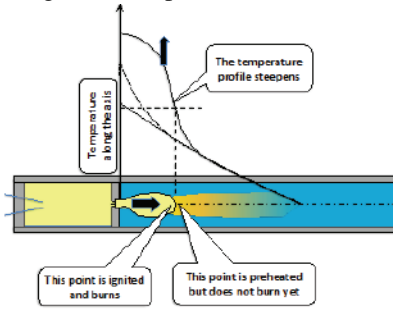
(b) Temperature gradient buildup



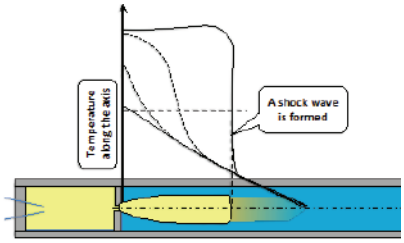
(c) Ignition temperature at orifice



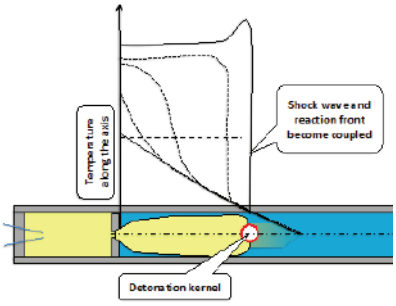
(d) Reaction near the orifice



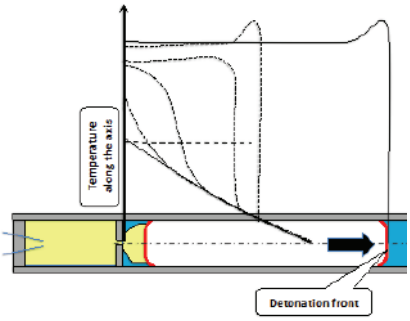
(e) Flame front amplification



(f) Shock wave amplification



(g) Detonation onset



(h) Detonation wave

Figure 12. The SWACER detonation mechanism.

The SWACER is a powerful mechanism to detonate an explosive gas mixture. In the case of the H_2–O_2 stoichiometric mix, the detonation occurs in less than 100 μs [26]. It is interesting to note that the detonation in a small diameter tube does not always induce a detonation in the large volume, while a deflagration can sometimes do that via the SWACER process.

4. Explosions Tests

4.1. Experimental setup

In order to develop a better understanding of the explosion mechanism that destroyed the reactor in 2004, we decided to perform different experiments with the H_2–O_2 stoichiometric mix.

The following experiments have been conducted.

- A first series of tests was made in glass tubes with dimensions similar to the original reactor. The aim was to check if a simple explosion would be able to break the tube. Several modes of ignition were utilized (hot wire, high voltage spark, and exploded wire).
- A second series of tests were made in steel tubes. The objective was to evaluate the explosion damaging pressure following the setup configuration. One particular test showed by serendipity the influence of the SWACER mechanism.
- A third series involved ignition in a pre-chamber connected by a long small diameter tube to the test tube to investigate the SWACER phenomenon.

In total, 28 shots were performed.

4.2. Explosions in glass tube

The tube in Pyrex glass has an external diameter of 25 mm similar to the internal tube of the original reactor. The wall thickness is 1 mm and the length 200 mm (Duran® from Schott).

The stoichiometric H_2–O_2 gas mix was produced by the electrolysis of light water added with some NaOH at the bottom of the Pyrex tube. The electrodes were made of iron.

Several modes of ignitions were utilized. Movies were recorded at 30 frames/s.

4.2.1. *Ignition by a hot wire*

The ignition was obtained by a small coil of 200 μm diameter Constantan wire, heated by an auxiliary current source. As explained in Section 3.2, the hot spot temperature must exceed 833 K (560°C) to initiate the reaction.

Figure 13 shows three successive photos taken from a movie. On the left-hand side, the heated wire is red hot. The brightness of the wire seems to correspond to a temperature higher than 833 K, although a precise evaluation is not possible. The middle picture 33 ms later is a snapshot of the flame travelling up the tube. This shows that the flame velocity is low. The silicone plug is still in place. 33 ms later, the flame is already extinguished and the silicone plug is thrown clear of the tube. It is clear that in this case a deflagration was observed, not a detonation. The glass tube was never broken in this series of shots. An evaluation of the pressure developed by the explosion was not possible.

