HySafe Research Priorities Workshop

Washington DC, 10-11 November 2014c

Deterministic separation distance from stationary and on-board hydrogen storage tank: calculation of the blast wave decay

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Outline

- Results of two tests with high-pressure hydrogen storage tank rupture in a fire
- Existing methodology for prediction of blast wave decay from a high pressure vessel rupture (physical explosion without combustion)
- Ulster methodology with combustion and comparison against two available tests
- Examples of deterministic separation distances from a stand-alone and under-vehicle tank rupture in a fire
- Concluding remarks

Two tests with blast wave measurements by N. Weyandt (2005-2006)

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Test No.1: stand-alone tank

- ❖ Tank 74.4 L, 34.3 MPa pressure
- ❖ Overpressures (test data):
  - 41 kPa at 6.5 m (>15% fatality)
  - 83 kPa at 4.2 m (death)
- ❖ Fireball diameter 7.6 m
- ❖ Missiles scattering up to 82 m

Test No.2: under-vehicle tank

- Tank 88 L, 31.8 MPa
- Overpressures (test data):
  - 30-69 kPa at 4.87 m (lung damage and fatal head injury)
- **Fireball diameter 24 m**
- **Car body frame moved in 22m**
- Other missiles – up to 107 m

Existing methodology for blast wave from high pressure tank rupture

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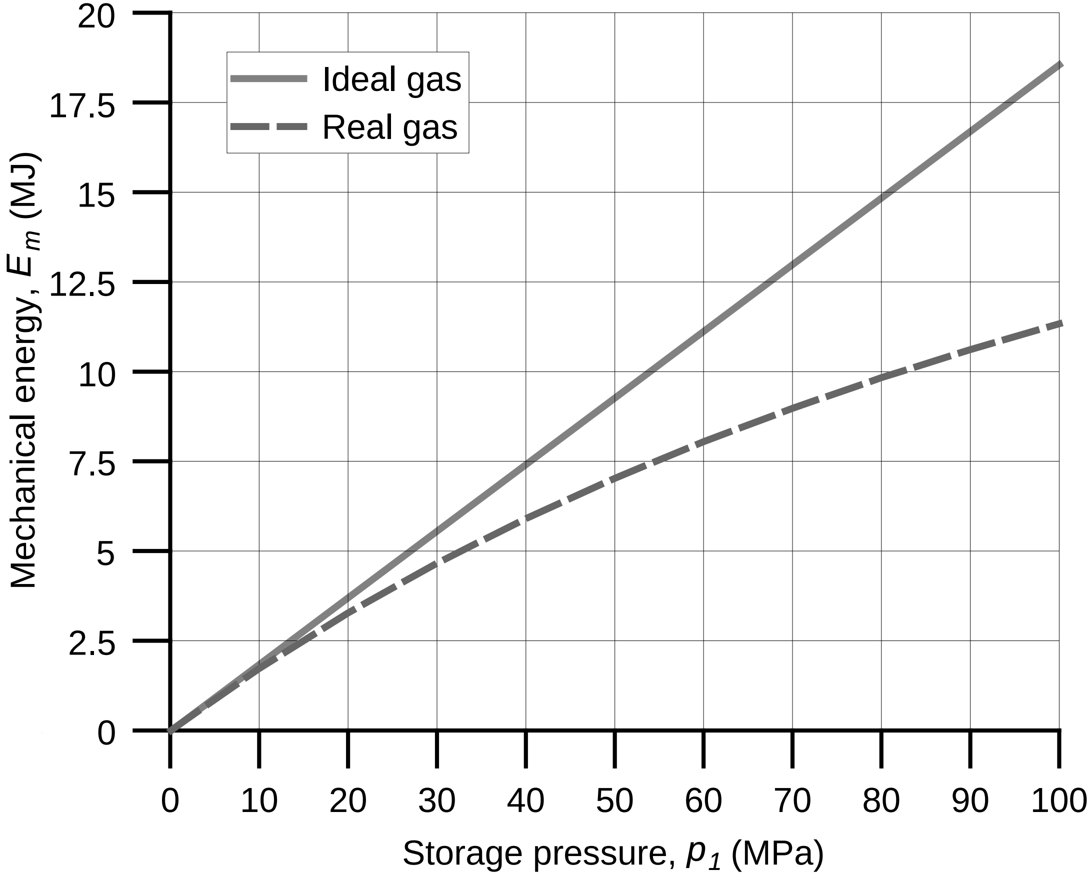
Energy of compressed hydrogen

