Reanalysis of an explosion

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Agenda

- Explosion of a calorimeter in 2004
- Examination of the reactor pieces: Explosion in the gas phase
- Review of the explosion mechanisms
- Explosion tests
- Possible scenario of the explosion of the calorimeter
- Review of the other similar events
- Recommendation for the safety of future experiments

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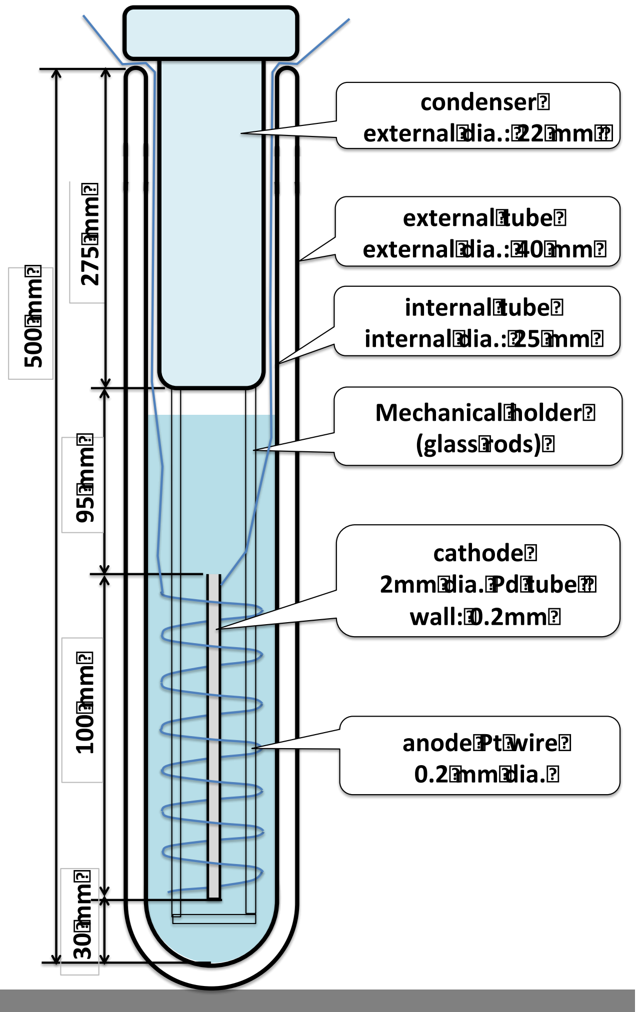
Calorimeter

Experience of calorimetry during electrolysis of D_2O with a Pd cathode by J.P. Biberian in 2004



Principle of the experience

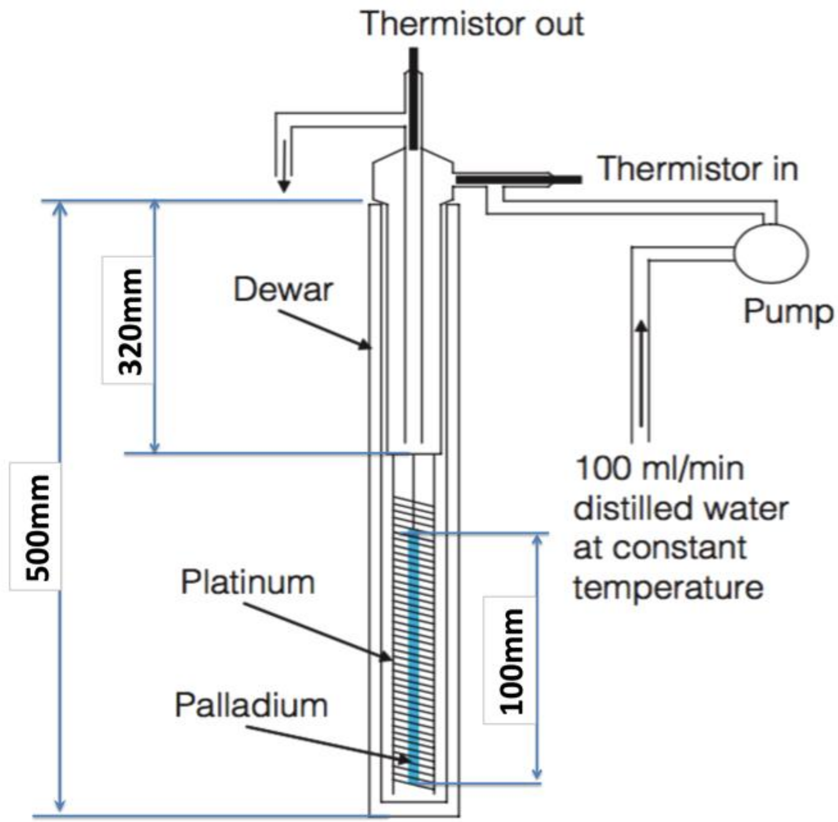
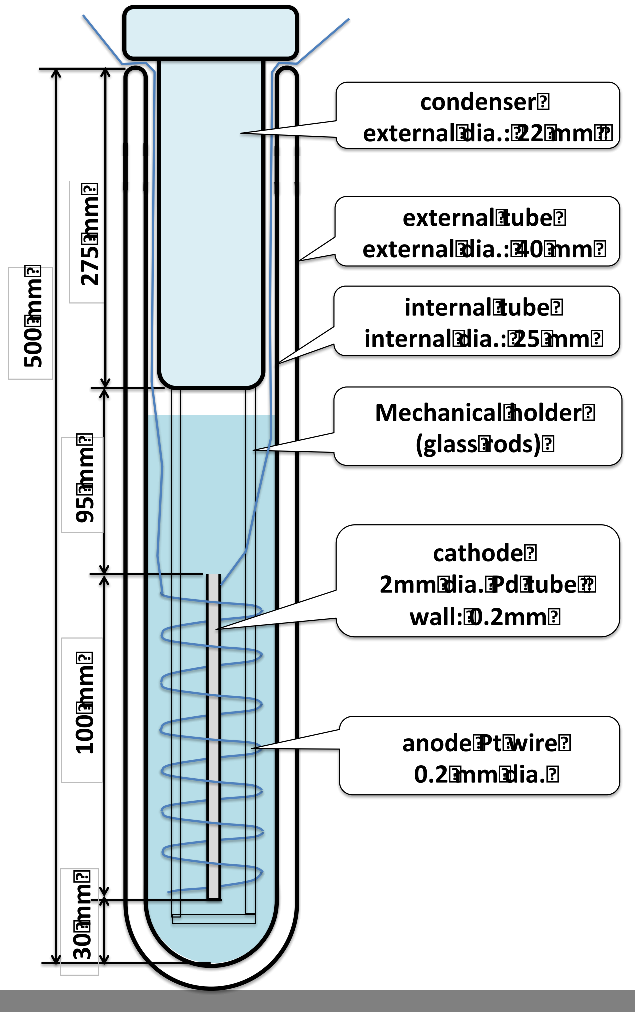
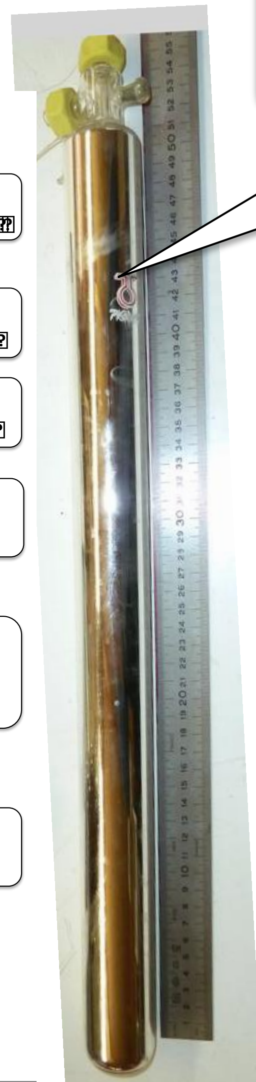


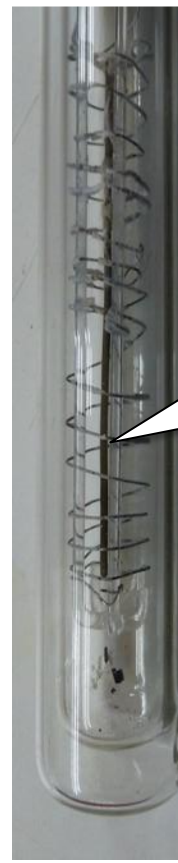
Figure 1. Schematic of the electrolytic cell.

Calorimeter





Cell identical to the original one
The double walls are silver coated



Original electrodes placed inside a similar cell
(No silver coating)

Calorimeter

Photographs of the fragments after the explosion

Calorimeter

- Strong explosion after 700h
- Origin of explosion not identified at that time
  - Tests with H_2-O_2 mix in a similar cell gave weak explosions
  - Explosion due to LENR?
- Reanalysis
  - Electrodes unaffected : Explosion in the gas phase
  - Hypothesis : Occurence of a gas detonation?

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Examination of cell pieces

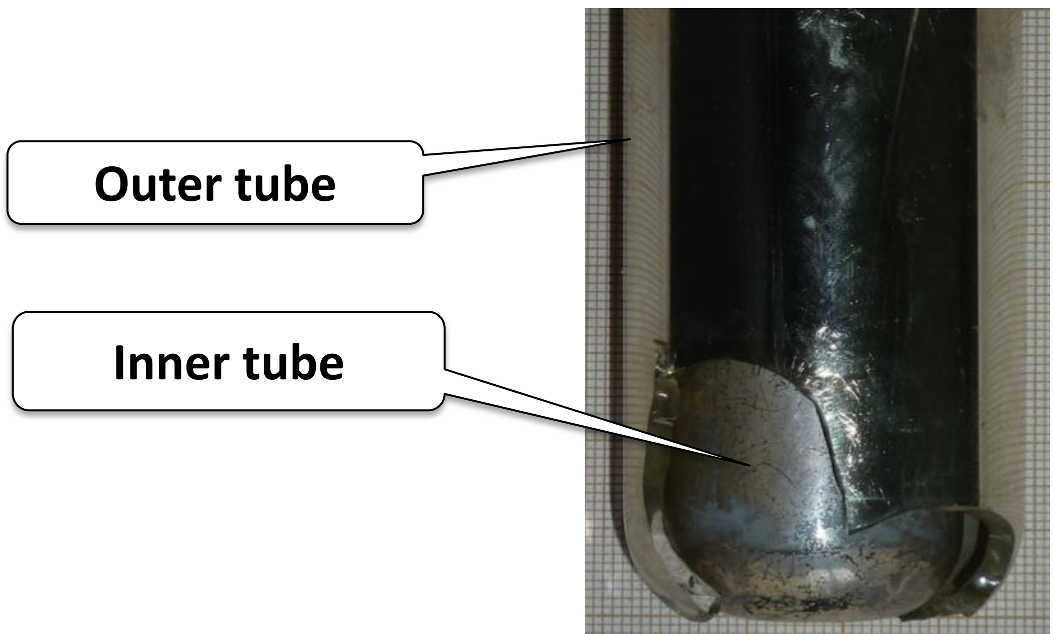
Only the large pieces have been recovered after the explosion