4.2.2. *Ignition by a high voltage spark*

In order to observe detonations, the energy of the ignition was increased. This was obtained by a spark triggered between an auxiliary electrode and the bath (Fig. 14). The length of the spark was 5 mm. In a movie taken at 30

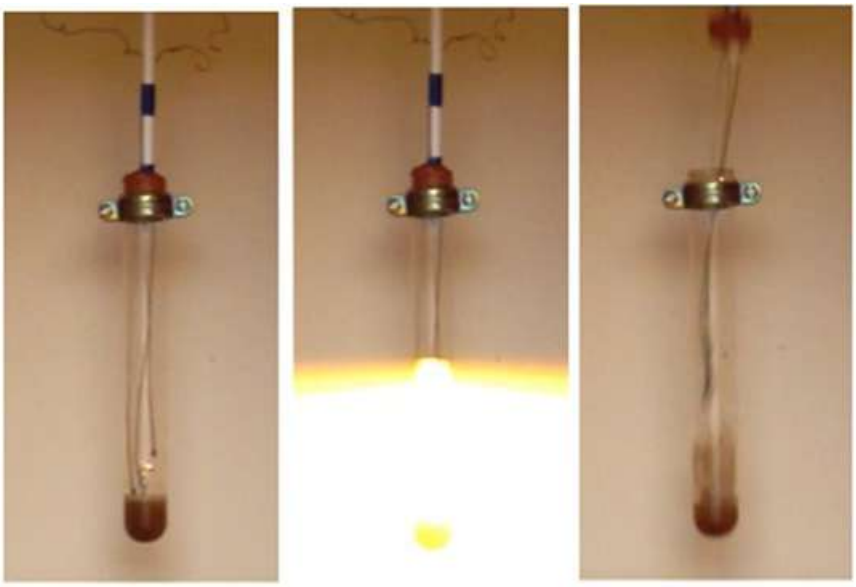


Figure 13. Deflagration ignited by a hot Constantan wire. Photographs at 33 ms intervals.

frames/s, the flame is visible in only one the pictures. The flame fills the whole tube indicating that the flame velocity is high. The explosion was much noisier and stronger. This probably corresponds to a detonation. However, the glass tube was never broken in this series of shots. An evaluation of the pressure developed by the explosion was not possible.

4.2.3. *Ignition by an exploded wire*

Another setup was tested in an attempt to quantify the peak pressure during the explosion. The tube was closed by a cover free to lift under the influence of the high gas pressure in the gas space. The cover weight was increased by a lead mass of 1100 g.

A high voltage 1 μF capacitor loaded up to 6 kV was discharged through a small coil of 70 μm diameter copper wire. Tests were performed with the exploded wire located at different heights along the tube axis. The explosions were likely detonations. The cover loaded by a 1100 g weight is lifted 20–30 mm, as shown on the right picture of Fig. 15. A 30 mm lift corresponds to an initial vertical velocity of 0.8 m s^{-1}. The momentum of the cover was then 0.88 kg m s^{-1}. Assuming very roughly that the impulse of the explosion lasted 1ms, the force exerted by the hot gases is 880 N. The section of the tube is 4.5 cm^2. The ratio of the force to the section gives a pressure of 19 bar. This is close to the P_{CJ} value (see Section 3.4), however this method can only give a rough estimate. In spite of the large pressure rise, the glass tube was never broken in this series of shots. In fact, the same glass tube was re-used for all the tests discussed in the above (10 shots).

4.3. Tests in steel tubes

These tests were done in 21 mm internal diameter steel tubes in order to evaluate the damaging pressure of the explosion, as explained in [17]. Aluminum disks at both ends close the steel tube. The internal pressure developed during