- **Brode's model (ideal gas)**

$$E_m = \frac{(p_1 - p_0)V}{(\gamma - 1)}$$

- **Ulster model (real gas)**

$$E_m = \frac{(p_1 - p_0)(V - mb)}{(\gamma - 1)}$$



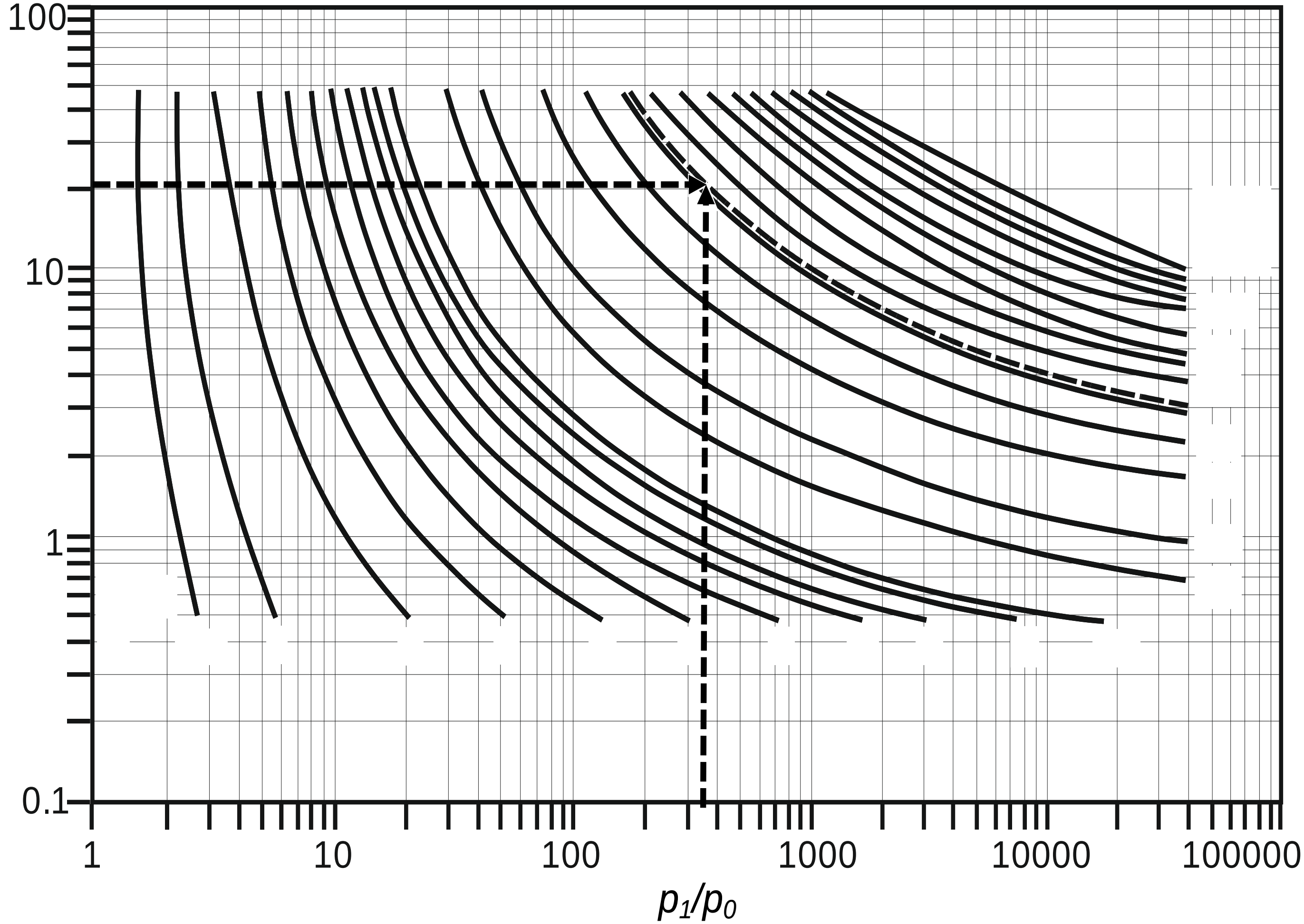
Starting shock (test No.1)

Speed of sound in air (ideal gas)

$$a_0 = \sqrt{\gamma_0 \frac{p_0}{\rho}},$$

Speed of sound in high pressure hydrogen (real gas)

$$a_1 = \sqrt{\frac{\gamma p_1}{\rho(1-b\rho)}}.$$



With p_1=343 bar the starting shock is 52 bar.