Pieces from the outer tube

Pieces from the inner tube

Examination of cell pieces

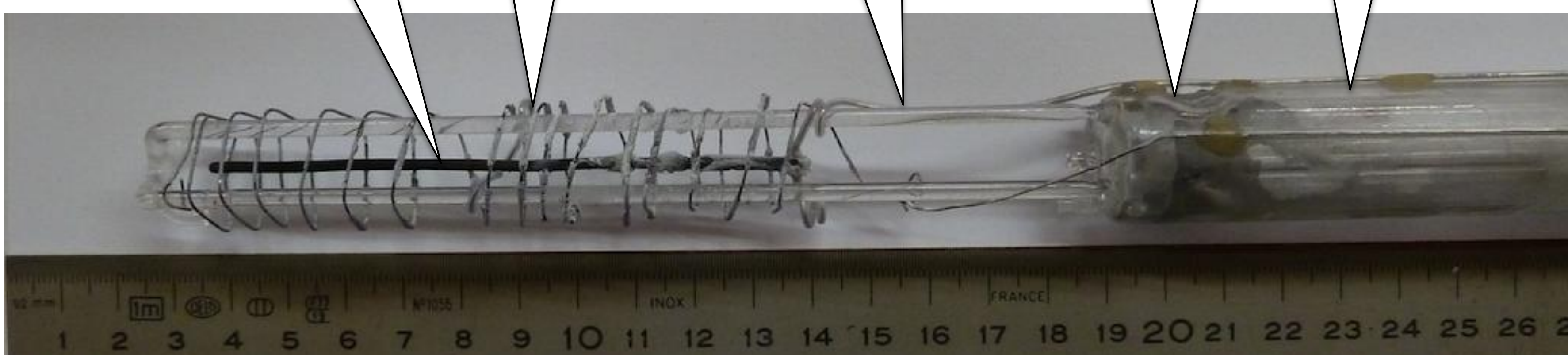
The bottom parts of the inner and the outer tube were not broken in small pieces
The inner tube punched the outer one that was resting on the table
It is possible to reconstruct the outer bottom with the pieces recovered
Apparently, the bottom was protected from the blast, probably by the presence of the liquid electrolyte



Examination of the electrodes

The electrodes seem unaffected by the explosion, nor is the condenser

1 of the 4 glass holder rods is broken



Preliminary conclusions

- **The electrodes look unaffected: The explosion occurred in the gas phase**
- **The glass cell is broken in small pieces, but the bottoms of the inner and the outer tubes are relatively unaffected: A liquid level of approx. 60mm protected the lower section from the explosion blast**
- **Gas mix in the headspace: 83 cm^3**

Hypothesis

- **Before concluding to a nuclear type of reaction, a working hypothesis is to examine the possibility of a chemical origin of the explosion**

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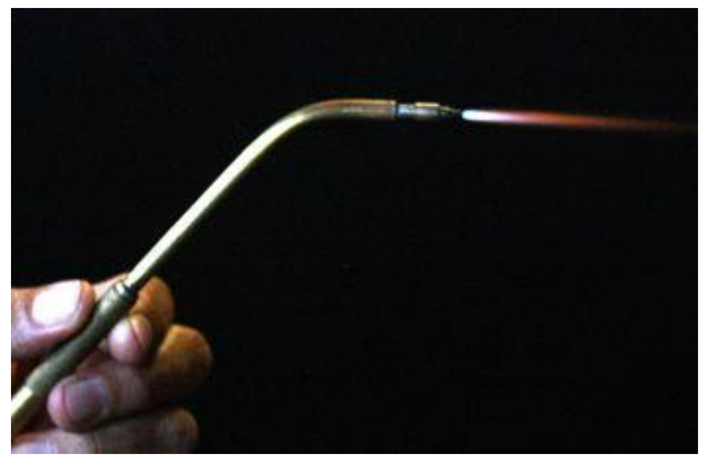
What is an explosion ?

- Sudden, violent release of chemical energy

- Understanding of the problem requires a review of the phenomena

$H_2 – O_2$ reaction

- $H_2 + 0.5O_2$ -----> H_2O + 286 kJ/mol
- Tube content : 83 cm^3 --> 710 J chemical energy
- Combustion of the stoichiometric mix:
  flame velocity = 11 $m.s^{-1}$

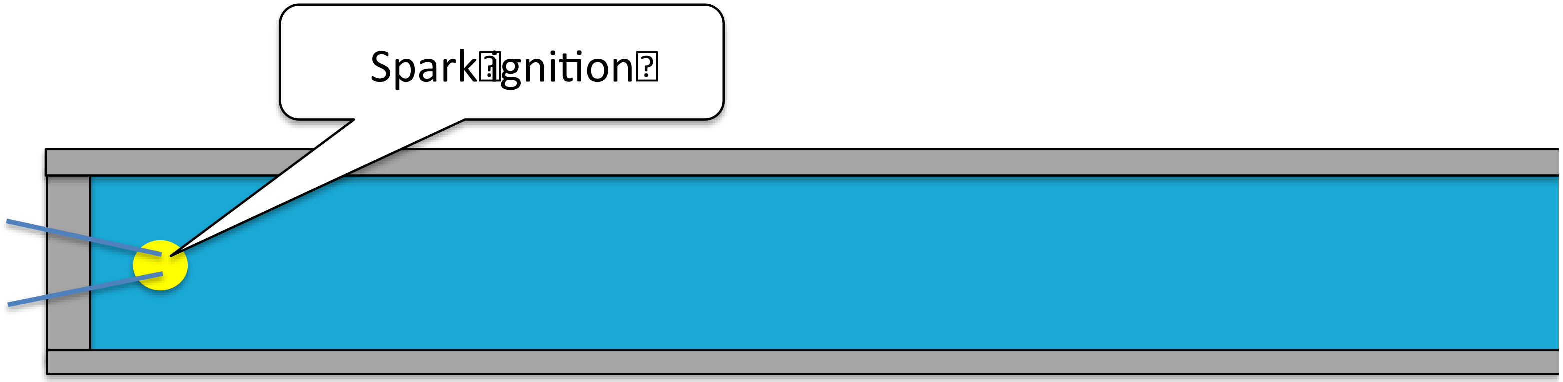


DEFLAGRATION AND DETONATION POSSIBLE

Deflagration and Detonation

- **Deflagration** : Subsonic flame velocity, modest pressure rise
- **Detonation**: Supersonic flame velocity, high pressure peaks
- Detonation can be produced by:
  - Deflagration to Detonation Transition **(DDT)**
  - Large ignition energy: Shock Detonation Transition **(SDT)**
  - Shock Wave Amplification by Coherent Energy Release **(SWACER)**

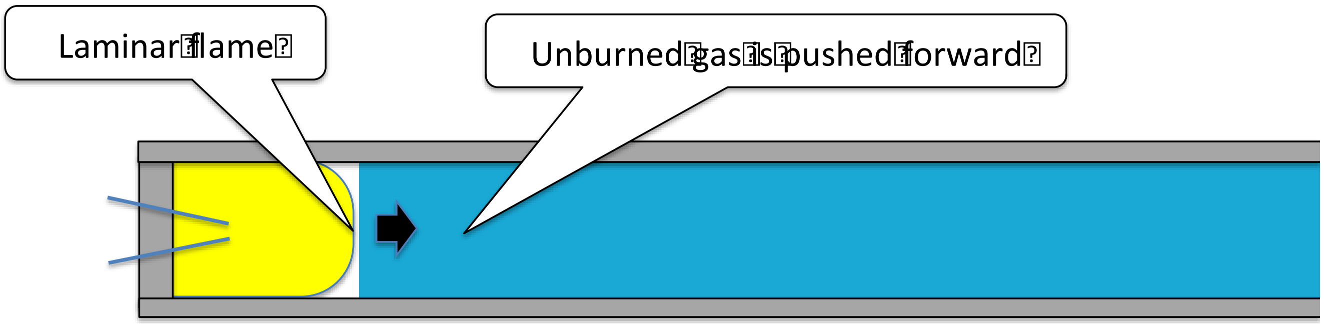
DDT 1/6 : Weak ignition



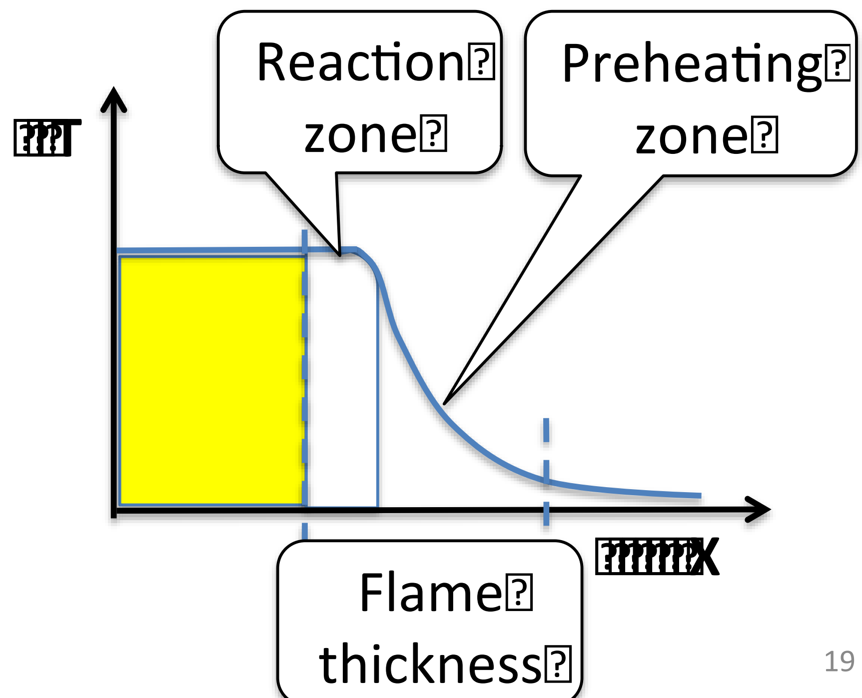
<u>Stoichiometric H_2 + 0.5 O_2</u>

Energy required for flame ignition: 3 µJ
Easily obtained by a spark, a hot wire - T > 833K (560°C)