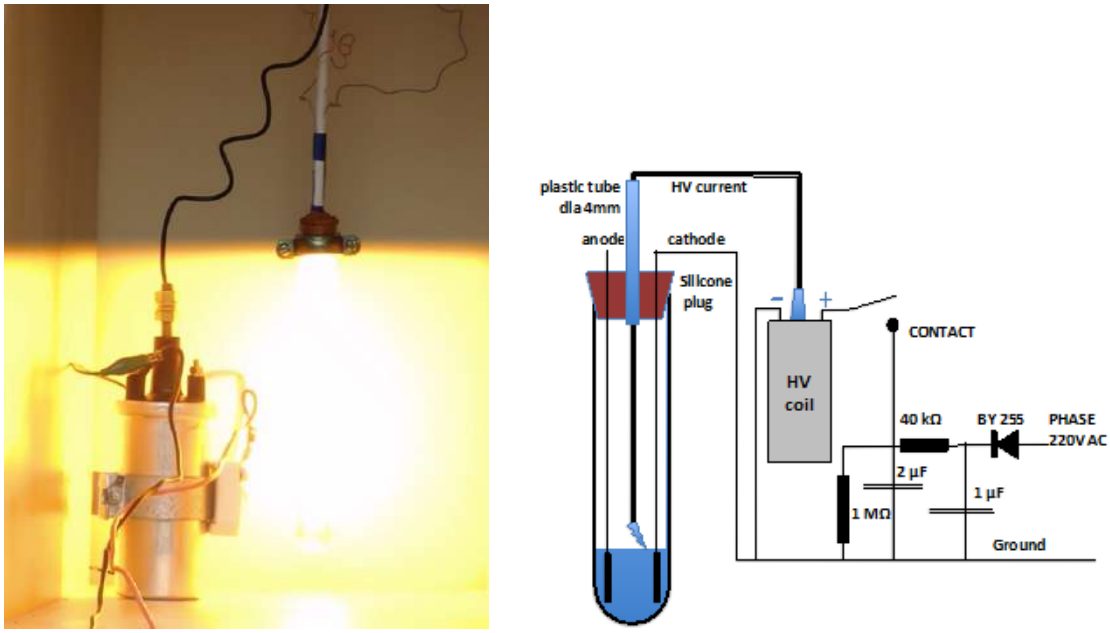


Figure 14. Explosion ignited by a high voltage spark.

the explosion deforms the disks permanently. This raises the possibility that we can estimate what the pressure peak was during the reflection of the shock wave at the tube end face. The aluminum disks thickness was 0.5 mm. The disks were annealed at 320°C before use to obtain reproducible mechanical characteristics. The relationship between

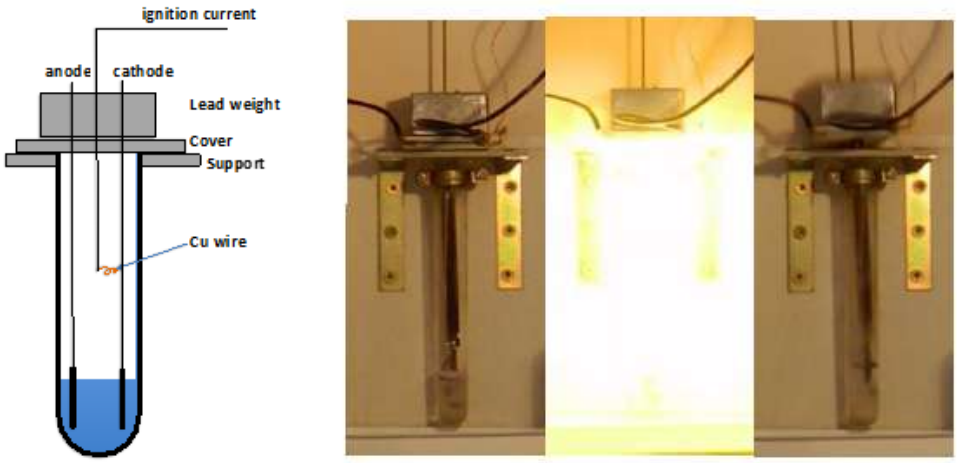


Figure 15. Ignition by an exploded wire. The tube is plugged by a lead weight, free to lift under the influence of the gas pressure. Pictures are taken at 33 ms intervals. The maximum altitude reached by the weight makes it possible to obtain a rough estimate of the gas pressure.

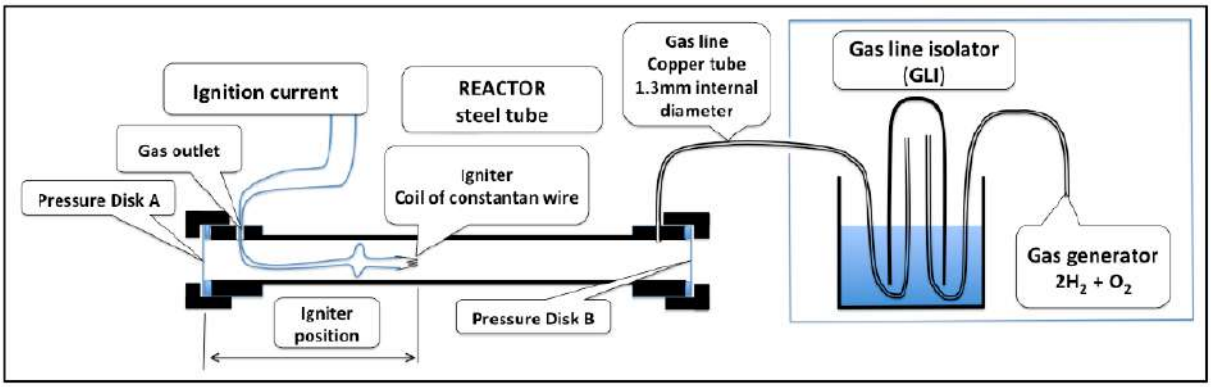


Figure 16. Sketch of the experiment in a steel tube.

