

DE LA RECHERCHE À L'INDUSTRIE



An Experimental Program to Characterize Confined Explosions of Hydrogen/Oxygen Mixtures in the Context of Radioactive Material Transport between CEA Nuclear Facilities

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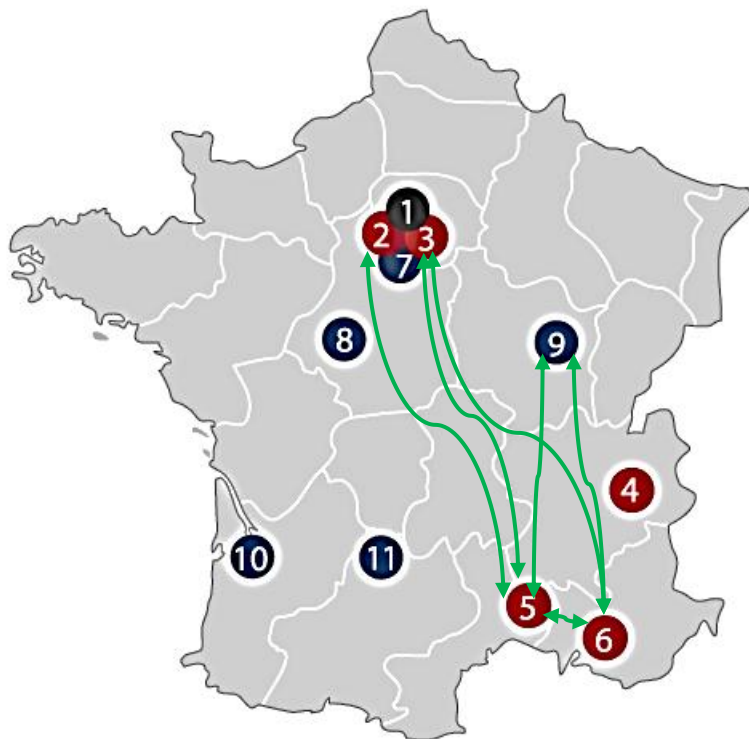
CEA/DEN/CAD/DSN/STMR
CEA, Cadarache Center (France)

www.cea.fr

Waste Management 2015, Phoenix, Arizona, USA

CEA research center location

- 7 DAM Ile-de-France
- 8 Le Ripault
- 9 Valduc
- 10 Cesta
- 11 Gramat



- ✓ Transports for nuclear facility operations (waste, liquid effluents, sources)
- ✓ DD activities
- ✓ Research programs

Typical transport routes

- ✓ **Performing safety studies**
- ✓ **Obtaining package approval or renewal for new and existing package contents**
- ✓ **Fabrication of new packagings**
- ✓ **Technical support for all CEA units**

- ✓ **Planning and operating radioactive material transports**
- ✓ **Package maintenance**

CEA transport package fleet



PN UO2



PN CN



FS 110

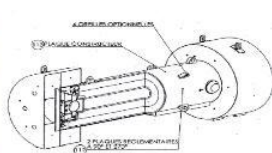
Uranium and
plutonium



IR001



IR100



IR200



IR500



IR800

Research fuel

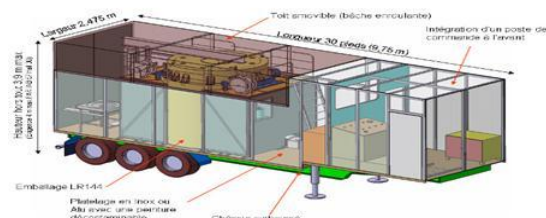
~1200 packages
~ 50 different types

Partnership with
AREVA TN

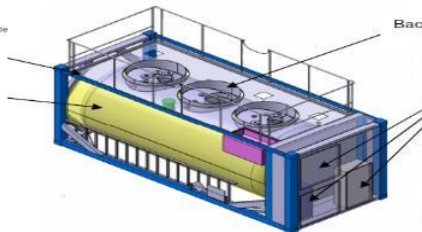
Sources



Waste



LR144



LR154



SORG

Liquid
effluents

More than 95% of radioactive material transports (including LLW radwaste transport) are made with type A or industrial package (IP2).

Low level waste is often transported in ISO 20' (IP2) containers.

- Requires no approval by safety authorities
- No major safety issues
- Low specific activity, limited decay heat
- **NO FLAMMABLE GAS GENERATION ISSUE**



Transport of radwaste with
ISO 20' container on CEA
Cadarache center

Use of Type B package requires approval by the competent authority :