DDT 2/6 : Laminar flame



- **The flame pushes the unburned gas mix**
- **Little pressure buildup**



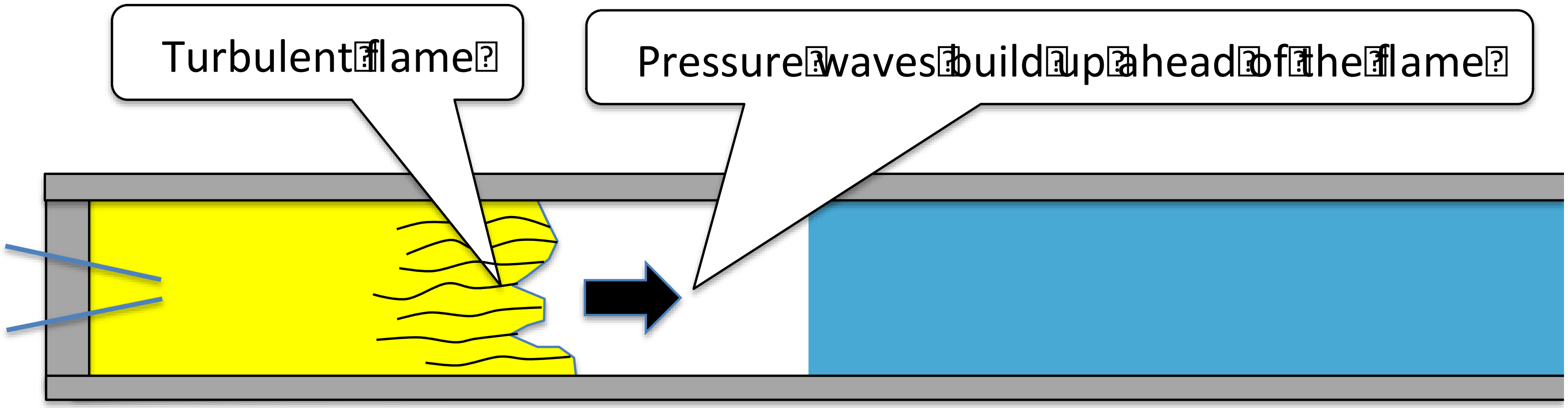
<u>Stoichiometric $H_2 + 0.5\ O_2$:</u>

Flame velocity = 11 $m.s^{-1}$

Flame thickness: 0.32mm

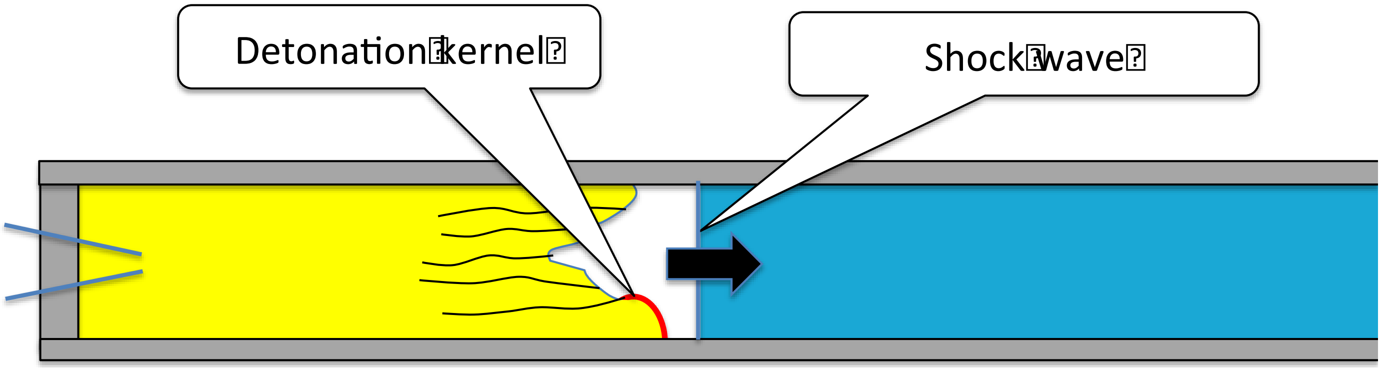
Induction time: 30 µs

DDT 3/6 : Deflagration

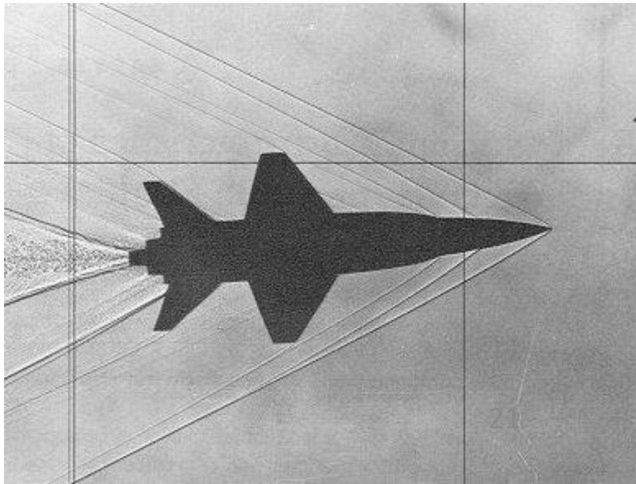


The turbulence increases the area of the flame reaction surface.
The heat release rate increases in the tube section where the reaction proceeds
The preheating of the unburned gas is enhanced,
The induction time in the flame decreases
The flame speed increases progressively to supersonic velocity
The unburned gas is pushed more and more rapidly. The pressure ahead of the flame builds up

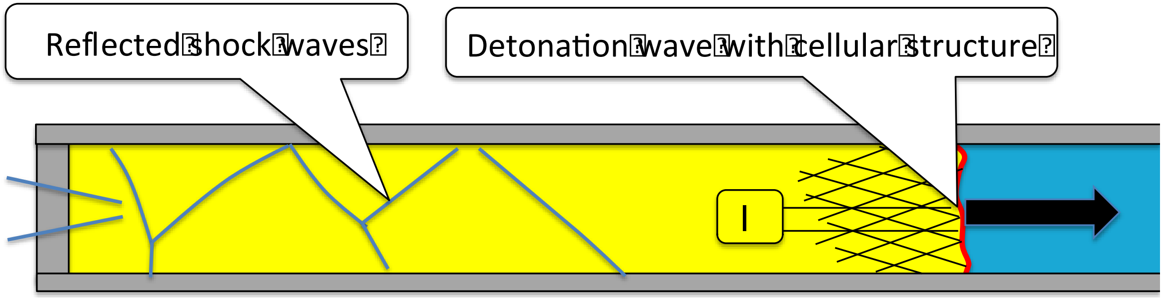
DDT 4/6 : Deflagration Detonation Transition



Once the flame velocity becomes supersonic, a shock wave is formed
The shock increases the gas temperature before the reaction, hence the reaction rate
At some point, the reaction rate is sufficient to generate a fast moving wave: this is the Deflagration Detonation Transition (DDT)

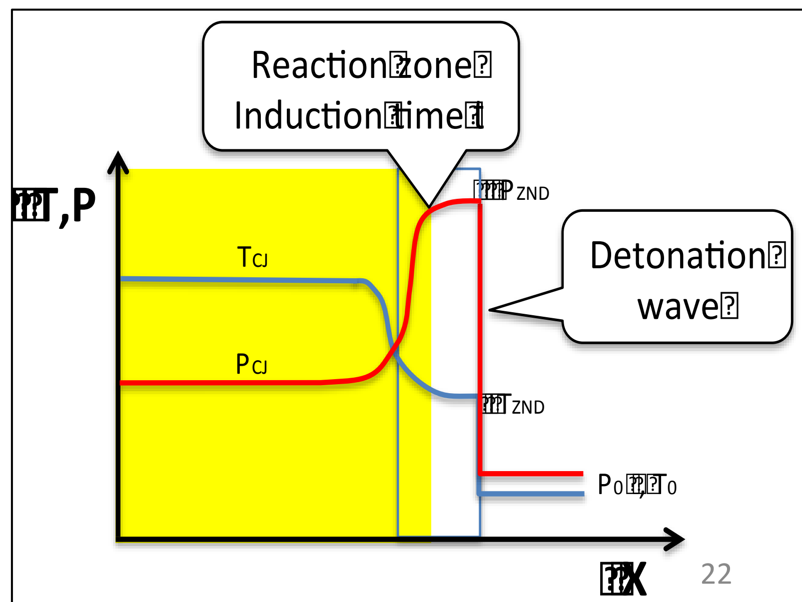


DDT 5/6 : Detonation

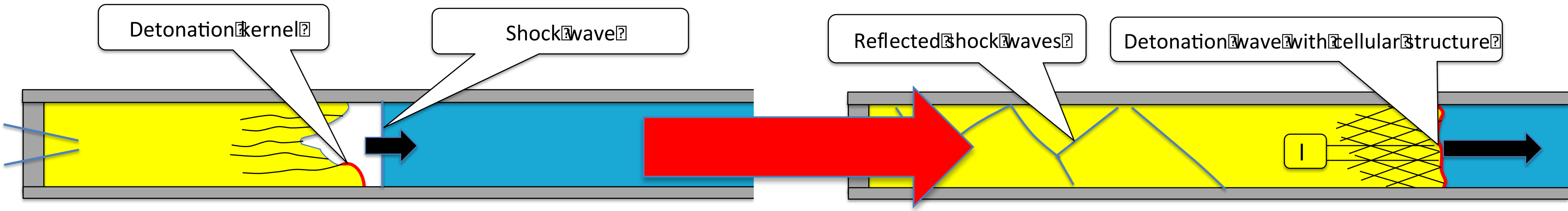


Detonation is described by the theories of Chapman-Jouguet (CJ) and Zeldovitch- von Neuman-Döring (ZND)
The detonation front has a cellular structure (λ)

<u>Stoichiometric H_2 + 0.5 O_2 :</u>
Cell size λ = 1.4mm
Detonation velocity : 2900 m.s^{-1} (Mach 5.05)
Flame thickness: 50 μm
Induction time: 17 ns
T_{CJ} = 3400K
$T_{ZND} \approx T_{CJ}/2$
P_{CJ} = 18 bars - $P_{ZND} \approx$ 41 bars



DDT 6/6 : Super-Detonation

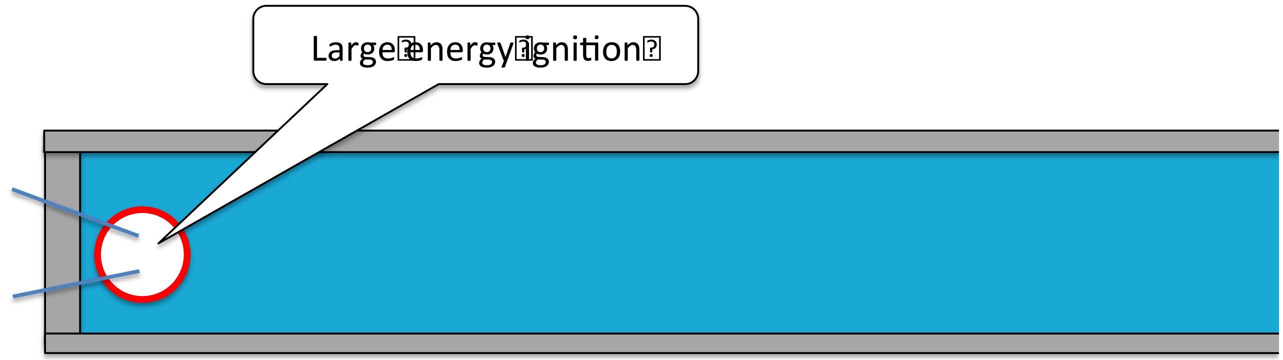


Between the local onset of detonation and the full development of the detonating front, the wave travels faster than 2900m.s^{-1} and the pressure is higher than P$_{ZND}$

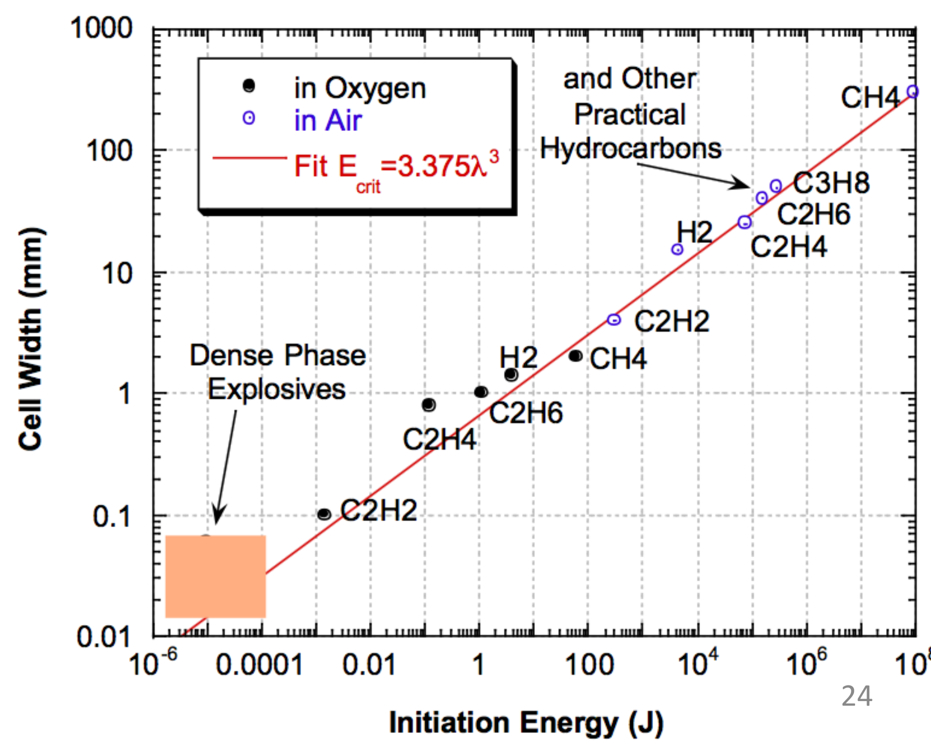
Many shock waves travel in the volume, interact with each other, are reflected by the walls – Very complicated phenomena