the disk deformation and the pressure was established by hydraulic tests. Figure 16 presents the principle of the experiment. The stoichiometric H_2–O_2 gas mix is fed by a 1.3 mm copper tube. Ignition was done by a hot wire or a HV spark. Figure 17 shows examples of disks before and after the test.

A test was prepared by a prolonged purge of the tube with the H_2–O_2 mix. The glass tube of the gas line isolator (GLI) was removed and the shot promptly fired to limit the effect of the leakage by the gas outlet hole.

Different tube lengths were used from 160 to 640 mm. Pressure peaks of about 40 bar were measured in the long tubes, in accordance with the P_{ZND} value mentioned in Section 3.4. This clearly demonstrates that full detonations were obtained.

The location of the igniter in the tube has an influence on the pressure peaks observed on the end plates. This is illustrated by the results shown in Fig. 18. In 160 mm long tubes, the igniter was located at different distances from the tube end. One can see that the pressure peaks developed on the opposite ends are different. The pressure is higher at the end opposite the igniter. However, the figure is not symmetric. This may be due to the influence of the igniter

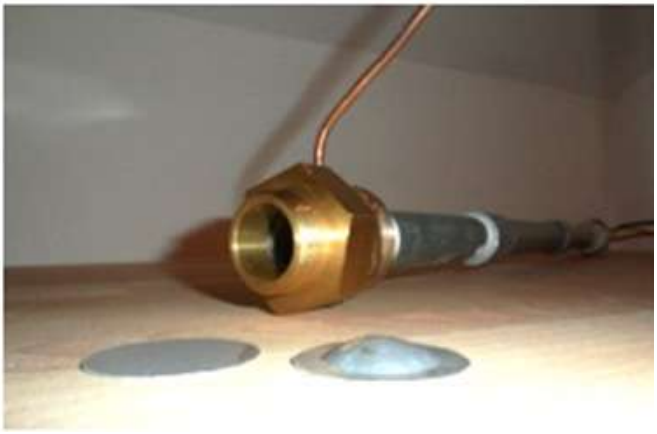


Figure 17. Picture of the reactor steel tube and of aluminum disks before and after a shot.

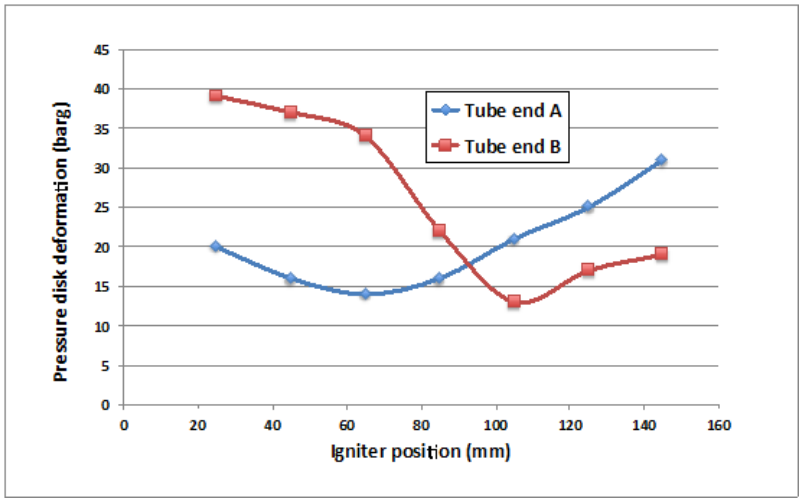


Figure 18. Influence of the igniter position on the pressure peaks at both ends of a 21 mm diameter 160 mm long steel tube.

connection wires on the turbulence within the tube.

The last test of this series was performed differently. The gas flow through the GLI was maintained in order to compensate the gas leakage until the shot (Fig. 19). Therefore, in the last test the isolator glass tube was left in place. The explosion was transmitted along the feeding line. The GLI glass tube was completely shattered, and the water bath glass container also broken. This experiment proved that a deflagration propagating along a small diameter tube could lead to a strong detonation, most probably via the SWACER mechanism. The explosion was not transmitted to the electrolyzer.

