Consequences of Liquid Hydrogen Tank Explosions (ID181)

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Content

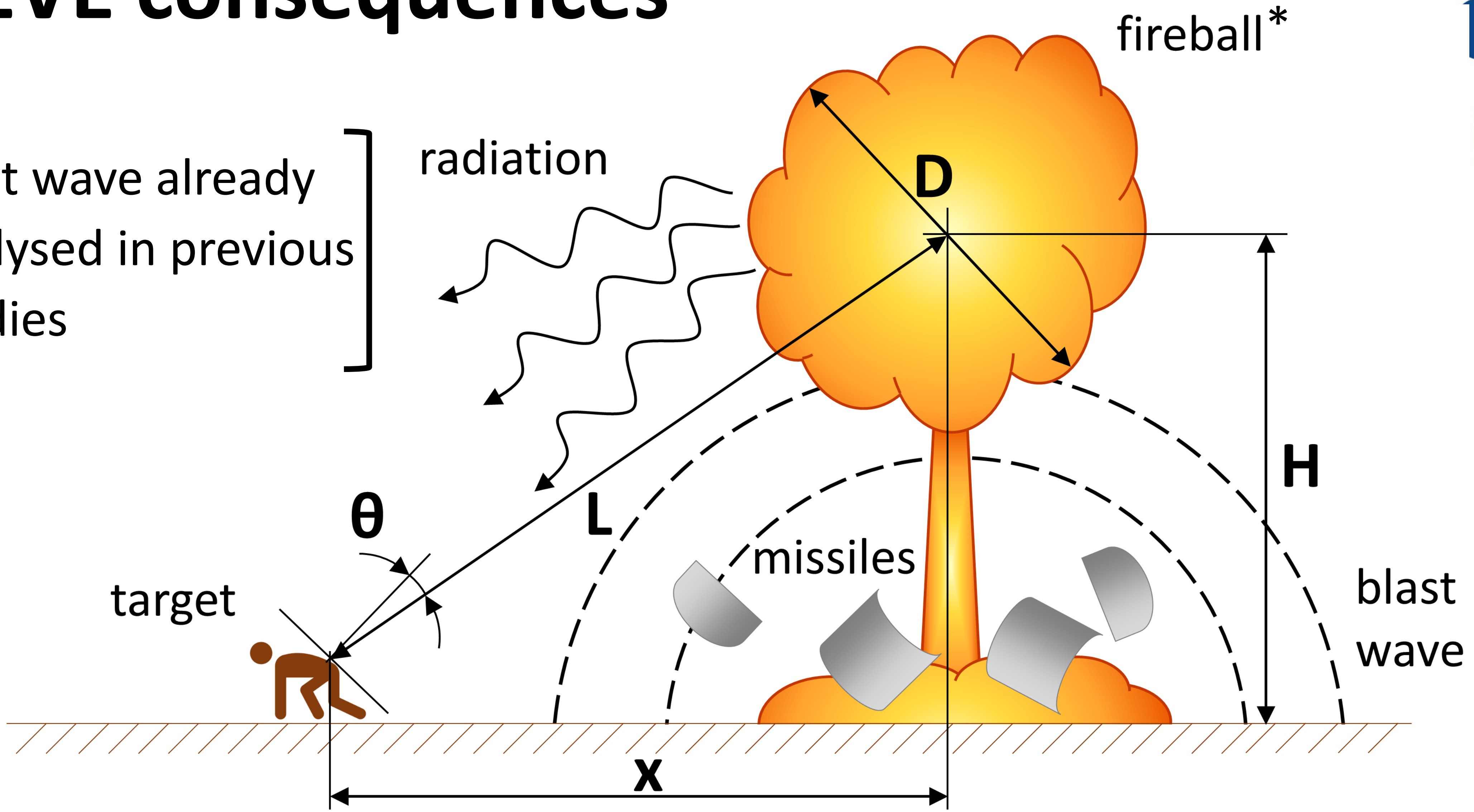
Introduction

Focus of the study: consequences of catastrophic rupture of double-walled vacuum-insulated liquid hydrogen tanks. Rupture of high-pressure hydrogen gas tanks is also considered in case of fireball.