Reflected waves may exceed 80bars

SDT : Shock Detonation Transition



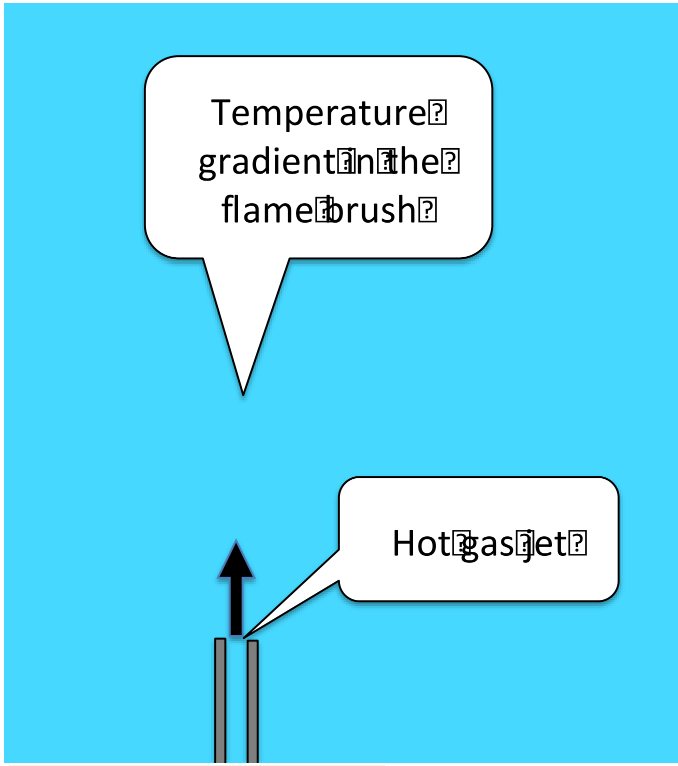
- **Detonation is initiated directly if the ignition energy is sufficient (powerful spark, exploded wire, explosive, projectile)**
- **<u>Stoichiometric H_2+ 0.5 O_2: 6J</u>**



SWACER (1 / 3)

- **Influence of a gradient of induction time in the unburned gas**
- **<u>For example:</u>**
- **A jet of burned gas injects a cloud of hot gas in the headspace.**
- **The temperature gradient induces a gradient of induction time**

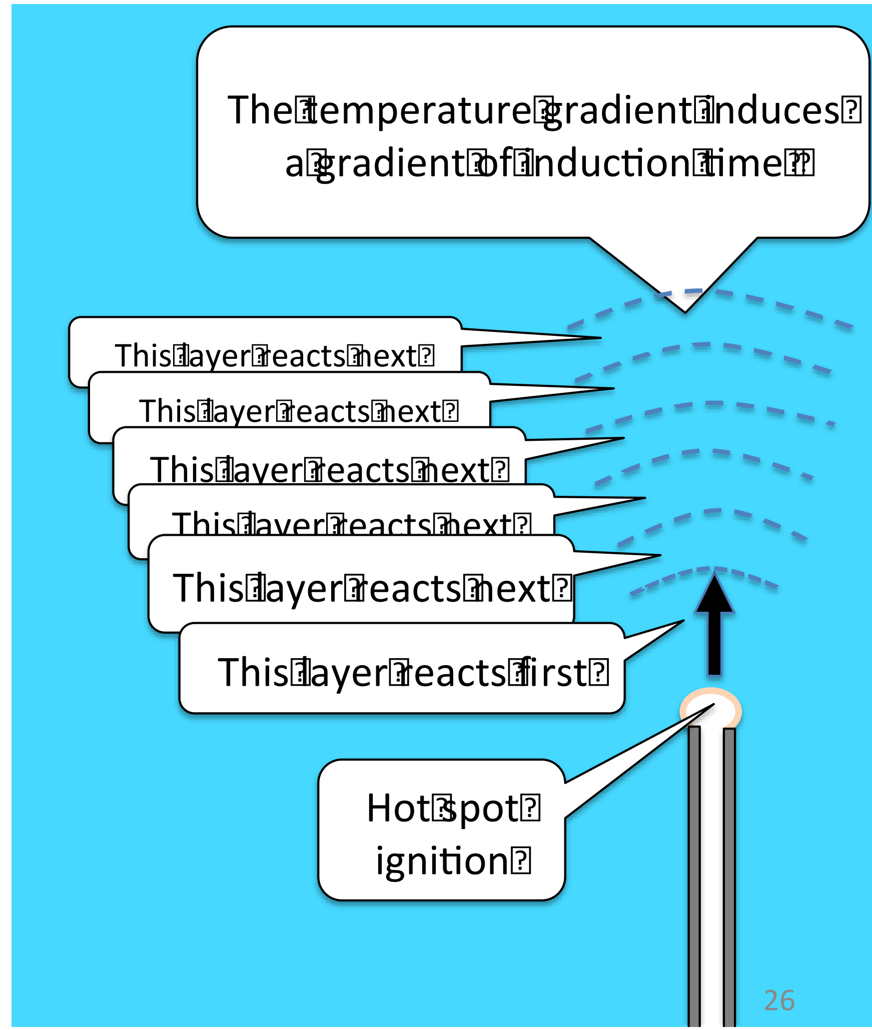
- **In addition, there is a gradient of the local sound speed**



$$v_{sound} = \sqrt{\frac{\gamma RT}{M}}$$

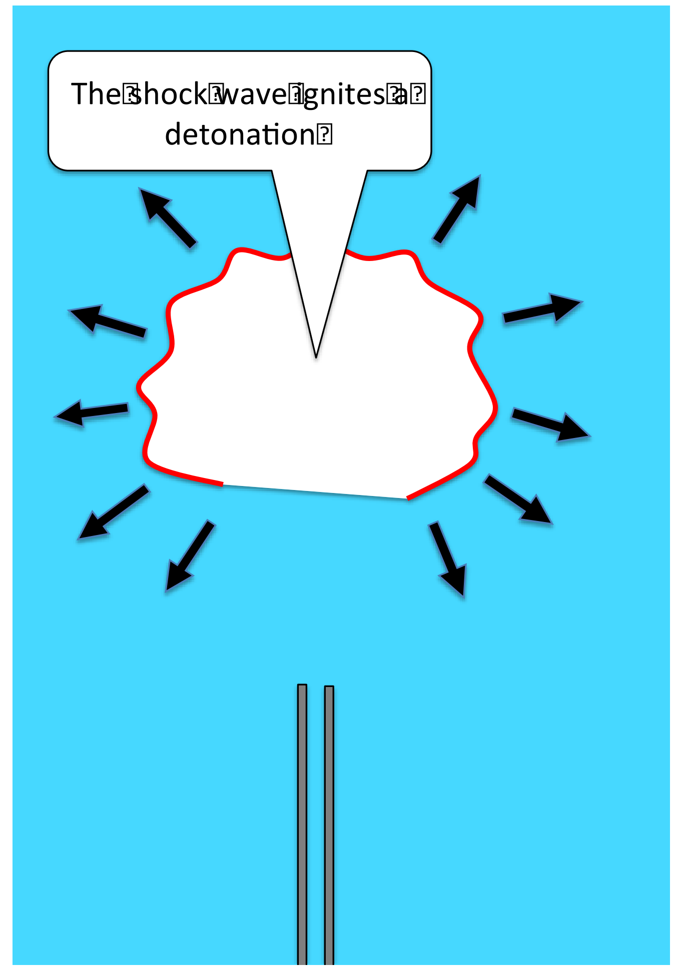
SWACER (2 / 3)

- **A hot spot triggers the combustion,**
- **The gas layer adjacent to the hot spot has the lowest induction time and reacts first**
- **The next layer with a slightly longer induction time reacts next**
- **The wave propagates rapidly, layer after layer and gains in force**



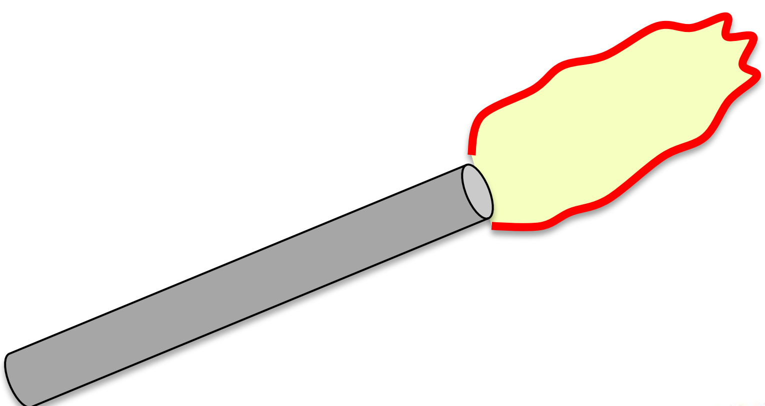
SWACER (3 / 3)

- As the wave proceeds, it travels in cooler unburned gas where the sound speed is lower. The Mach number increases and the pressure front steepens (shock wave)
- The Shock Wave is Amplified by Coherent Energy Release (SWACER)
- The shock wave may trigger the detonation



SWACER ignition by a weak source

- **Combustion in small tubes : Deflagration strength increases over a short distance**



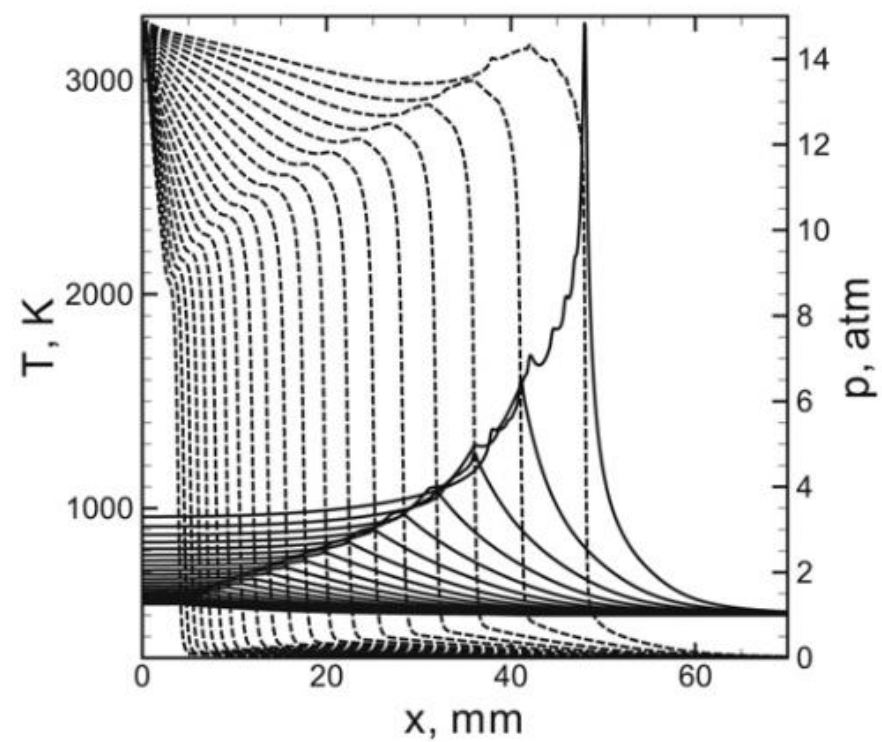
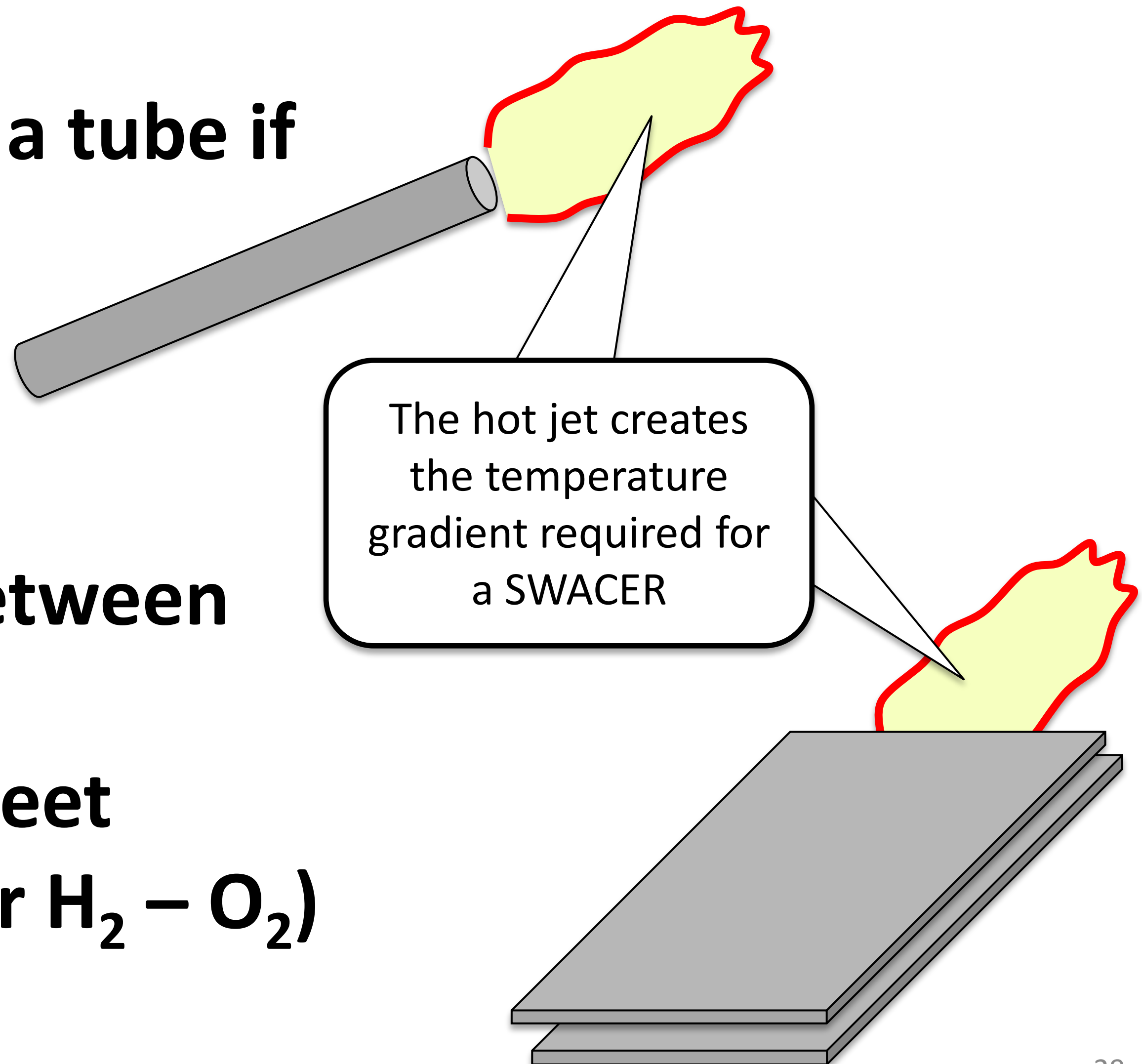