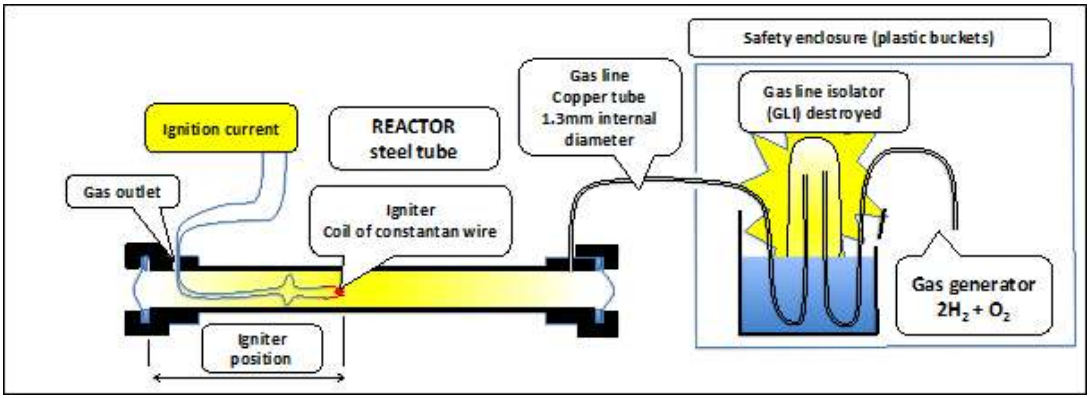


Figure 19. Last test of the series in steel tubes. The explosion is transmitted to the GLI and induces an SWACER in the glass tube that is shattered.

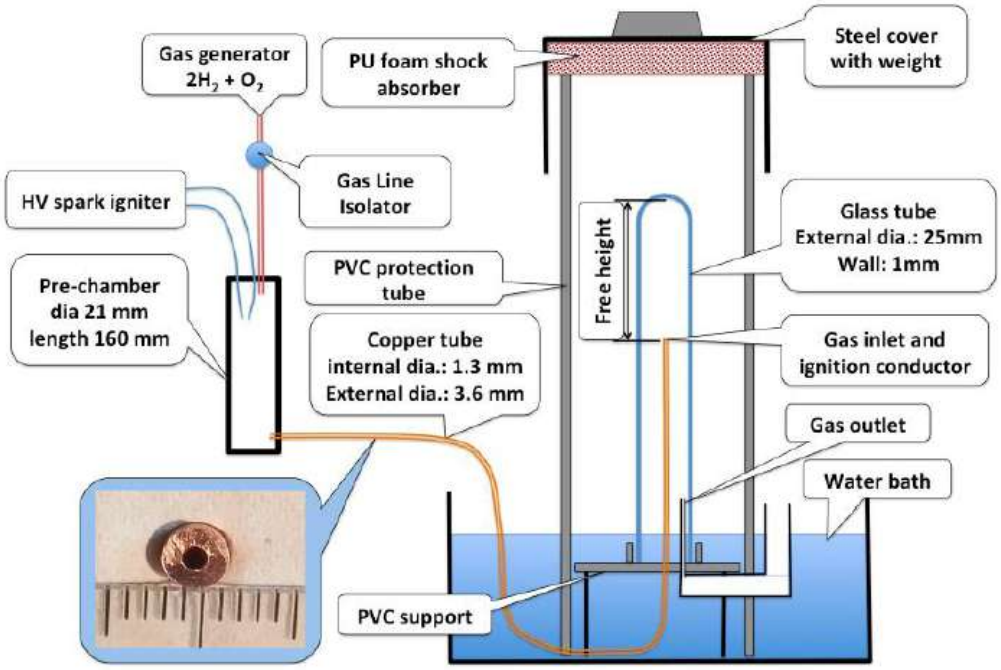


Figure 20. The gas is ignited in the pre-chamber. The deflagration propagates along the copper tube to the glass tube. A protection is provided in order to avoid the projection of glass debris by the detonation. The insert shows a cut of the copper tube.