Aim: preliminary analysis **fireball** and **distribution of fragments** in the area around the LH2 vessel after its failure.

BLEVE consequences

Blast wave already analysed in previous studies



*Fireball if substance is flammable and ignition source is present

State of the art

Hydrogen fireball analysis

Literature correlations

Diameter [m]

$$D = 7.93\ m_f^{1/3}$$

$$D_{hms} = 9.8\ m_{H_2}^{1/3}$$

$$D_{hmsc} = 19.5\ m_{H_2}^{1/3}$$

Duration [s]

$$t_{md} = 0.45\ m_f^{1/3} \text{ momentum-driven}$$

$$t_{bd} = 2.60\ m_f^{1/6} \text{ buoyancy-driven}$$

m_f = m_{H2} = hydrogen mass [kg]

State of the art

Hydrogen fireball analysis

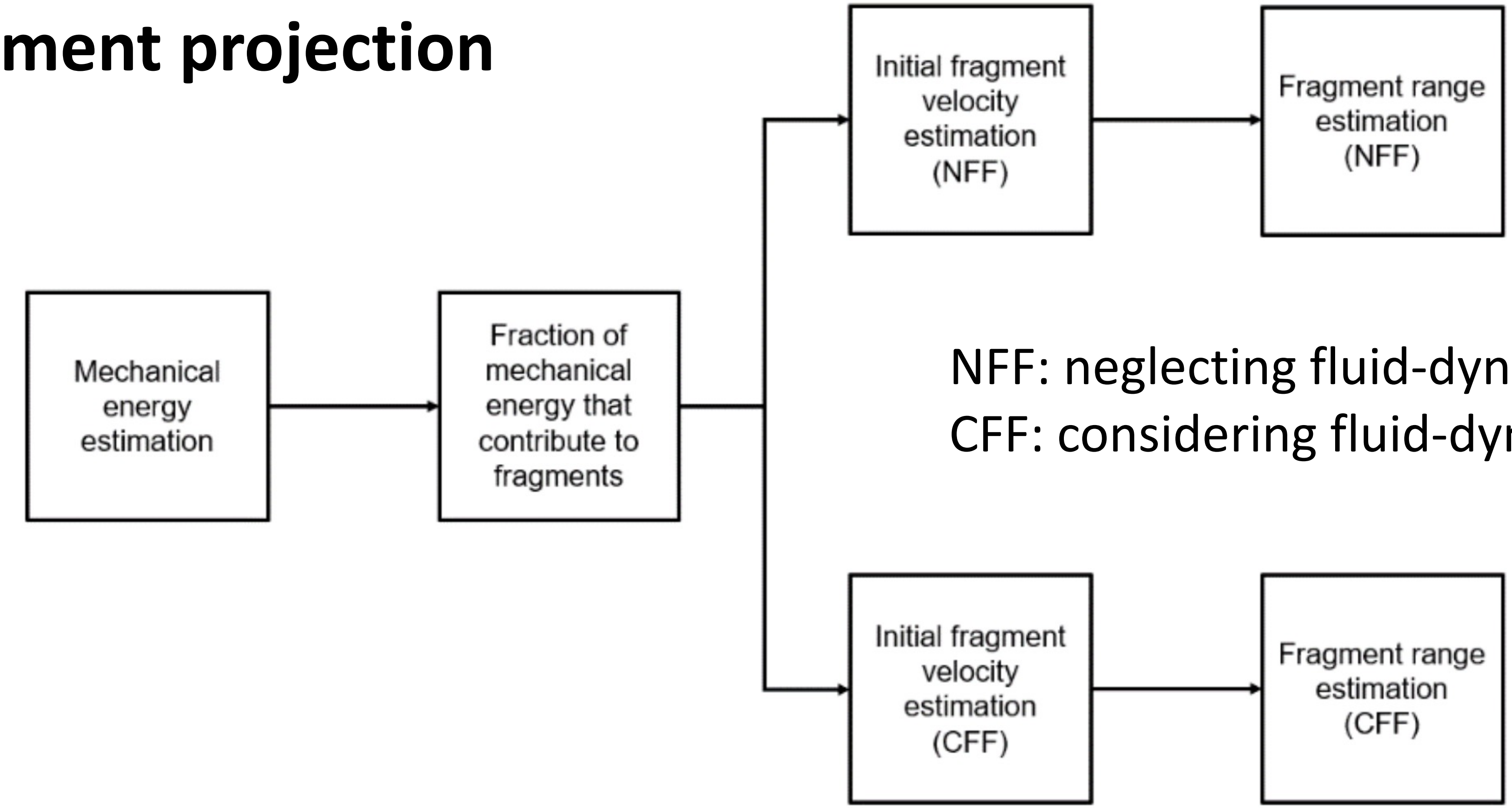
- from pressure vessel burst, PVB (high-pressure GH2 tank)
- from BLEVE (LH2 tank)