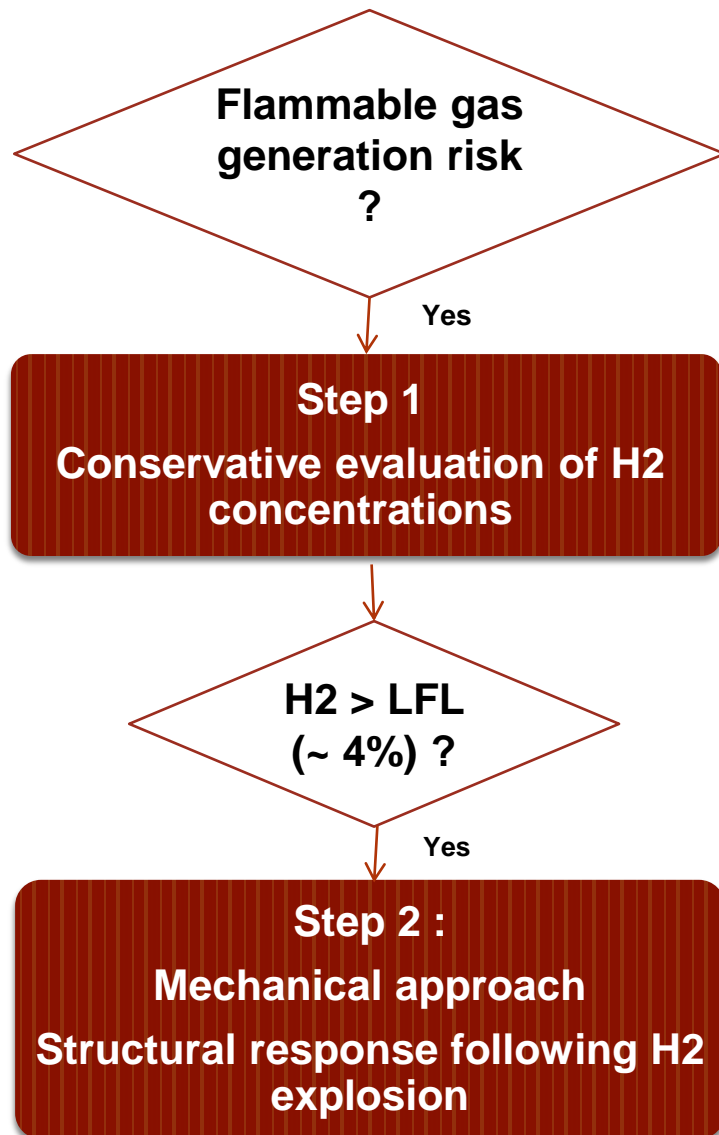
- ☐ a complete and exhaustive safety analysis
- ☐ in routine, normal and accident transport conditions
- ☐ safety functions must be maintained :
 - (a) containment of the *radioactive contents*
 - (b) control of external *radiation levels*
 - (c) prevention of criticality
 - (d) prevention of damage caused by heat.



Transport of radwaste with a type B package (DGD)

In the last few years, flammable gas generation issues, in particular production of hydrogen by radiolysis, has become a major issue.

Safety analysis of H₂ gas production



Different gas generation processes :
→ Radiolysis, thermolysis

Different gas species
→ H₂, other gases

Transportation scenario
Conservative approach

Need for pressure profiles of H₂ detonation explosions

Safety analysis of H₂ gas production : a 2 step approach

STEP 1

Objective : calculate maximum H₂ concentration inside any void volume in the containment vessel and demonstrate it is always lower than H₂ lower flammability limit (LFL) during transportation time

1. Use conservative assumptions and calculations :

- ☐ Bounding values of G(H₂)
- ☐ Maximum temperature and pressure calculated on the basis of a defined scenario
- ☐ Tendency to use very simple models (proportional to P(W))

2. Typical transport scenario defined for a safety analysis :

- ☐ X days of transport including loading / unloading operations in normal conditions of transport (including solar insolation)
- ☐ 7 days for unforeseen transportation events in normal conditions of transport
- ☐ Occurrence of accident conditions of transport = fire (normalised fire at 800°C during 30 minutes)
- ☐ 7 days following fire accident



More and more difficult to succeed in safety demonstration : uncertainties in waste content, sealing of primary containers, H₂ concentration in small waste enclosures



Safety analysis of H₂ gas production : a 2 step approach

STEP 2 :

Demonstrate package safety function is maintained after H₂ explosion

1. Safety function impaired after explosion = containment function → No loss of radioactive content > regulatory limits
2. Need to calculate the structural response of containment vessel or design pressure resistant vessel cavity or primary containment (waste container, fuel canister)
3. Requires pressure loads as source term to mechanical calculations = pressure profiles (detonation peak pressure, peak duration, residual pressure)
4. Pressure profiles may be found in literature or be characterized through an experimental program



Reasons to conduct an experimental program :

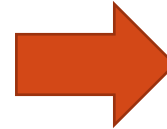
- ☐ Literature data = no data representative of transport conditions
- ☐ Presence of water to be investigated

Example of transports with H₂ gas generation issues

Transportation of irradiated fuel / fresh fuel

Nuclear fuel transport

- with package loading in storage pool
- insufficient dewatering after vacuum draining



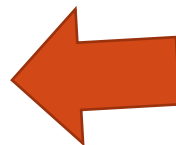
Transport of nuclear research fuel with IR100 package

Transport of irradiated research fuel

- Under very severe irradiation conditions, defects may appear in fuel cladding : it is not possible to exclude water leakage inside clad



Transport of PuO₂ powder with TNBGC package



Transport of UO₂ or PuO₂ powders

- Adsorbed water on powders with no possibility to degas before transport (old sealed containers)

Example of transports with H₂ gas generation issues

Radwaste transport

Radwaste transport :

- Legacy waste with gas generation during storage ; waste containers cannot be opened before transport

Radwaste transport :

- Important payloads with organic content or plastic/vynil conditioning



Transport of radwaste with DGD-M package



Transport of radwaste with RD30 package

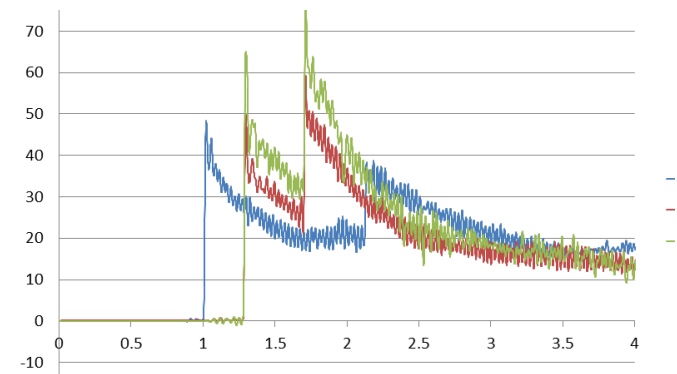
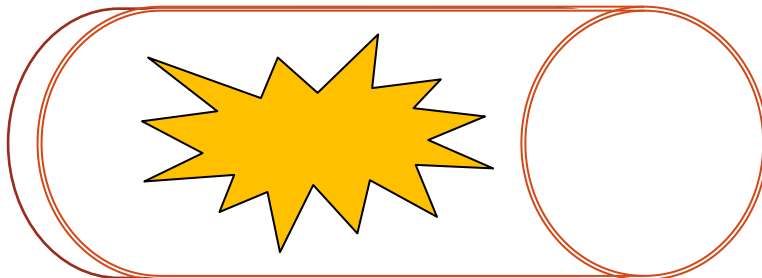
Radwaste transport :