4.4. Ignition in a pre-chamber

This series of tests is a direct consequence of the unexpected result described above. The aim was to explore some of the parameters that lead to the SWACER mechanism. In particular, it was decided to investigate the influence of the

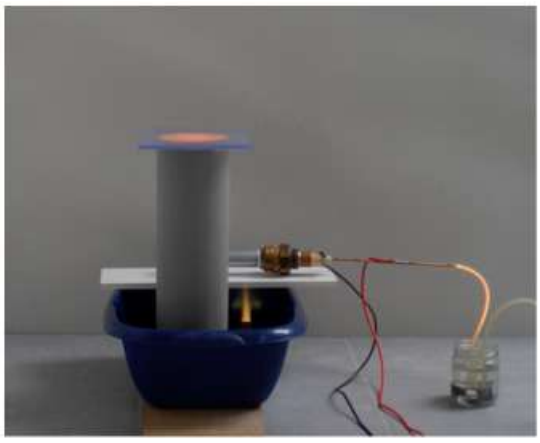


Figure 21. Picture taken during a shot. In this case there was no detonation. The protection cover with a foam shock absorber was replaced here by a transparent plastic sheet. The pre-chamber is the steel tube in background. The flame is visible through the cover, as a jet through the gas outlet, and in the transparent gas feeding line up to the gas line isolator on the right of the image.

Figure 22. Examples of glass debris settled on the tube support after strong detonations. On the left picture, the protection tube has been removed and the water level lowered to make the support visible. On the right picture the assembly has been taken out of the bath. Note that the glass tube section that was immersed in water during the shot is not completely pulverized.

position of the small tube opening inside the glass tube. Figure 20 presents the corresponding setup.

The photo of Fig. 21 is taken from a movie made during a test that led to a simple deflagration, just at the time of the flame flash. The glass tube was not broken in this case but thrown-up onto the cover.

Figure 22 shows the results of full detonation experiments. After removal of the protection tube, glass debris were found on the tube support. Small glass fragments were also encrusted on the internal surface of the protection tube by the force of the explosion.

Different distances between the glass bottom and the copper tube opening have been tested. The results are summarized in Fig. 23. The SWACER occurred for 60 and 90 mm. The tube was left intact for 30 and 140 mm. It was broken into a few large pieces for a distance of 110 mm. This demonstrates that the precise configuration of the setup is a decisive factor to trigger the SWACER mechanism or not. This is probably linked to the presence of turbulent eddies within the tube, more or less favorable for the occurrence of the SWACER mechanism.

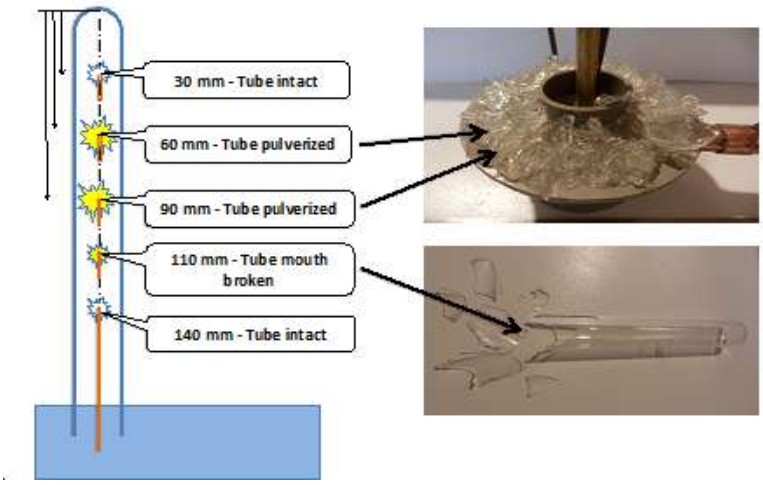


Figure 23. Tests with the small ignition tube located at different height along the glass tube center line. Pictures of the glass tube debris after different shots.

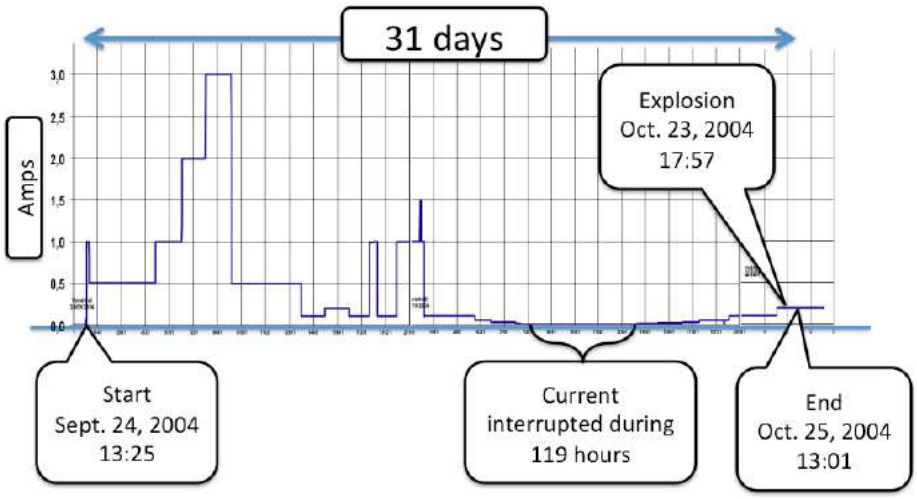


Figure 24. Electrical current during the experiment.