Fig. 15 – Evolution of temperature (dashed lines) and pressure (solid lines) profiles on the flame tip; $D = 0.5$ mm,

SWACER can be ignited by a weak source

- **Deflagration in a tube if $d/\lambda > \approx 1$**

- **Deflagration between parallel plates, e.g. a folded sheet ($e > 0.26$mm for $H_2 - O_2$)**



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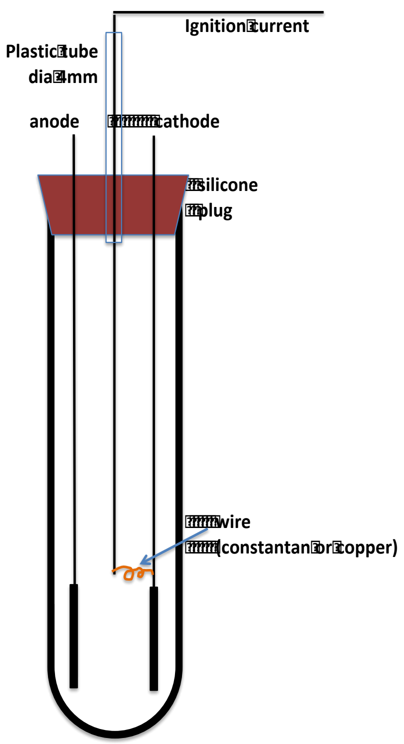
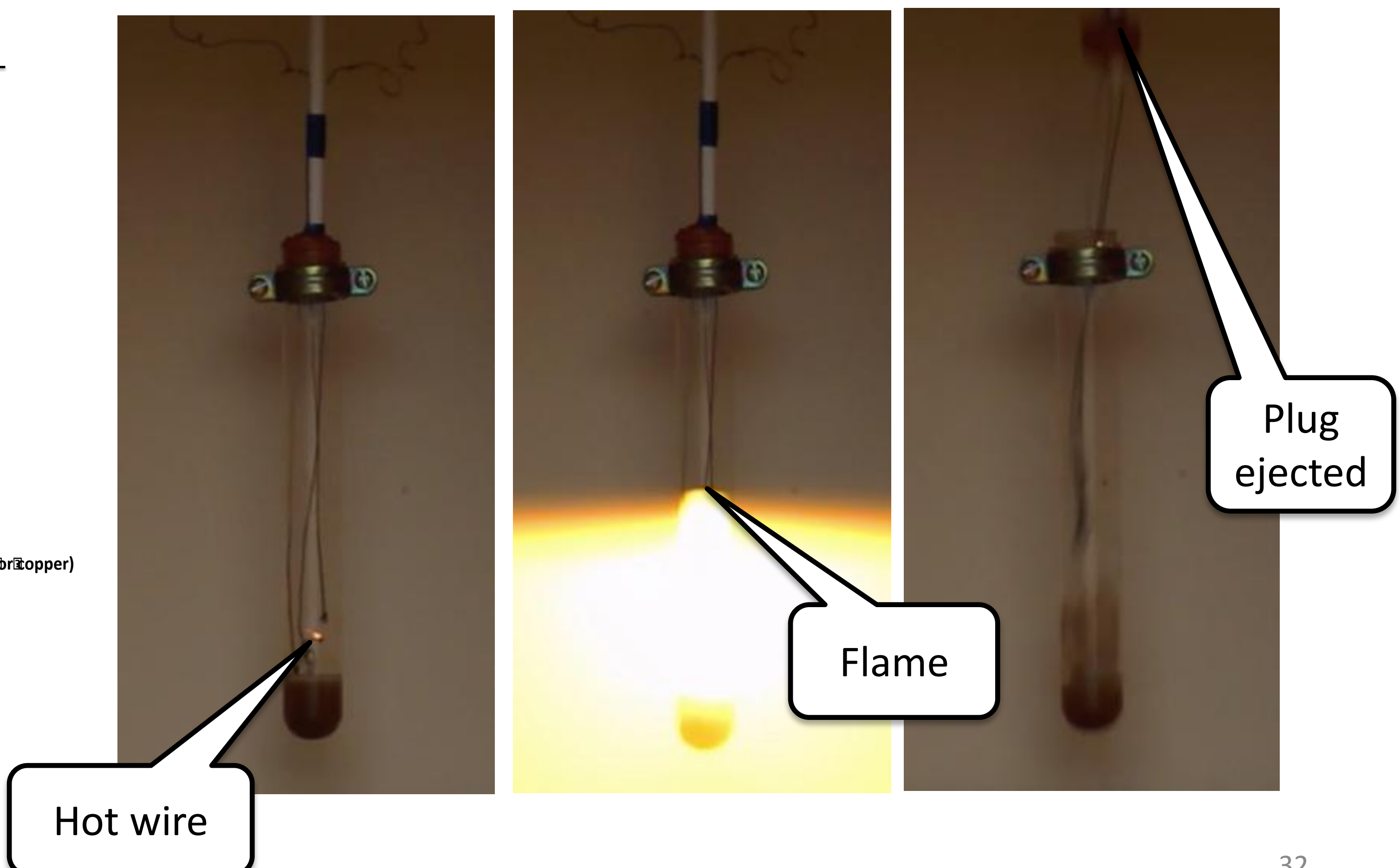
Experimentation

- Tests with stoichiometric $H_2 + 0.5\ O_2$
- Tubes Pyrex 25mm outer diameter
- Ignition systems tested:
  - HV spark
  - Hot wire 200 μm constantan
  - Exploded Cu wire 70 μm
  - 1.3mm dia. tube connected to a prechamber
- 28 shots in total

Deflagration – Hot wire

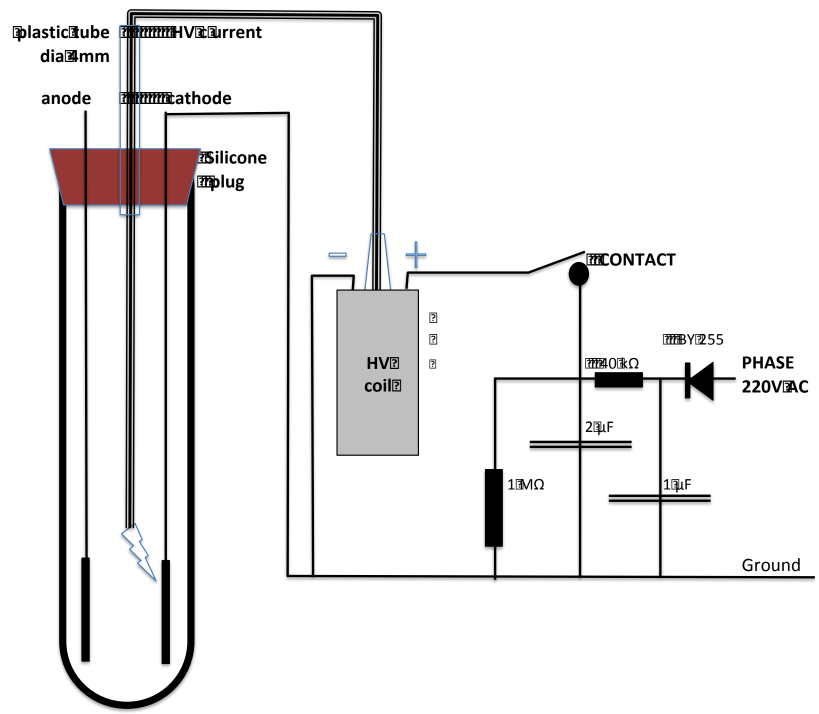
Low flame velocity
Glass tube not broken