- Radwaste with contents that cannot be fully characterized
- Is is often required to make conservative assumptions and to assume H₂ generation

Experimental programme objectives

Objective : to simulate H₂/O₂ mixture explosions that could occur during the transport of radioactive material that would have produced an explosible atmosphere inside the transport package cavity

- ☐ To characterize and record pressure profiles in detonation conditions :
 - ✓ peak pressure and duration
 - ✓ residual pressure (post peak)
- ☐ To obtain a conservative explosive mixture → stoichiometric H₂ / O₂ mixture explosion
- ☐ To obtain representative geometry and dimensions of a transport package cavity → cylindrical confined space
- ☐ To be representative of transport conditions → high pressure and high temperature ; presence of water vapor)



A 3-step experimental programme

→ 1st series of explosion tests :

- ✓ Simple design
- ✓ To obtain detonation conditions

→ 2nd series of explosions tests :

- ✓ To obtain more reliable results
- ✓ To enhance detonation
- ✓ To investigate effects of temperature and pressure conditions
- ✓ To study the influence of water vapor
- ✓ To qualify sensors

→ 3rd series of explosions tests :

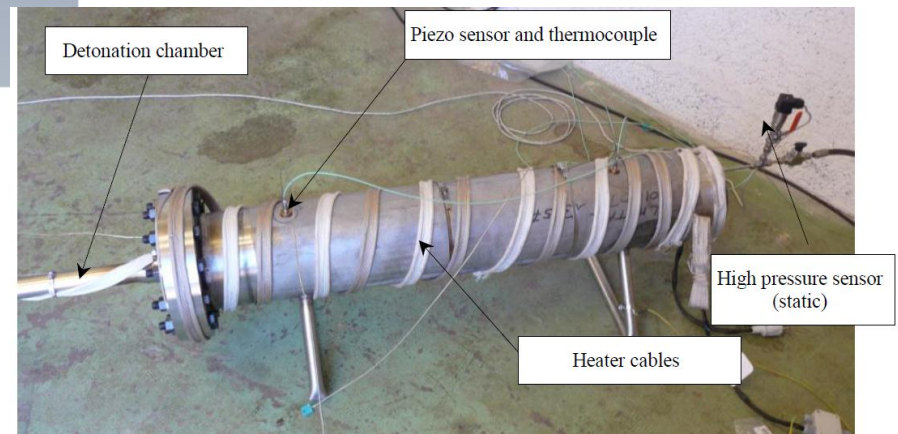
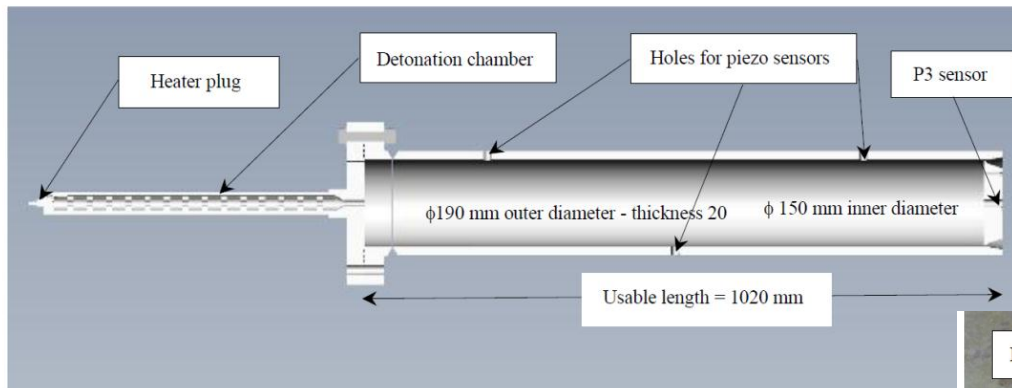
- ✓ To study 2D effects
- ✓ To be closer to vessel cavity shape and geometry

Experimental set up

1st series of explosion tests

Experimental set-up :

- ❑ Explosion cavity dimensions :
 - ✓ Length = 1 m
 - ✓ Diameter = 150 mm
 - ✓ Volume = 2,5 L
- ❑ Equipped with radial and axial pressure sensors
- ❑ Detonation chamber → to facilitate explosion conditions



Initial conditions :

- ☐ Initial pressure : between 1,5 and 2,33 bar
- ☐ Stochiometric H₂/air mixtures
- ☐ Temperature : between 20°C (68°F) and 108°C (226°F)

Results :

- ☐ Detonation conditions obtained : P max = 200 bar over 40 to 50 µs
- ☐ Lack of repeatability

Improvements :

- ☐ To adapt the detonation chamber
- ☐ To fit velocity sensors → to control shock wave velocity

Experimental set up

2nd series of explosion tests

Experimental setup changes and improvements :