5. Scenario of the Reactor Explosion

The above explanations and tests invite one to consider the following scenario to explain the event that occurred in 2004.

Figure 24 shows the current recorded during the 31 days of the experiment. The current was varied several times. It was interrupted during 119 h. No addition of D_2O was done during the whole duration of the experiment. The explosion happened on a Saturday evening. Although the reactor was broken, there was sufficient electrolyte left at the bottom to maintain the 0.2 A current. The problem was discovered on the following Monday.

The following scenario is proposed (see Figs. 25a–f).

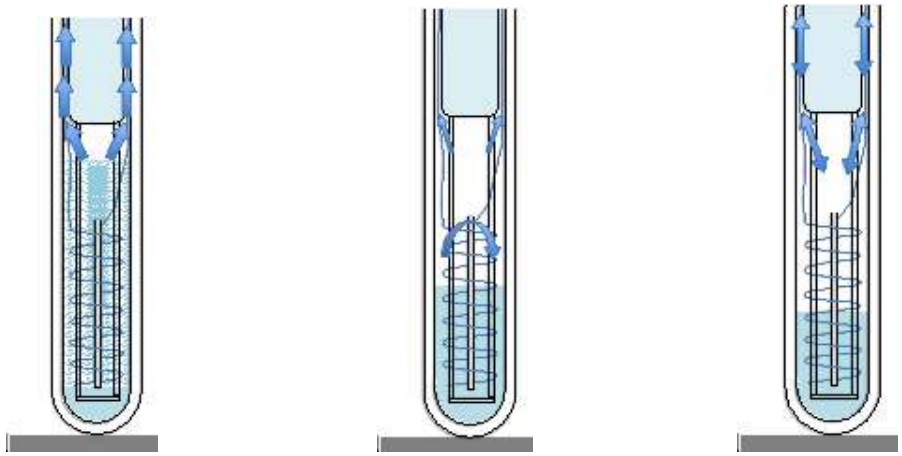
At the start of the experiment, the reactor is filled with 100 cm^3 of D_2O added with LiOD. (A trace of the initial level is still visible on the condenser, see Fig. 4.) During this phase of the experiment the Pd cathode is loaded with deuterium. The surplus of D_2 and O_2 escapes between the condenser and glass tube.

The liquid level drops progressively. The top of the Pd cathode emerges. The Pd and the Pt surfaces catalyze the recombination of a part of the gas mix, slowing down the loss of liquid. The current is interrupted. During that period, the Pd loses a part or all of the dissolved deuterium.

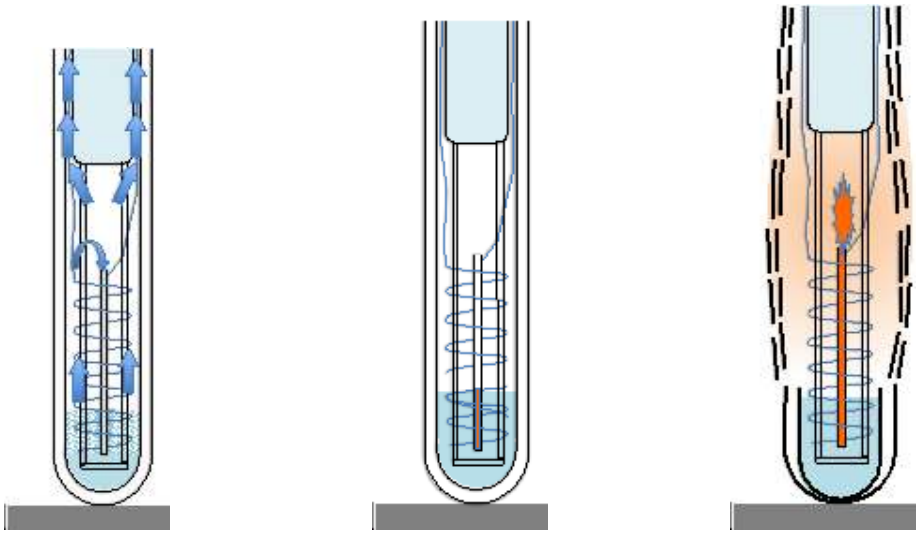
The gas space is filled again by D_2–O_2. The D_2–O_2 mix diffuses inside the Pd tube because its opening is exposed to the gas space. The Pd metallic wall of the cathode is reloaded with deuterium. The deuterium diffuses through the Pd tube wall and builds up in the Pd wall in the bottom part still immersed in the electrolyte.