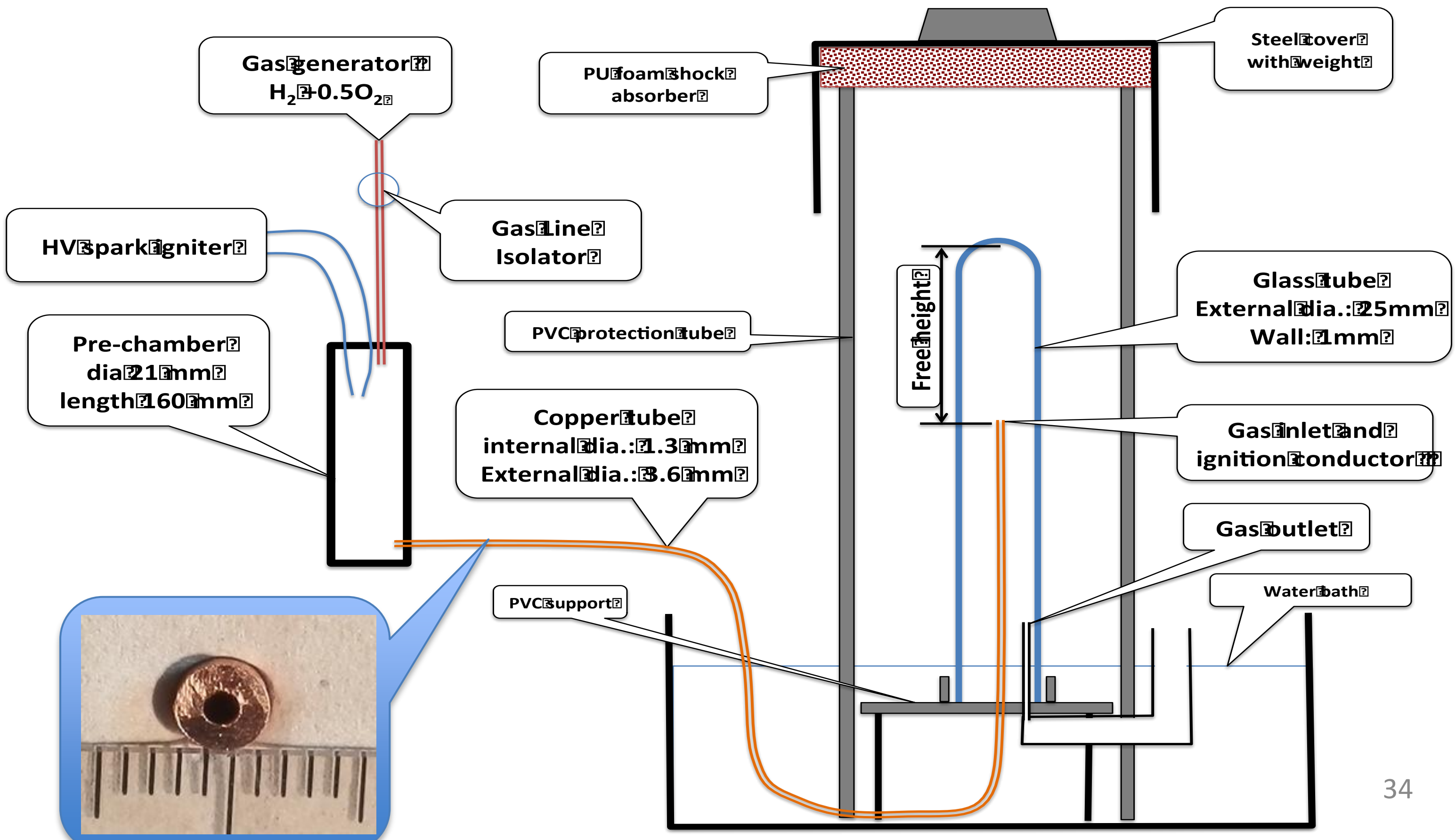
Strong deflagration – HV spark

High flame velocity
Glass tube not broken



Ignition by a small tube

Reaction in a pre-chamber connected to the glass tube by a long small diameter copper tube



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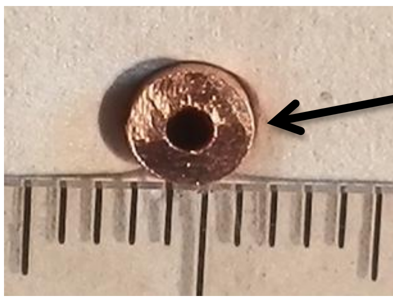
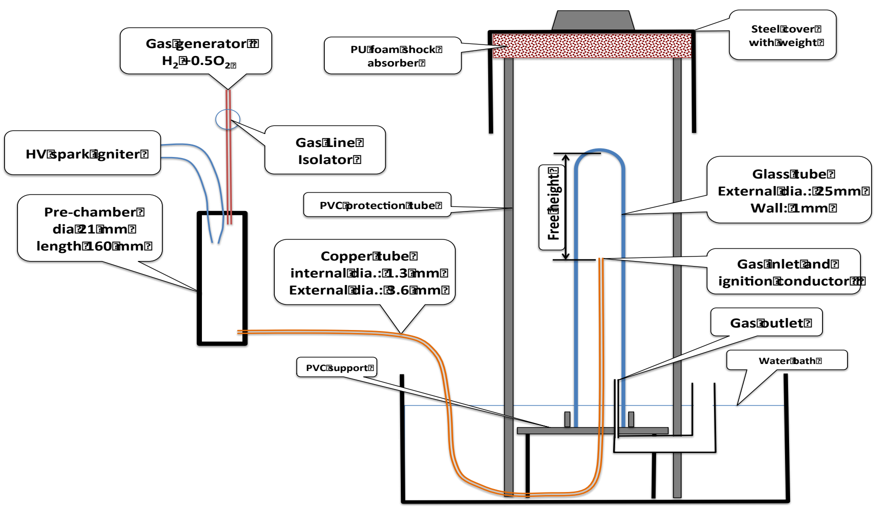


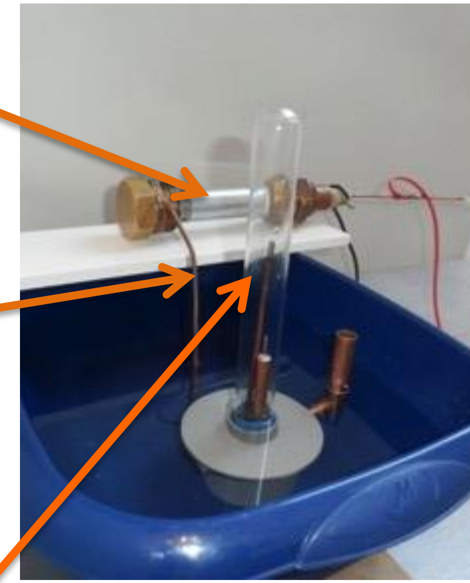


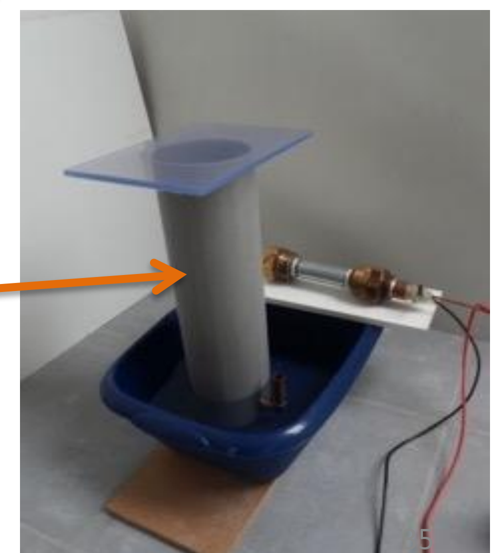
<u>Pre-chamber</u>
<u>Spark ignition</u>
Int. Dia.: 21mm
Length : 150mm