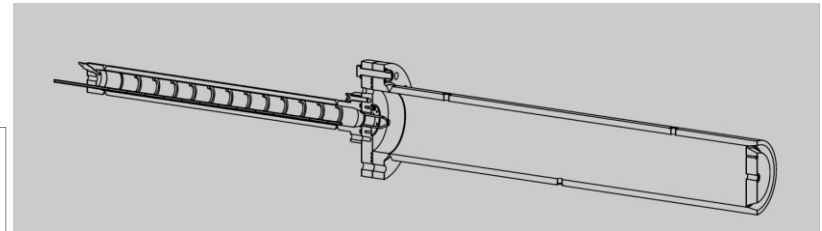
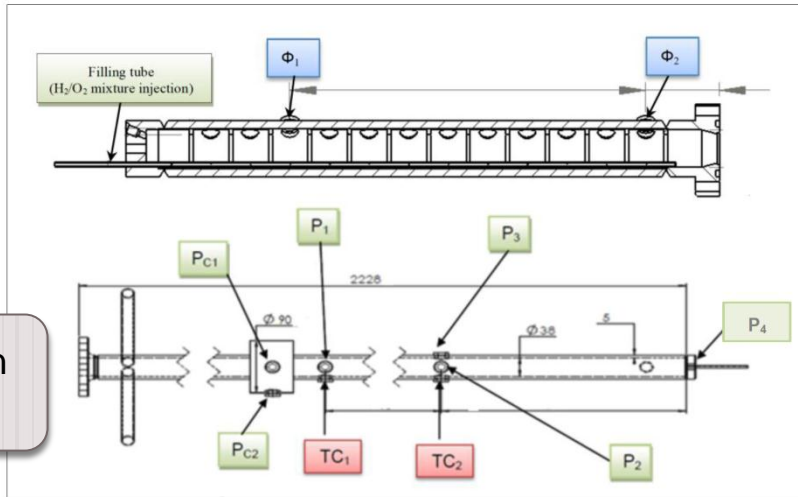
- ❑ Longer vessel design :
 - ✓ Length = 2,2 m
 - ✓ Diameter = 38 mm
- ❑ Detonation chamber improved replaced by a flame accelerator tube (FAT)
- ❑ 2 photodiodes to measure wave velocity
- ❑ 5 radial and 1 axial pressure sensors
- ❑ 2 temperature sensors

Initial conditions :

- ❑ Initial pressure : from 1 to 7 bar (dry conditions), from 1 to 5 bar (humid conditions)
- ❑ Stoichiometric H₂/air mixtures (and vapor pressure)
- ❑ Temperature : room temperature (dry conditions), up to 140°C (284°F) in humid conditions

FAT

Explosion cavity



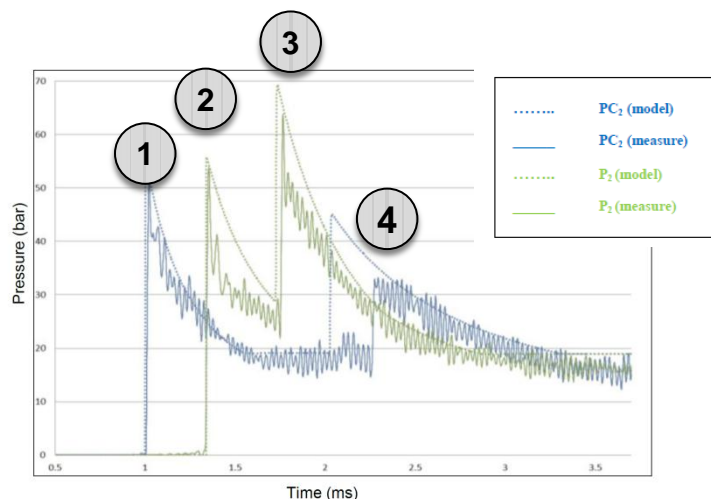
FAT

Explosion cavity

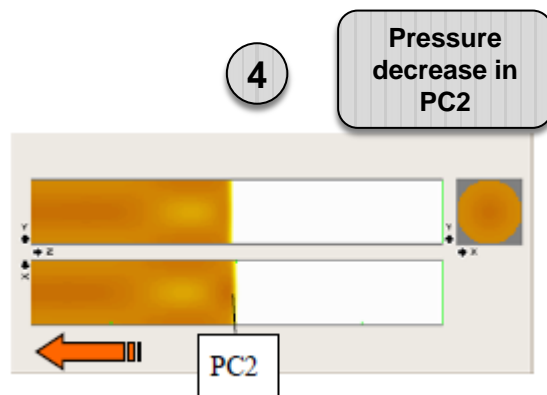


Experimental results in dry conditions

2nd series of explosion tests

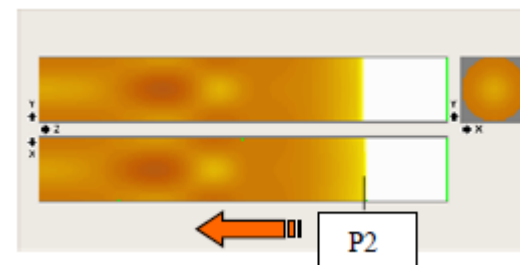
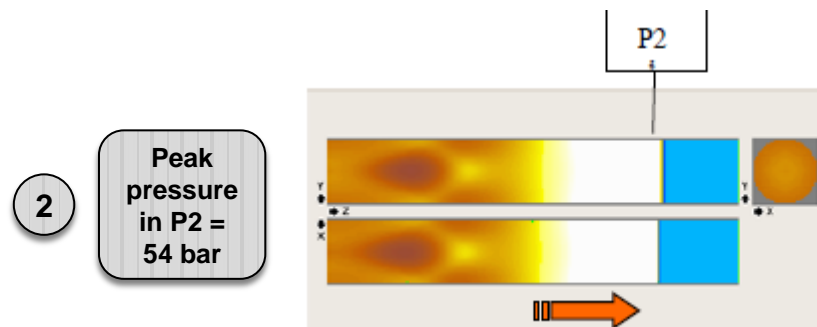
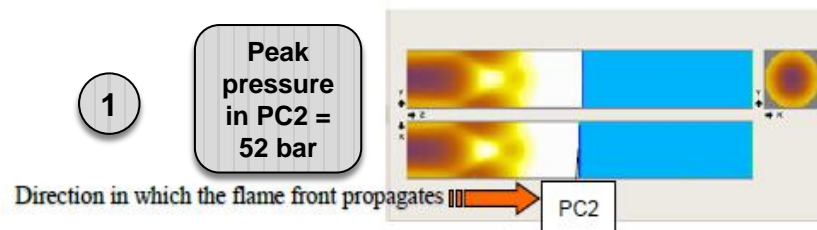