The deuterium dissolved in the palladium diffuses across the wall and comes to the inner tube face. The Pd catalyzes the recombination of the D atoms with the oxygen present inside the tube void. The local reaction creates a hot spot inside the Pd cathode at the bottom

The local reaction ignites a flame inside the Pd tube, leading to a deflagration. The deflagration in the small hollow cathode triggers the SWACER mechanism in the gas space. The reactor explodes. This sequence based on prosaic phenomena may explain the explosion event observed in the reactor in 2004. If confirmed, then it would mean that non-conventional reactions are not required.



(a) Initial electrolysis period (b) Prolonged electrolysis period (c) Current interruption



(d) Electrolysis is resumed (e) Reaction in the hollow cathode (f) Explosion of the reactor

Figure 25. Proposed scenario of the explosion.

6. Review of Similar Events

The literature reports other experiments that also ended with explosions. Three of them are discussed here.

6.1. Experiences at Beijing National Laboratory for molecular sciences [27,28]

The experimental system included a glass tube (23 mm int. dia.) a Pd tubular cathode (1.07 mm int. dia., 80 mm long) in heavy water. Three explosions occurred. The initial liquid level in the cell was 94 mm. It is then possible that after some hours of operation the top of the Pd tube emerged. The explosions might then be explained by a sequence of phenomena similar to that presented in the last section.

6.2. Accident at SRI [29,30]

The cell 4″ dia. $\times$ 6″ height was designed for high pressure. The cathode was a Pd plate shaped 1 cm^3 electrode. The cell exploded after the disconnection, while it was removed from the water bath. Because of leaks, the pressure was close to ambient. A hypothetical explanation may be the formation of a concentration gradient, resulting in the SWACER phenomenon. Unfortunately, this accident resulted in the death of a researcher.

6.3. Experiences at Hokkaido University [31,32]

The cell had a volume of 1000 cm^3 and was closed by a tight cover. It contained 700 cm^3 of light-water based electrolyte to study plasma electrolysis. A plasma discharge was conducted with a tungsten cathode wire 1.5 mm in diameter. The explosion occurred after about 10 s of normal electrolysis under a voltage of 15 V and a current of 1.5 A. Many parameters were recorded, including the bath temperature and the flow of hydrogen that was much higher than for normal electrolysis because of the pyrolysis of the water. Oxygen was also produced by the same reactions. The temperature increased from 20°C to more than 70°C just before the explosion. The amount of energy responsible for the fast heating is much larger than the electrical input and might result from non-conventional reactions. The accident report acknowledges: “It is possible that the tungsten cathode may have been exposed to the gas in the headspace”. In that case, the explosion itself of the H_2–O_2 may have resulted from a phenomenon that took place in the gas phase, the SWACER triggered by non-homogeneities in the gas composition and a spark.

7. Safety Recommendations

The occurrence of powerful explosions in electrolytic systems is a problem that should not be ignored. Even a limited amount of explosive gas may result in an accident if the conditions for the SWACER mechanism are unfortunately satisfied.

Safety measures must be observed. Some of them make common sense:

- Keep a safe distance, remote control is best.
- Place a protective screen between the cell and the operators.
- Wear appropriate personal protection: eyes goggles, gloves, ear plugs, non-flammable clothes.
- Make sure the safety measures are obeyed by all attendants.

The possibility of occurrence of the SWACER mechanism should be minimized. The following precautions are advised.

- If not required by the setup, do not confine the explosive gases in the cell.

- If you need to confine the gases (e.g. because the setup includes a recombiner in the gas space) make sure that pieces of catalytic metal like Pd or Pt electrodes are never exposed to the gas phase and remain submerged in the liquid.
- If pieces of such metals must be in the gas phase, make sure there is no hollow structure like a small diameter tube or a folded foil with a narrow gap.

8. Conclusions

The re-analysis of the explosion that occurred in 2004 at J.-P. Biberian's laboratory is done via a review of the literature and dedicated experiments. It shows that the explosion may result from the SWACER mechanism. This type of reaction may also be responsible for other explosions that happened in similar experimental setups. It must be taken into consideration to employ the correct safety measures in the future.

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