Table 1. Experimental data for hydrogen BLEVEs and PVBs (abbreviation: FB: fireball).

Test	Year	Type	Mass [kg]	Burst pressure [MPa]	FB Diameter [m]	FB Duration [s]
BMW	1996	BLEVE	1.80 ÷ 5.40	< 1.29	20	4.0
SH2IFT	2021	BLEVE	27.00	5.00	26	5.0
Zalosh-1	2005	PVB	1.64	35.70	8	2.0
Zalosh-2	2007	PVB	1.87	34.50	24	2.0
Tamura-1	2006	PVB	1.41	99.50	18	2.0
Tamura-2	2006	PVB	1.37	94.50	18	2.0
Shen	2018	PVB	3.90	43.70	7 ÷ 8	1.5

State of the art

Fragment projection



NFF: neglecting fluid-dynamic forces
CFF: considering fluid-dynamic forces

Figure 1 – Block diagram showing the procedure to apply models for predicting the horizontal range of fragments.

State of the art

Fragment projection (NFF)

Initial velocity of fragment	$v_i = \sqrt{\frac{2 \cdot \lambda \cdot E_{av}}{M_v}}$

Horizontal range	$R = \frac{v_i^2 \cdot sin(2\alpha)}{g}$

E_{av} : energy released by explosion [J/kg]
λ : energy fraction [%]
M_v : mass of the empty vessel [kg]
α : fragment initial angle [°]
g : acceleration of gravity (9.81 m/s2)

Few experimental data are available for LH2 tank fragment projection

State of the art

Fragment projection (CFF)

Fluid dynamic forces (lift & drag)	$\begin{cases} F_L = C_L A_L \frac{\rho_a \cdot v_i^2}{2} \\ F_D = C_D A_D \frac{\rho_a \cdot v_i^2}{2} \end{cases}$
Initial velocity of fragment	$\bar{v_i} = \frac{C_D A_D \cdot \rho_a \cdot v_i^2}{M_f \cdot g}$
Horizontal range	$\mathrm{R} = \frac{\bar{R} \cdot M_f}{C_D A_D \cdot \rho_a}$

C_L , C_D : lift and drag coefficients [-]
A_L , A_D : lift and drag area of the fragment [m2]
ρ_a : air density [kg/m3]
M_f : mass of fragment [kg]

Methodology

Hydrogen fireball analysis

Proposed Correlations

Diameter [m]

$$D = 16.44\ m_f^{1/3}\ \text{BMW-fit}$$

$$D = 10.97\ m_f^{1/3}\ \text{SH}_2\text{IFT-fit}$$

Duration [s]

$$t = 3.63\ m_{H_2}^{1/6}\ \text{BMW-fit}$$

$$t = 3.26\ m_{H_2}^{1/6}\ \text{SH}_2\text{IFT-fit}$$

m_f = hydrogen mass [kg]

- **Comparison** between proposed correlations and literature ones was performed.
- **Experimental data of H2 PVB and LH2 BLEVE** were used to validate correlations