Example of a typical pressure profile graph (pressure vs time) and comparison with a shock wave displacement model inside the cavity vessel (steps 1 to 4)



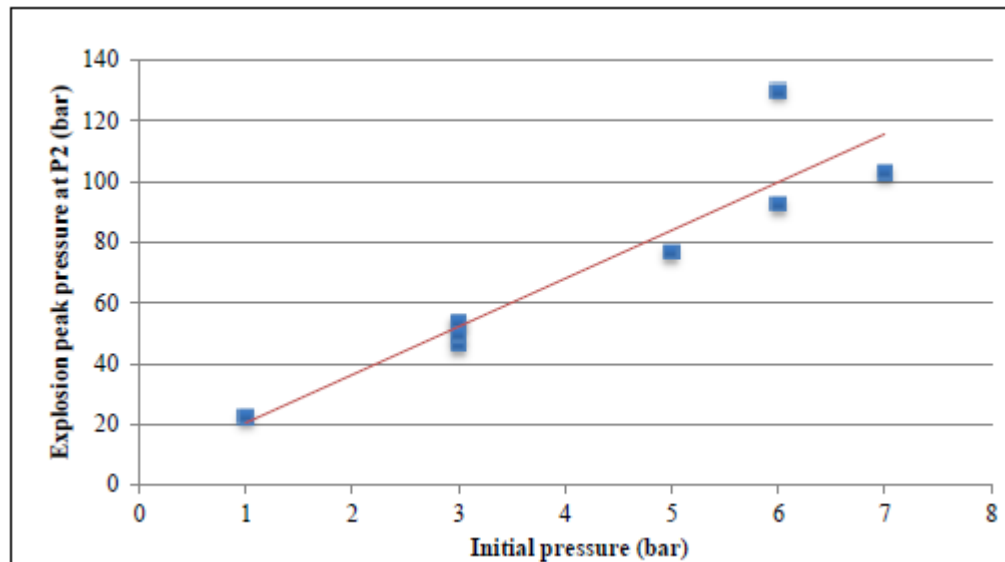
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Amplification / reflection of the shock wave on the cavity end
Peak pressure = 64 bar (P_2)



Overall results :

- ❑ Good reproducibility
- ❑ Detonation conditions obtained
- ❑ Pressure peak proportional to initial pressure (see graph below)
- ❑ Demonstration of the amplification effect due to shock wave reflection
- ❑ Pressure results : from 15 to 100 bars
- ❑ Good fit between experimental and model results (20% to 30%)



Experimental results in humid conditions

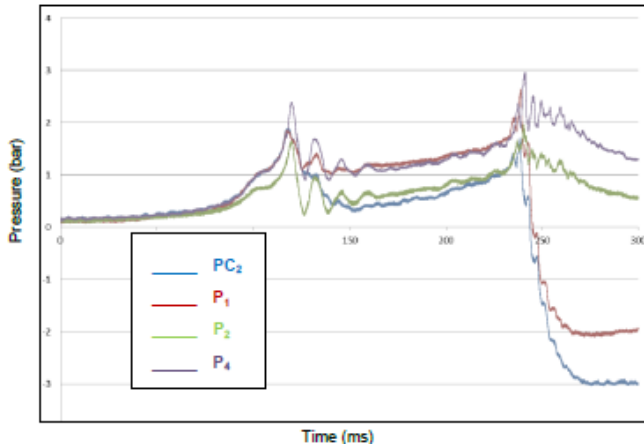
2nd series of explosion tests

Initial conditions :

- ☐ Water concentration : from 2 to 72%
- ☐ Temperature : from 20°C (68°F) to 140°C (284°F)
- ☐ Pressure : from 1 to 5 bar

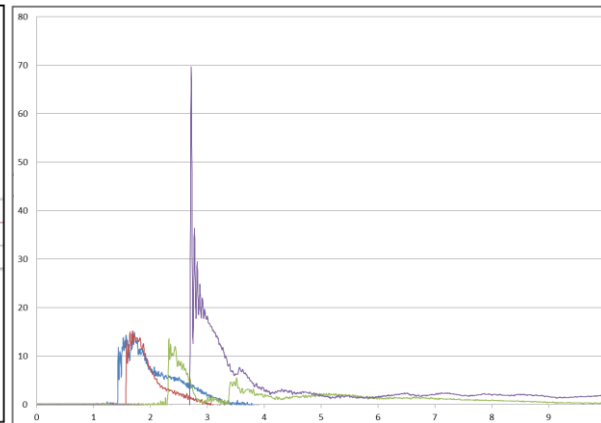
Overall results :