<u>Cu tube</u>
Int. Dia.: 1.3mm
Length : 500mm

<u>Glass tube</u>
Int. Dia.: 23mm
Length : 200mm

<u>PVC protection tube</u>

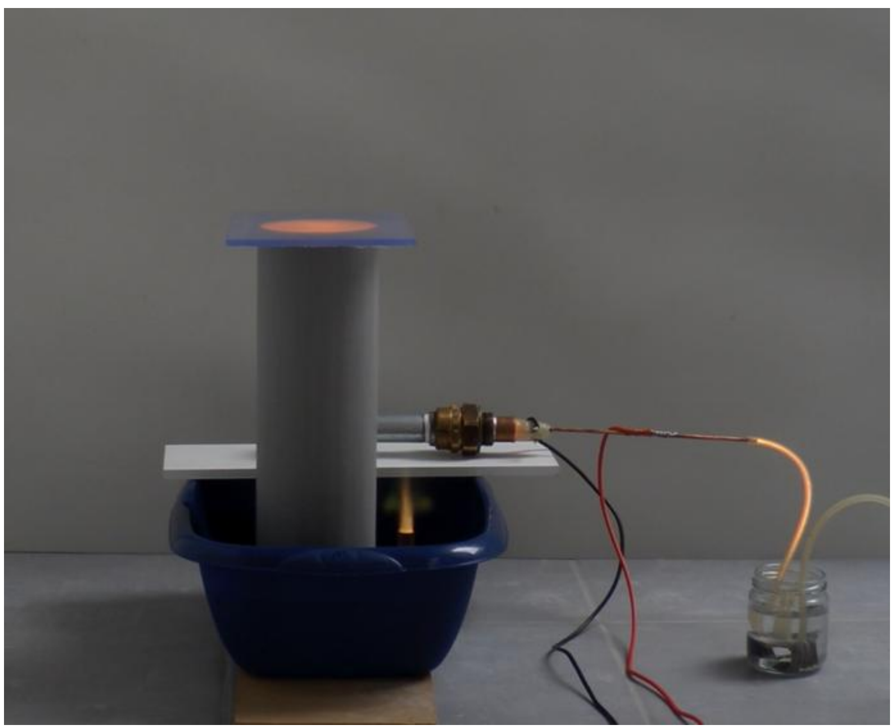


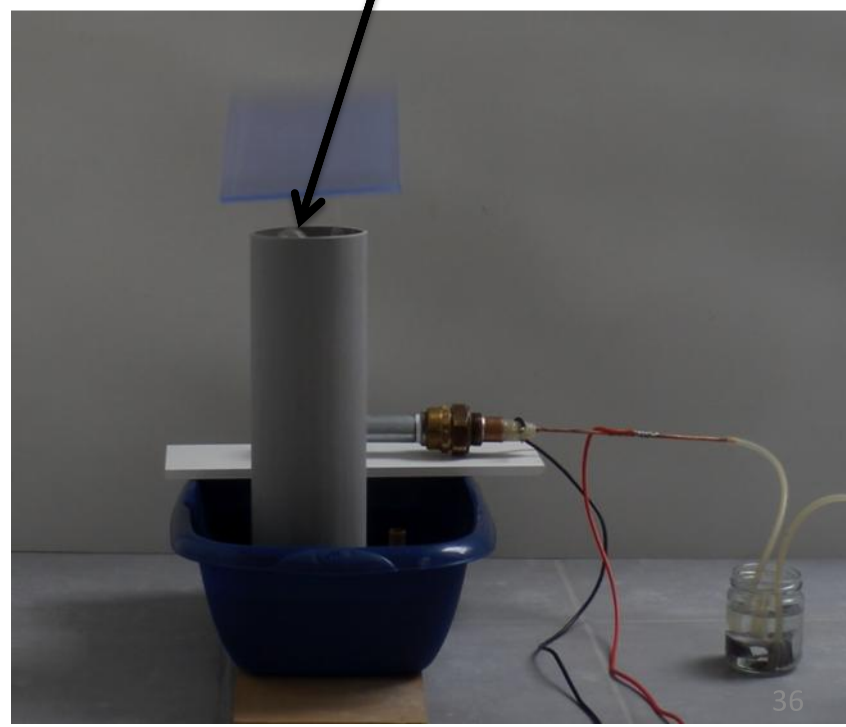


Example of deflagration: Tube not broken

Ignition
Flame visible in the glass tube, the gas feeding tube, the gas outlet

30 ms later
The glass tube is thrown onto the cover, but is not broken





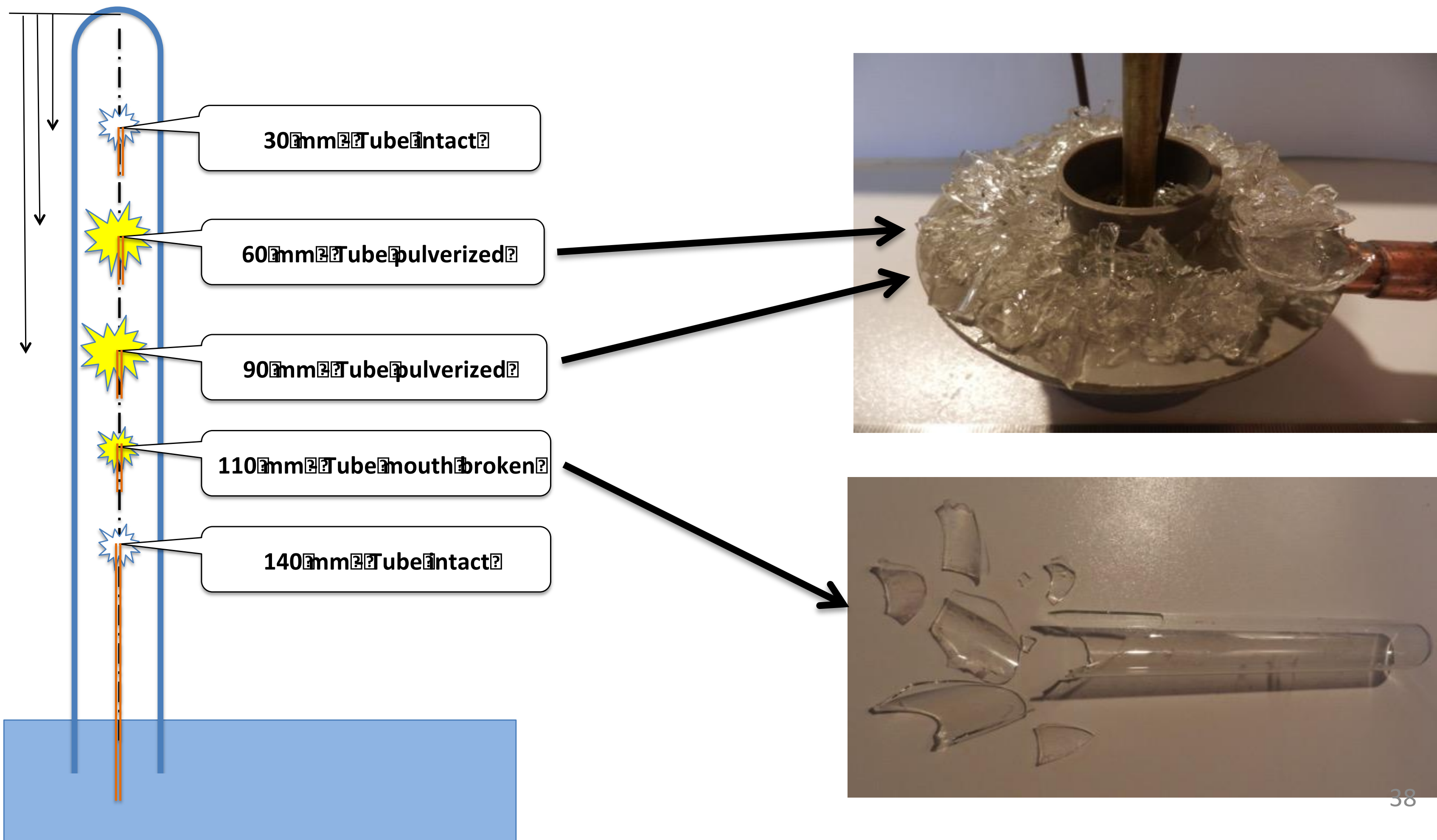
Example of detonation: tube pulverized

Examples of glass tube debris settled on the base after removal of the protection PVC tube and the water bath

The glass is pulverized, except the zone located below the water level (where the glass is shattered into large pieces)

Tests with small tube opening at different heights

The glass is pulverized or not, depending on the position of the small tube opening along the axis



Lessons from litterature and experiments

- The stoichiometric mix $H_2 + 0.5\ O_2$ reacts easily
- The energy to initiate a combustion is small (3μJ)
- The quantity of gas contained in the reactor is sufficient to develop a violent explosion (710J)
- The glass is broken only if a strong detonation occurs
- The strong detonation can be triggered by a SWACER mechanism
- A small diameter tube or a folded sheet can induce a SWACER

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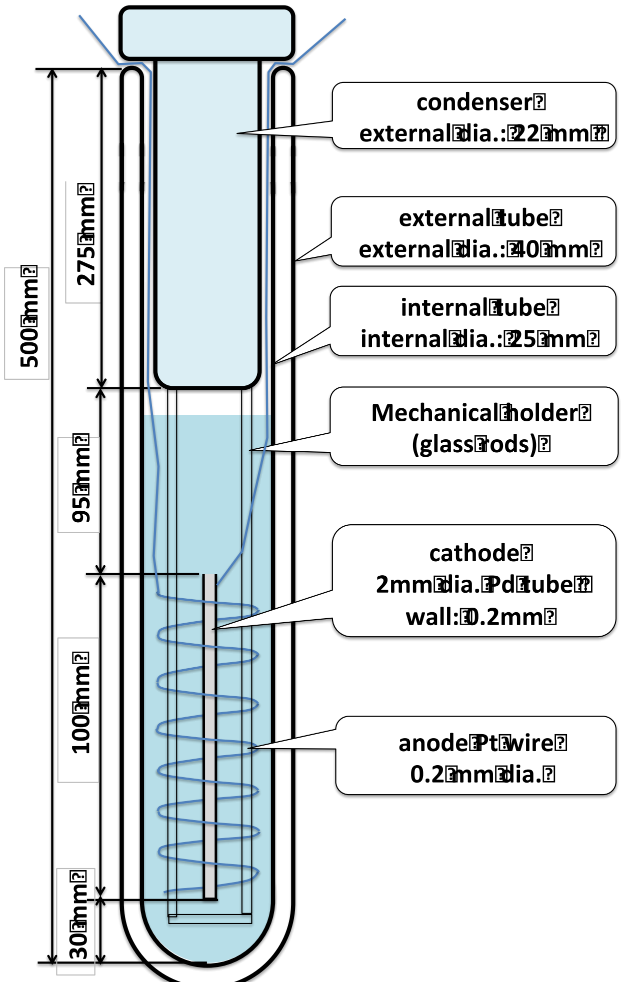
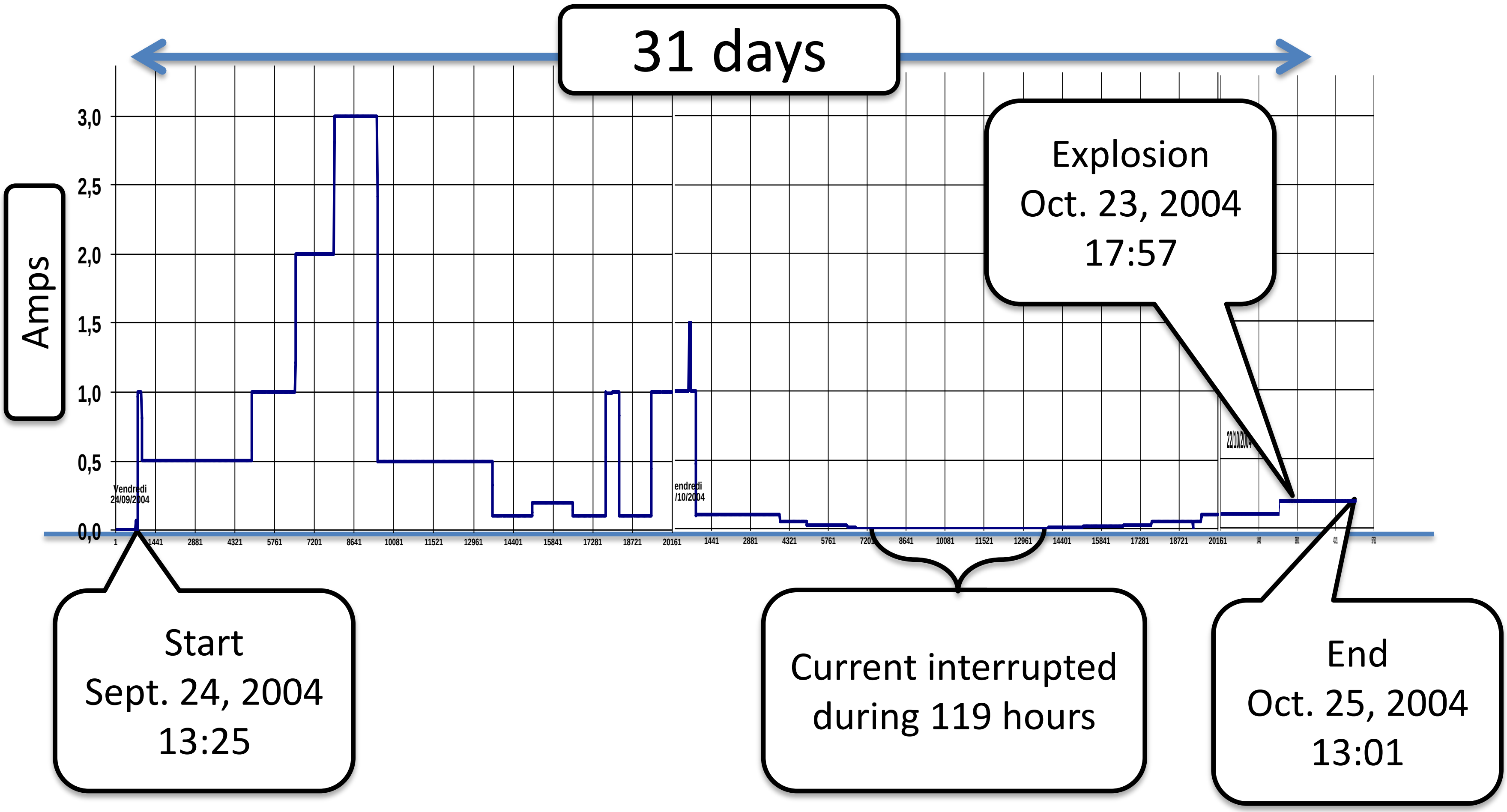
Review of the 2004 experience



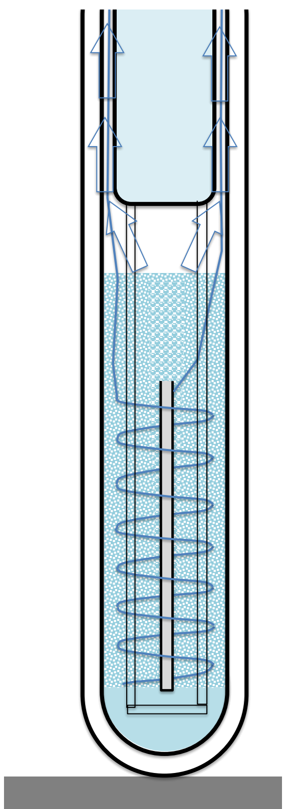
- **Total duration : 700 h**
- **No addition of heavy water**
- **Electrolysis current was varied during the experience**
- **The current was interrupted during 4 days**
- **Explosion occurred after resuming the electrolysis**

Current record

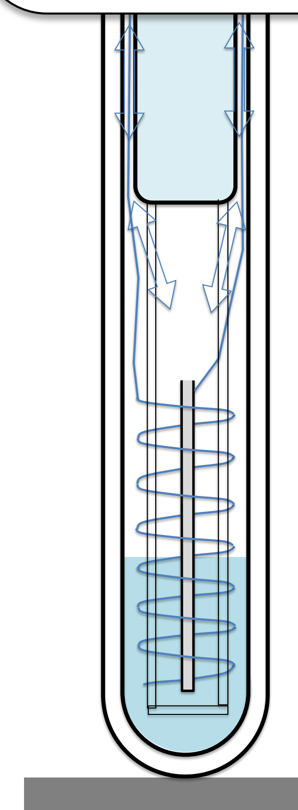


Possible scenario of the explosion (1/4)

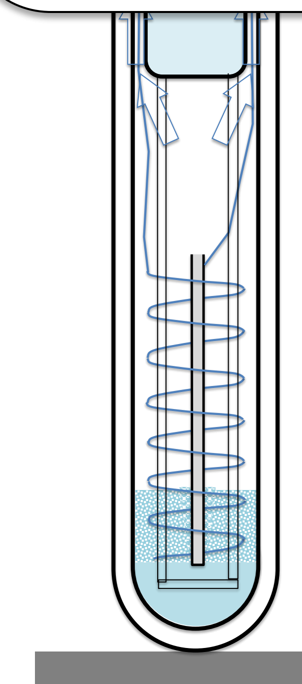
**Initial electrolysis
The liquid level drops progressively**