Methodology

Fragment projection

Fragment No.	X	Y	Distance in r	mass in kg
[Event]	20.09.21 10:23:24			
bleve2-gzero (position of vessel)	392,670,325	5,774,327,492		
bleve2-frag01	392,671,232	5,774,334,081	6.65	124.00
bleve2-frag02	392,673,730	5,774,331,114	4.97	1.00
bleve2-frag03	392,672,926	5,774,330,026	3.63	2.00
bleve2-frag04	392,680,643	5,774,328,451	10.36	61.00
bleve2-frag05	392,688,638	5,774,305,413	28.69	1.00
bleve2-frag06	392,691,672	5,774,301,201	33.87	4.00
bleve2-frag07	392,689,618	5,774,291,531	40.81	
bleve2-frag08	392,651,980	5,774,300,290	32.81	
[Event]	20.09.21 10:46:26			
bleve2-frag09	392,654,816	5,774,306,013	26.49	
bleve2-frag10	392,653,593	5,774,316,580	19.98	13.00
bleve2-frag11	392,653,716	5,774,320,323	18.09	
bleve2-frag12	392,646,420	5,774,319,837	25.10	
bleve2-frag13	392,640,636	5,774,316,882	31.53	1.00
bleve2-frag14	392,653,804	5,774,331,442	16.99	
bleve2-frag15	392,664,413	5,774,329,344	6.20	
bleve2-frag16	392,657,236	5,774,337,234	16.32	
bleve2-frag17	392,650,849	5,774,336,288	21.37	
[Event]	20.09.21 11:26:07			
[Event]	20.09.21 11:28:22			
bleve2-frag18	392,644,649	5,774,340,906	28.97	
bleve2-frag19	392,643,550	5,774,341,289	30.12	261.00
bleve2-frag20	392,644,005	5,774,355,908	38.73	
bleve2-frag21	392,643,173	5,774,356,207	39.52	
bleve2-frag22	392,658,225	5,774,357,310	32.18	1.00
bleve2-frag23	392,658,989	5,774,357,477	32.06	1.00
bleve2-frag24	392,660,318	5,774,359,147	33.20	
bleve2-frag25	392,660,382	5,774,360,276	34.26	
bleve2-frag26	392,663,485	5,774,361,550	34.74	
[Event]	20.09.21 11:41:41			
bleve2-frag27	392,663,366	5,774,346,601	20.34	
bleve2-frag28	392,668,707	5,774,355,475	28.03	2.00
bleve2-frag29	392,669,479	5,774,355,627	28.15	
[illegible]	[illegible]	[illegible]	[illegible]	

Analysis of data on fragment distribution from **SH2IFT project** (BLEVE) tests:

- Position (coordinates)
- Mass
- Pictures

Generation of:

1. Scatter graph showing fragments position
2. Graph taking into consideration the different weight of the generated fragments