- ☐ Detonation conditions below $T=100^{\circ}\text{C}$
- ☐ At $T=120^{\circ}\text{C}$ (248°F) , vapor contraction reaches 60%, detonation/deflagration limit
- ☐ At $T=140^{\circ}\text{C}$ (284°F) , deflagration conditions



3

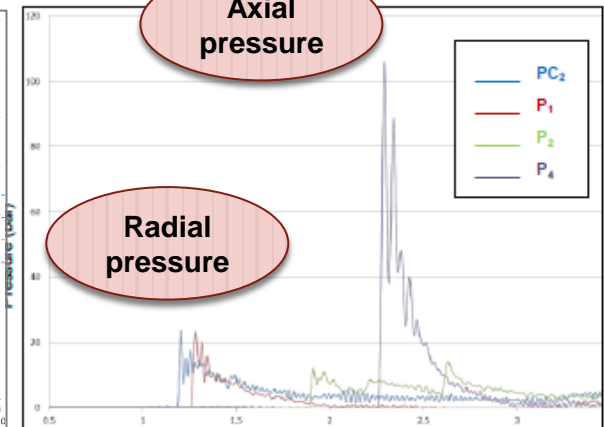
Deflagration
at $T=140^{\circ}\text{C}$



2

Detonation limit at
 $T=120^{\circ}\text{C}$

Axial peak pressure
= 70 bar

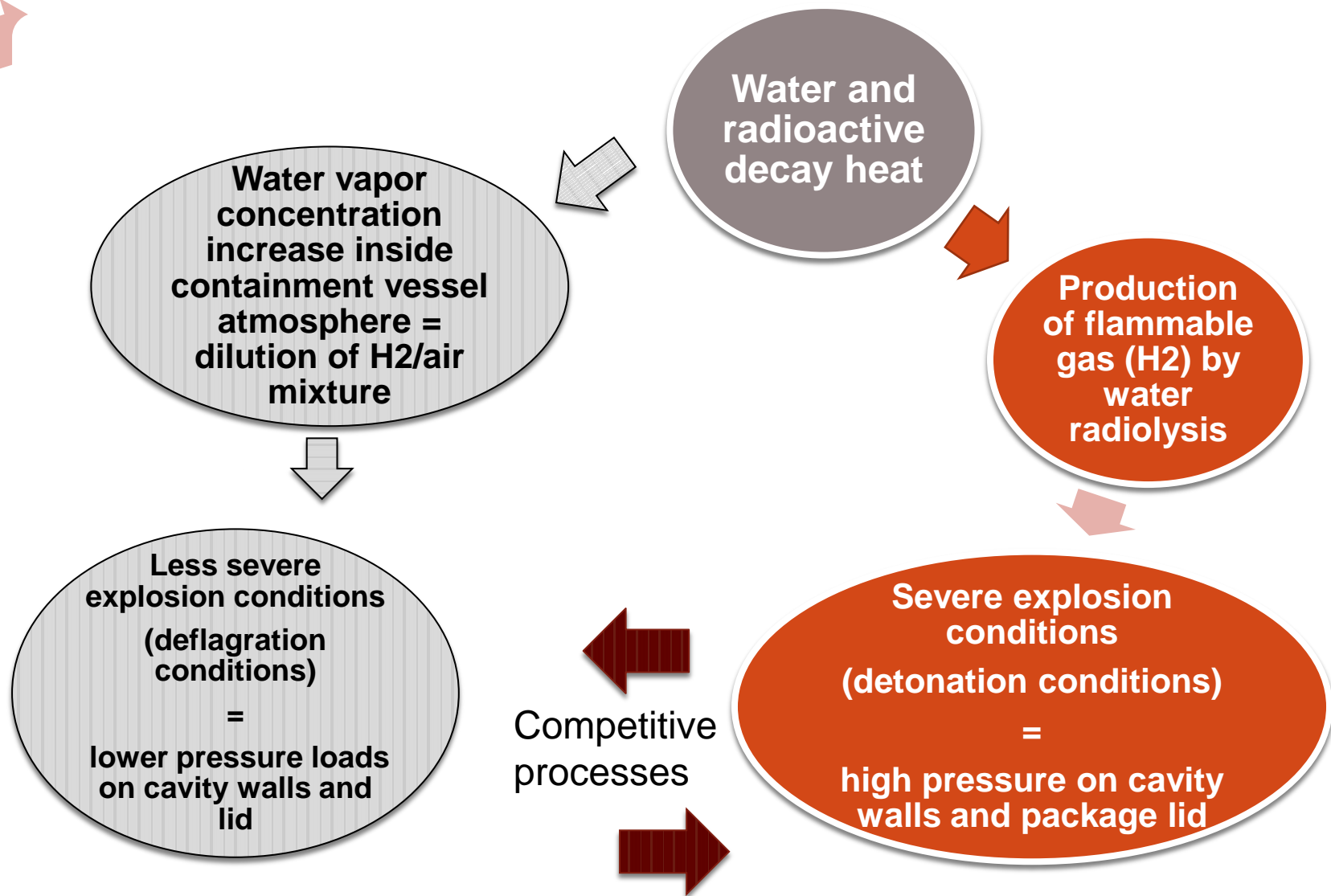


1

Detonation at
 $T=100^{\circ}\text{C}$

Axial peak pressure
= 105 bar

Experimental results in humid conditions

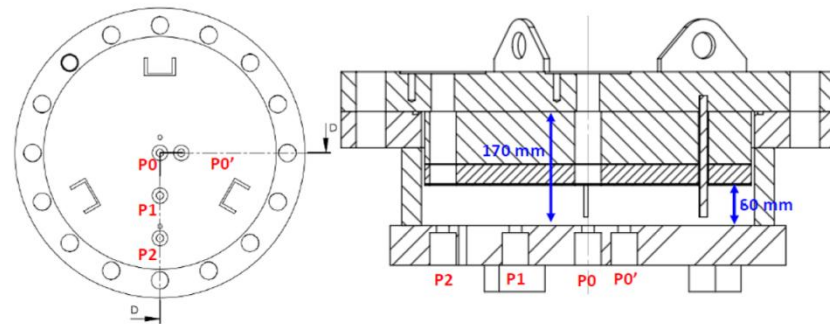
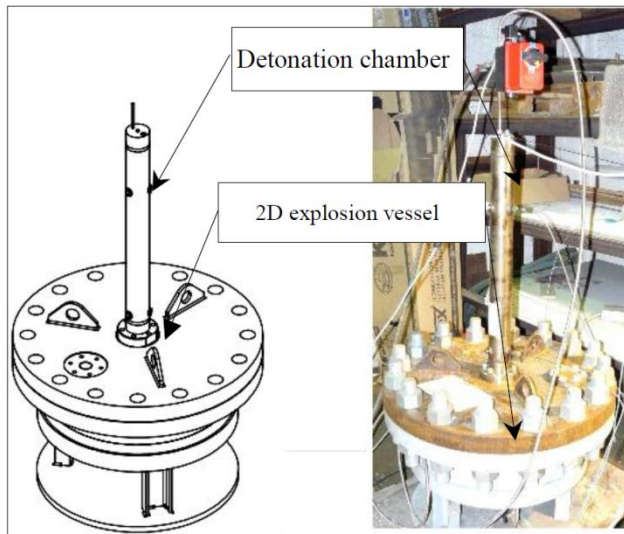


Experimental set up

3rd series of explosion tests

Experimental set-up :

- ❑ Explosion cavity dimensions :
 - ✓ 2 volumes : 11.8 L and 33.4 L
 - ✓ 2 vessel lengths : 60 and 170 mm
- ❑ 4 pressure sensors (1 in the axis = P_0)