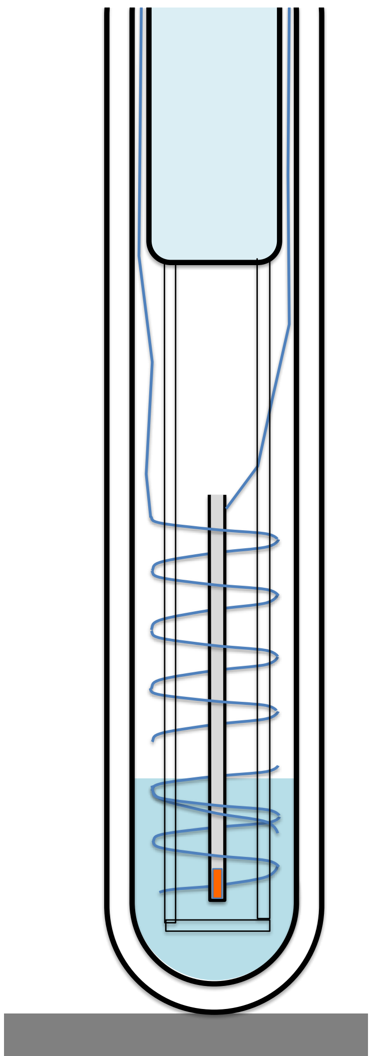
**Current interruption
The Pd tube is deloaded**



**Electrolysis is resumed
The headspace and the Pd tube are filled by the D_2+O_2 gas mix**

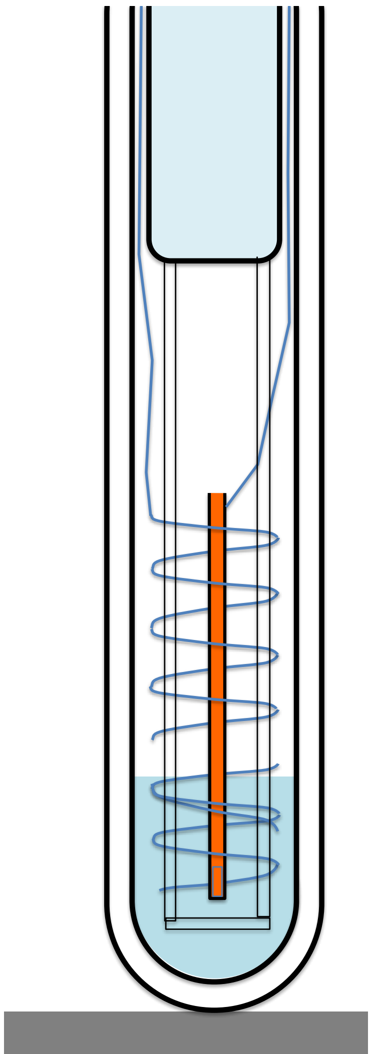


Possible scenario of the explosion (2/4)



1 - Once the Pd wall is reloaded with deuterium, free radicals appear on the tube inner surface. A hot spot lights up a flame at the bottom of the Pd tube

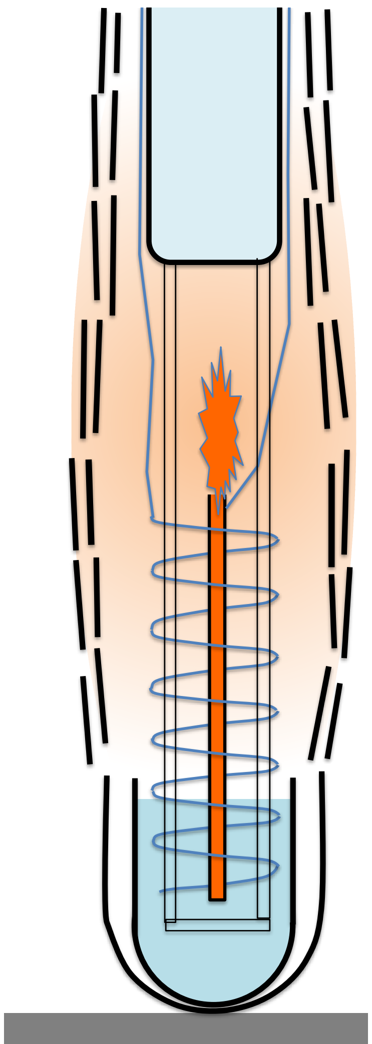
Possible scenario of the explosion (3/4)



1 - Once the Pd wall is reloaded with deuterium, free radicals appear on the tube inner surface. A hot spot lights up a flame at the bottom of the Pd tube

2 – A deflagration occurs in the tube

Possible scenario of the explosion (4/4)



1 - Once the Pd wall is reloaded with deuterium, free radicals appear on the tube inner surface. A hot spot lights up a flame at the bottom of the Pd tube

2 – A deflagration occurs in the tube

3 – The hot jet triggers the detonation in the headspace (SWACER)

Conclusion of the reanalysis

- **The explosion of the calorimeter may be due to a detonation of the gas contained in the reactor**
- **A SWACER mechanism may have triggered the strong detonation**
- **No nuclear mechanism is required**
- **However, the reason of the hot spot remains unclear (H radicals on the inner Pd tube surface ?)**

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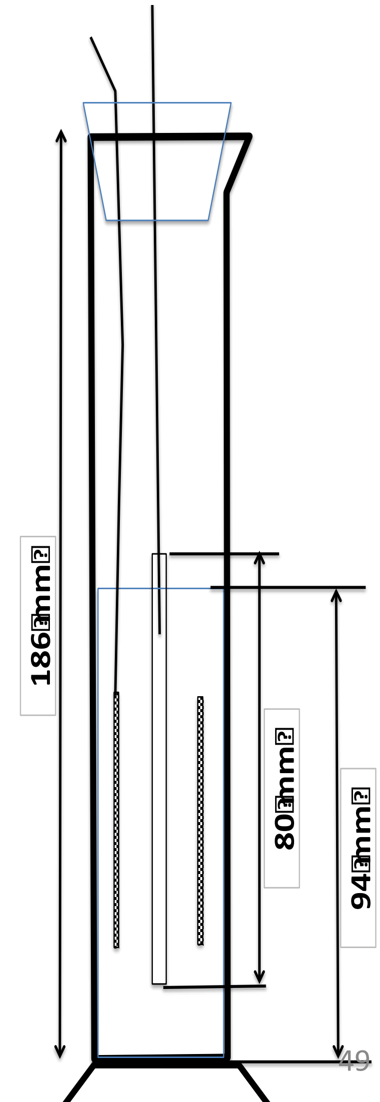
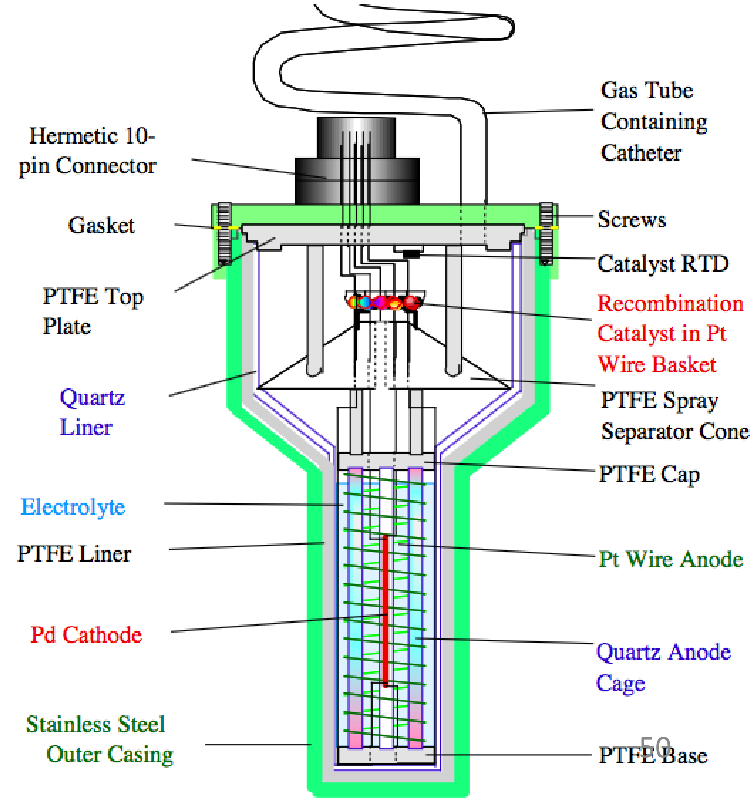
Other similar events: Explosions reported by Zhang – April 1991

- 186mm high vessel containing 39 cm^3 electrolyte D_2O (94mm liquid height)
- Pd tube cathode 1.67mm ext. dia. 80mm long
- Vessel plugged
- Low current density
- 3 explosions occurred
- The Pd tube top was probably emerged
- SWACER may be responsible (similar Biberian)



Other similar events: Accident at SRI January 02, 1992

- Cell: 4'' dia. X 6'' height designed for high pressure
- Steel wall 1/2'' thick
- 1cm^3 Pd plate-shaped cathode
- The cell exploded after the disconnection, while it was removed from the water bath
- Because of leaks, the pressure was close to ambient
- A potential explanation may be the formation of a concentration gradient, resulting in a SWACER ?
- Andrew Riley died in the accident



Other similar events: Explosion of a Mizuno reactor on January 24, 2005

- 1000 cm^3 vessel containing 700 cm^3 electrolyte
- Tight cover
- Tungsten wire cathode 1.5mm dia. 29cm long separated from the anode mesh by a quartz funnel
- Explosion occurred « soon after electrolysis began » - The quantity of H_2 is said to be small
- H_2 - O_2 left from an earlier plasma electrolysis ?
- " it is possible that the tungsten cathode may have been exposed to the gas in the headspace." (accident report)
- "Bright white flash on the lower portion of the cathode. Light expanded and at the same time the cell exploded" (accident report)
- SWACER ? (if enough H_2 present)

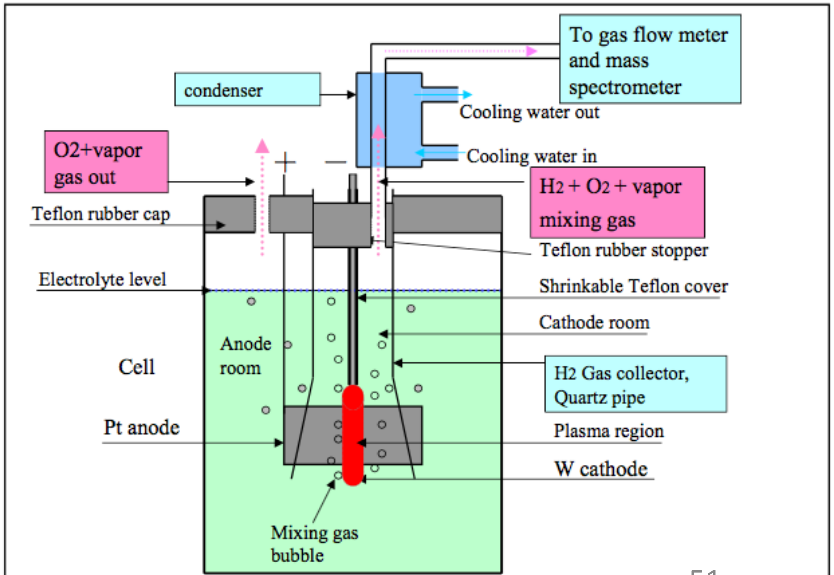


Fig. 3. Detail of the gas measurement

Agenda

- Explosion of a calorimeter in 2004
- Examination of the reactor pieces: Explosion in the gas phase
- Review of the explosion mechanisms
- Explosion tests
- Possible scenario of the explosion of the calorimeter
- Review of the other similar events
- Recommendation for the safety of future experiments

Safety recommendations for electrolytic systems

1. Install the equipment with appropriate safety protection to minimize the consequences of a potential explosion
2. Do not confine the $H_2 + O_2$ gas in the reactor
3. If you need to do so (e.g. with a recombiner) make sure that pieces of catalytic metals (Pd, Pt, Ni, etc.) are never exposed to the gas phase, and remain submersed in the liquid
4. If pieces of such metals must be in the gas, make sure there is no hollow structure (tube, folded foil, etc.)

Thank you for your attention

Please remember to make your best efforts to avoid accidents