Results & discussion

Fireball analysis

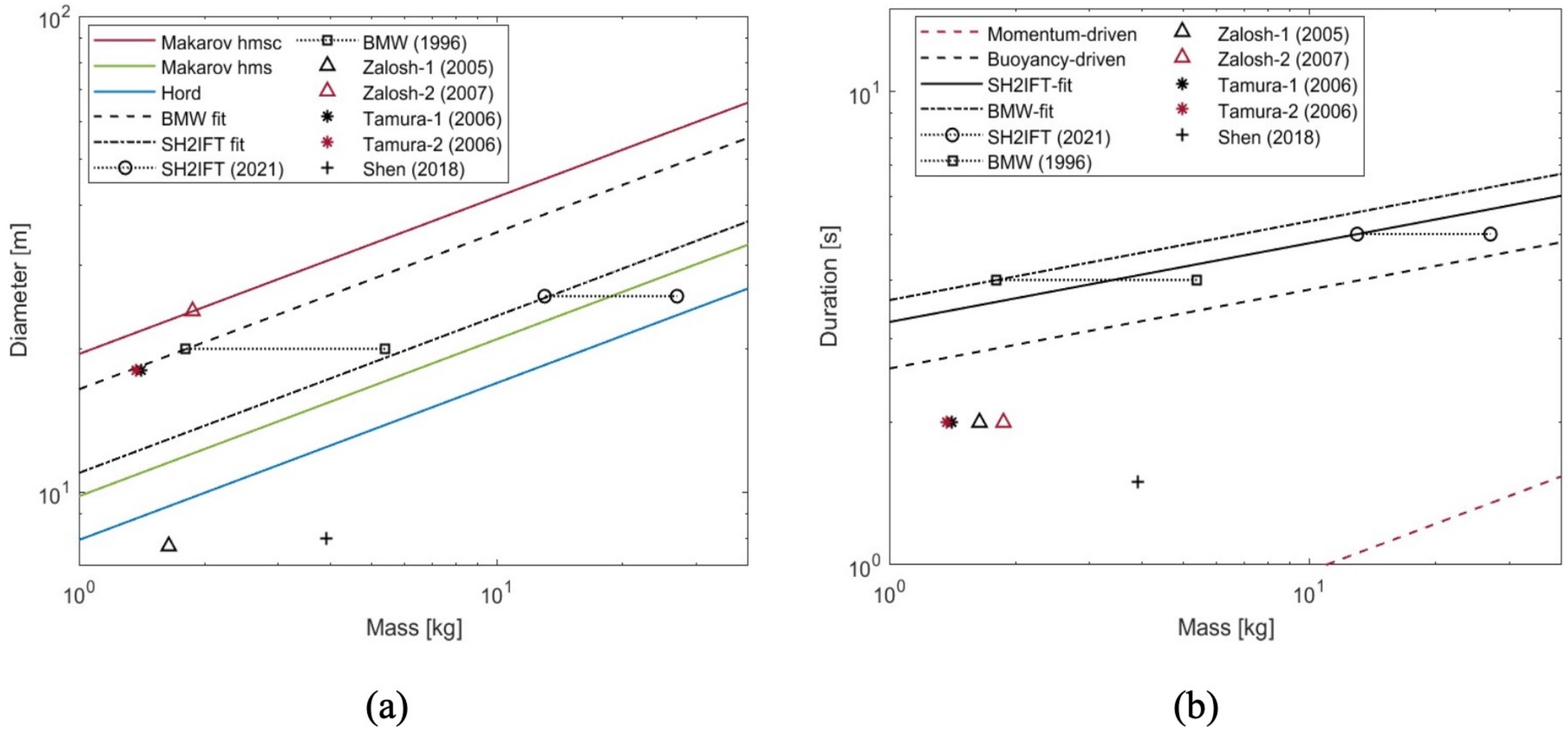


Figure 2: Comparison between experimental data and predictions fireball (a) diameters and (b) durations for different hydrogen masses. The uncertainties concerning the liquid hydrogen BLEVE masses are indicated by the thin dashed lines.

Results & discussion

Fireball analysis

Table 2. Comparison between the experimental results and the most conservative model (BMW-fit) outcomes.