- ❑ 2D explosion chamber representative of a waste drum



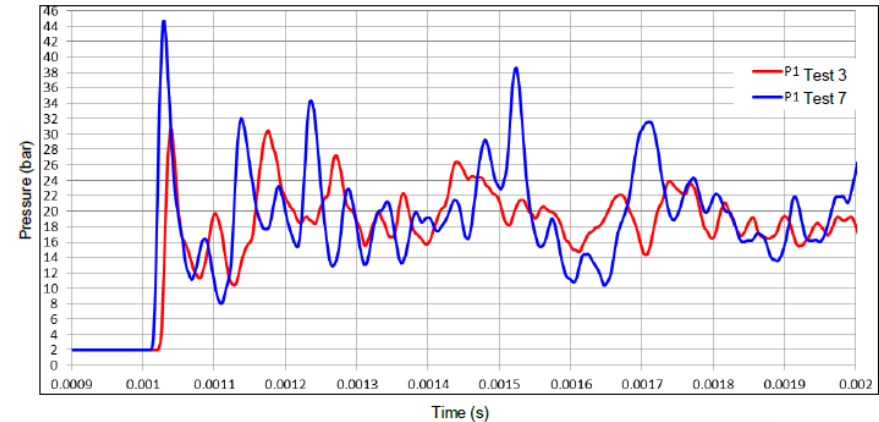
Experimental results (peak pressure)

3rd series of explosion tests

		Initial pressure (bar)		Ratio
		1.6 bar	2.0 bar	
Cavity volume	11.8 L	25	31	1.24
	33.4 L	36	45	1.25

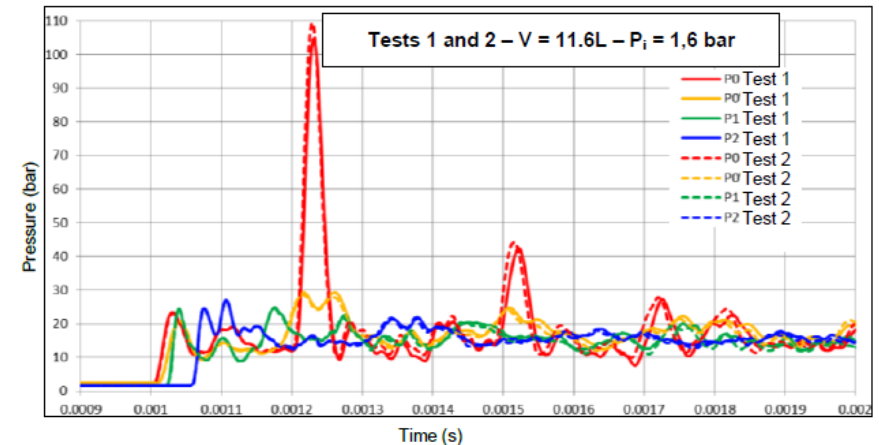
1

Peak pressure \propto initial pressure



2

Influence of cavity shape/volume



3

**Amplification due to shock wave reflection
Pressure in the center 4 times higher**

Overall results

1. Proportionality between initial pressure and peak pressure is confirmed
2. Influence of cavity shape and volume \rightarrow amplification phenomenon is sharper
3. Very high pressure measured in small areas close to the center of the cavity (4 times higher than other sensors) \rightarrow amplification phenomenon in the center of the cavity

Experimental results (residual pressure)