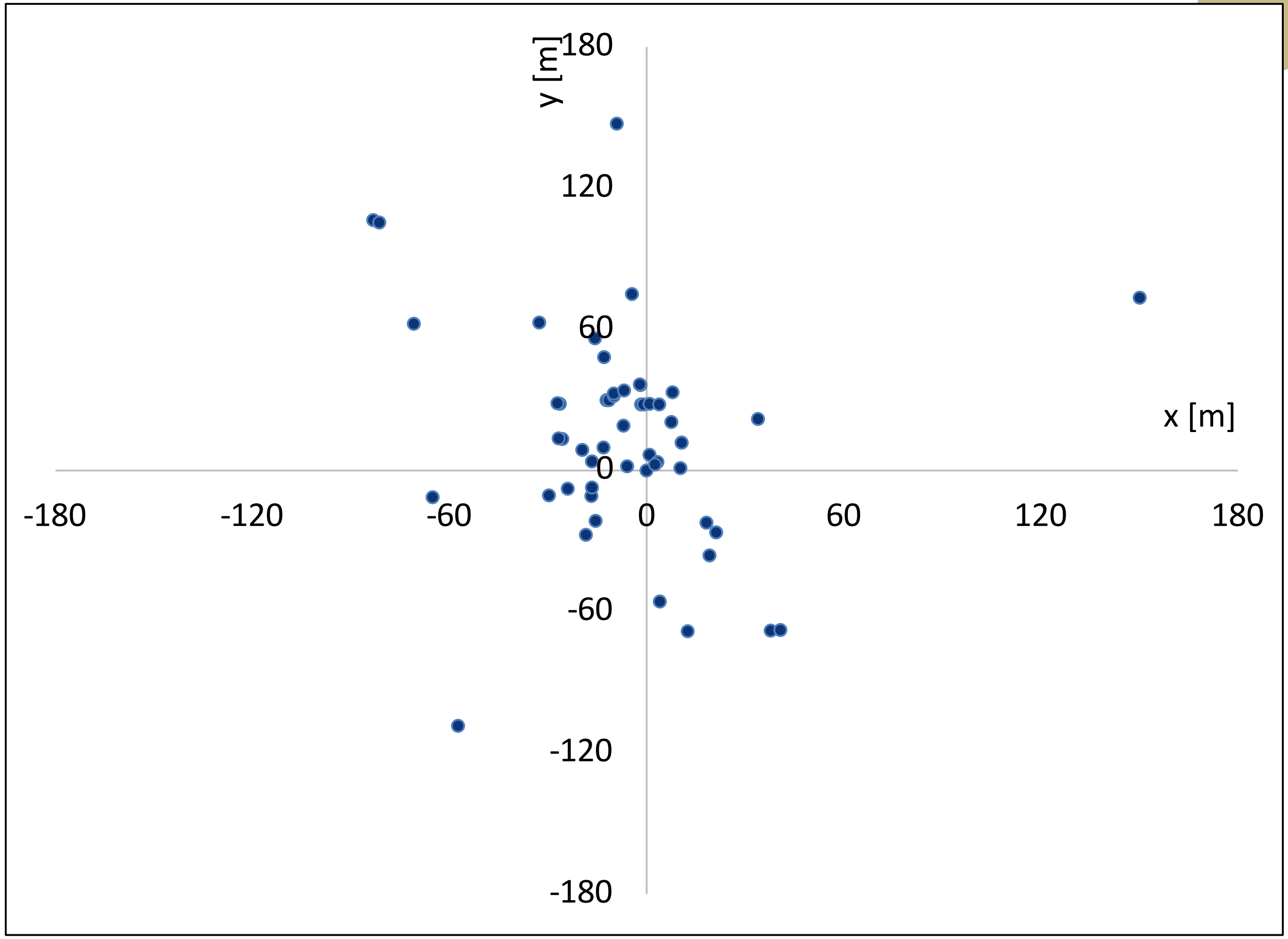
	Experimental Data		Simulation		Errors	
Test	Diameter [m]	Duration [s]	Diameter [m]	Duration [s]	Diameter Error [%]	Duration Error [%]
BMW	20	4.0	20	4.0	0	0
SH_2IFT	26	5.0	38	5.5	46	11
Zalosh-1	8	2.0	23	3.9	188	96
Zalosh-2	24	2.0	20	4.0	-15	103
Tamura-1	18	2.0	18	3.8	2	92
Tamura-2	18	2.0	18	3.8	2	89
Shen	7 ÷ 8	1.5	30	3.9	275	160

Results & discussion

Vessel fragmentation

Observations:

- 53 fragments
- No preferential direction
- Longest distance: 167 m



Results & discussion

Vessel fragmentation

Outer Vessel

[kg]

- 261 — Part of the shell + support
- 76 — End cap
- 72 — End cap
- 65 — Part of the shell