3rd series of explosion tests

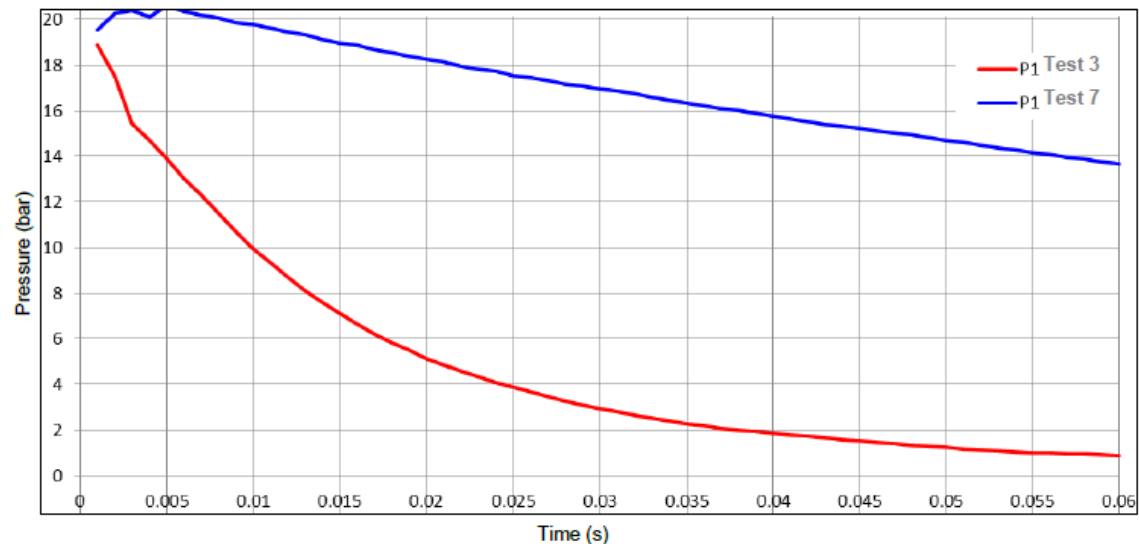
Overall results

Influence of cavity shape on pressure profile → the residual pressure decreases rapidly and is much lower if burnt gases are allowed to cool down against cavity walls

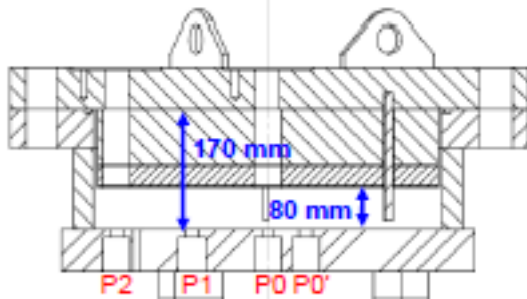
It is a very important results as regards the mechanical behavior and resistance of the containment system.

Wide cavity geometry / big volume =
cooling is less rapid

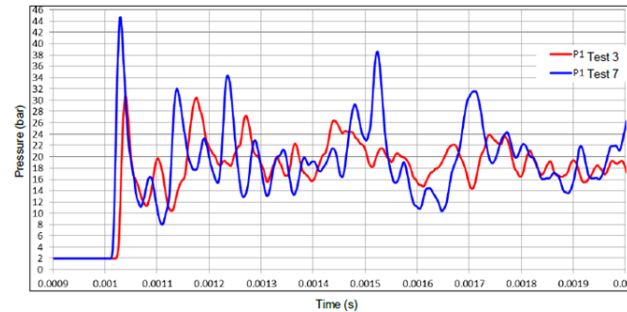
Narrow cavity geometry /
small volume = cooling is
enhanced



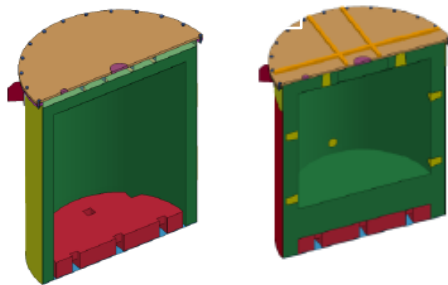
Example of possible use of experimental results to design reinforced steel waste containers



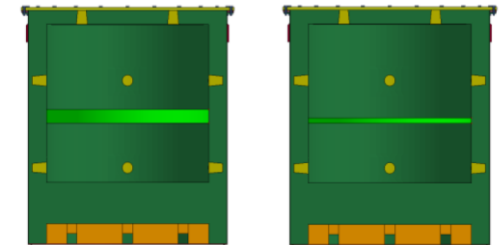
Experimental set-up with 2 possible heights



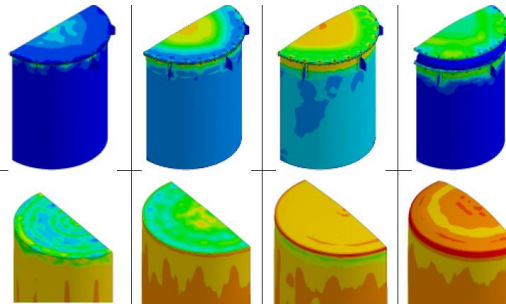
Pressure profiles from detonation explosions



Container lid reinforcement solutions



Container model with 2 corresponding explosion volumes



Container structural response

Conclusion

1. Application for package approval requires a complete and thorough safety demonstration in which **flammable gas has become a major and very challenging issue** in the last few years.
2. In some cases, it cannot be demonstrated that hydrogen concentrations are **maintained below LFL** value during transportation.
3. An alternative approach consists of designing primary containers or packagings that **resist to high pressure loads** due to hydrogen explosion.
4. Pressure profiles **from detonating explosions** are required as an input to mechanical modelling and calculations.
5. An **experimental program** has been conducted and has allowed to :
 - ☐ obtain reproducible detonation conditions,
 - ☐ characterize pressure profiles for hydrogen/oxygen mixtures in P,T conditions representative of nuclear transport,
 - ☐ obtain input data (pressure loads) for mechanical calculations with conservative detonation conditions.