Inner Vessel

- 124 — Shell + end cap
- 61 — End cap

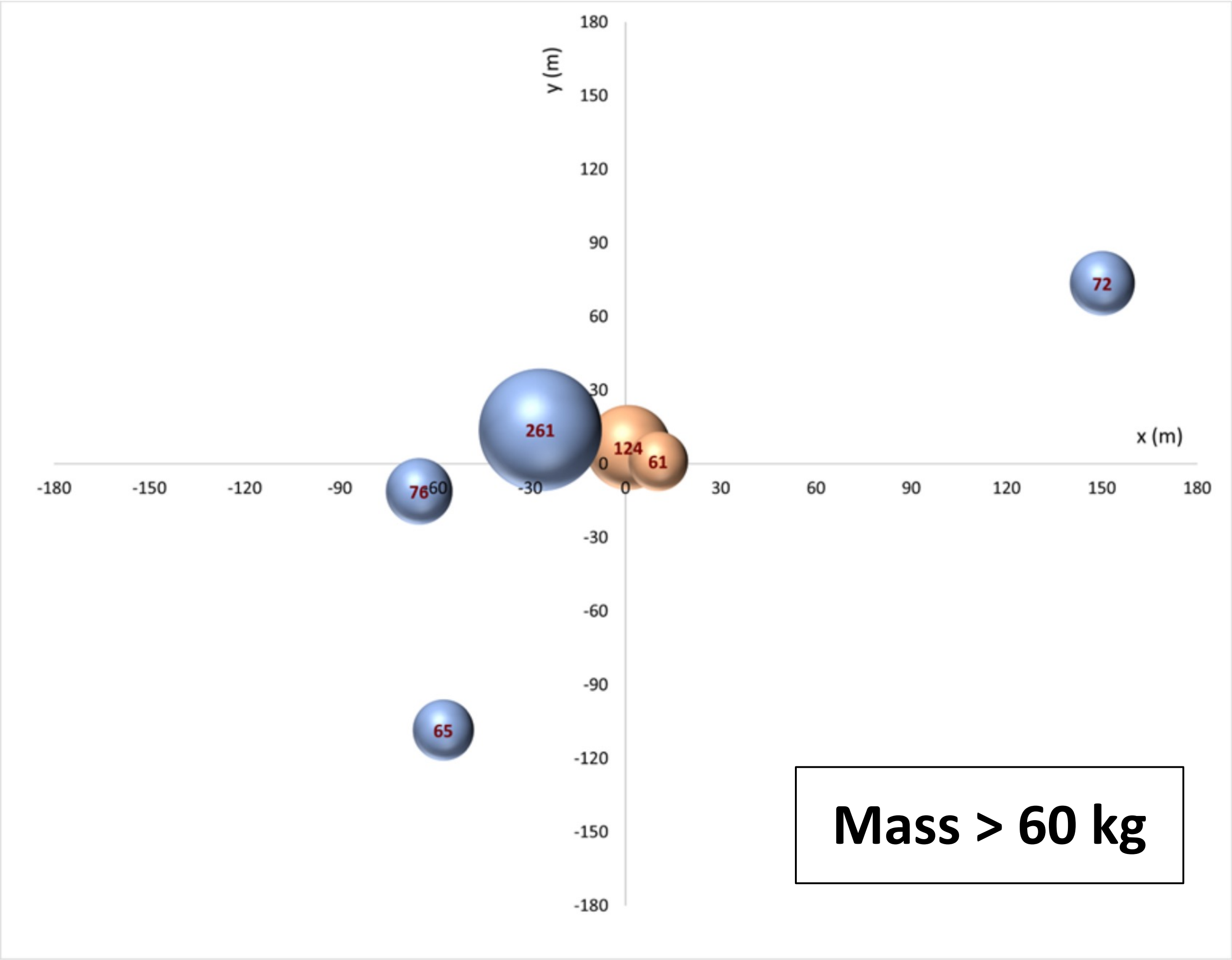


Figure 3 – Distribution of main fragments (m > 60 kg). The size of the bubbles is related to the mass (red label) of each fragment of the tank (blue bubbles for outer vessel and red bubbles for inner vessel).

Conclusion

- **Difference** in behaviour between LH2 and GH2 **fireball duration**
- **Buoyancy-driven model** is better to estimate **GH2** fireball duration
- **Proposed equation** is the best for **LH2** fireball duration
- **Data** on **fireballs** and **fragments** from LH2 tank ruptures **are lacking**
- **Makarov correlations** from literature seem **too conservative** to estimate diameter of **LH2 fireballs**
- **Fragment distribution** for LH2 tank seems to **not** have **preferred distribution**.

Future studies

- **Radiation** from LH2 hydrogen fireballs must be analysed
- Models to simulate **fragment trajectory** will be applied

Thank you for your attention

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