Dimensionless vessel radius (No.1)

Dimensionless radius of a high-pressure vessel in test No.1 (needed along the starting shock to choose a curve, see next slide):

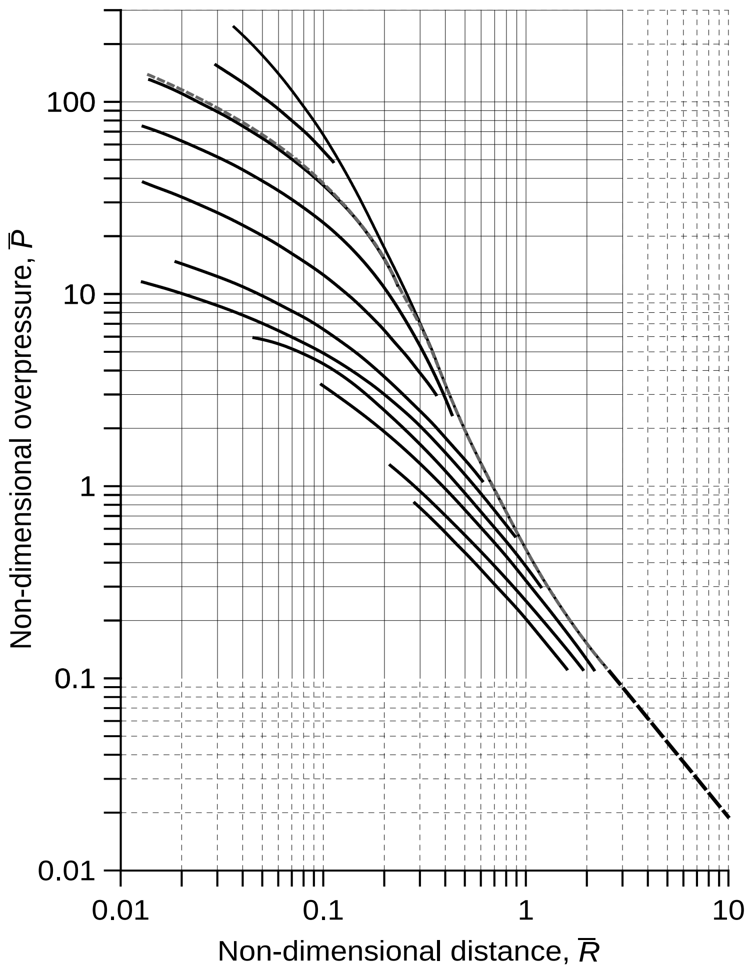
$$\bar{r}_{ves} = \frac{r_{ves} p_0^{1/3}}{E_m^{1/3}},$$

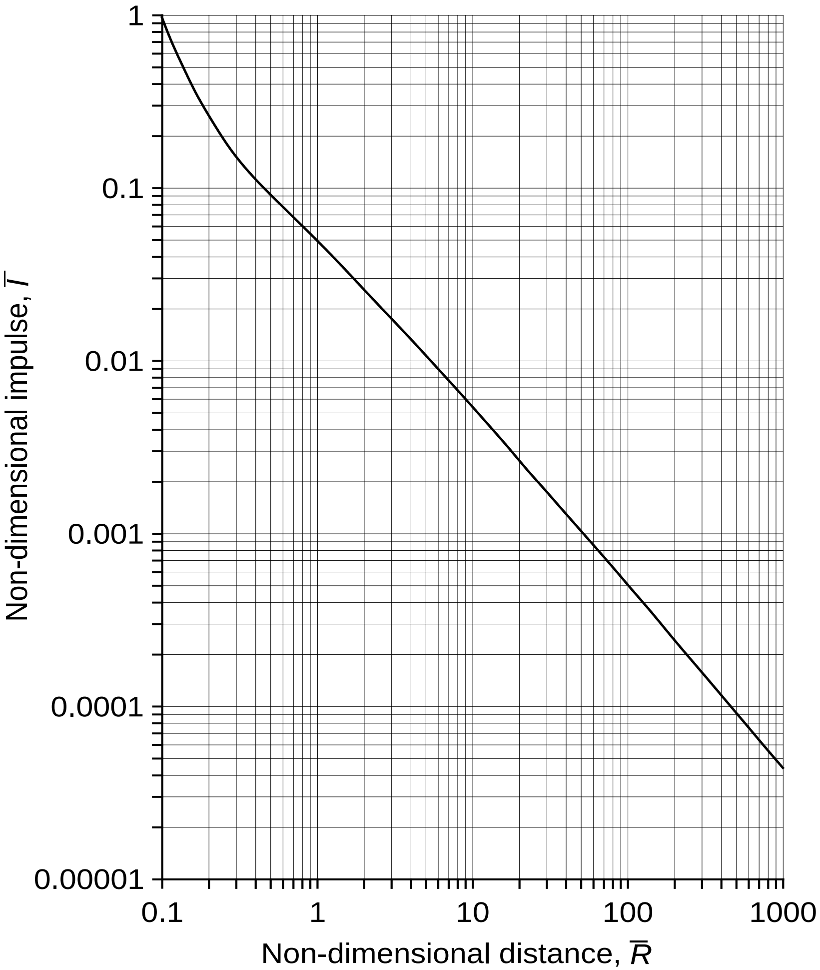
where the vessel radius is:

$$r_{ves} = \left(\frac{3V}{4\pi} \right)^{1/3}.$$

At *p_1*=343 bar dimensionless vessel radius is 0.07.

Dimensionless overpressure and impulse





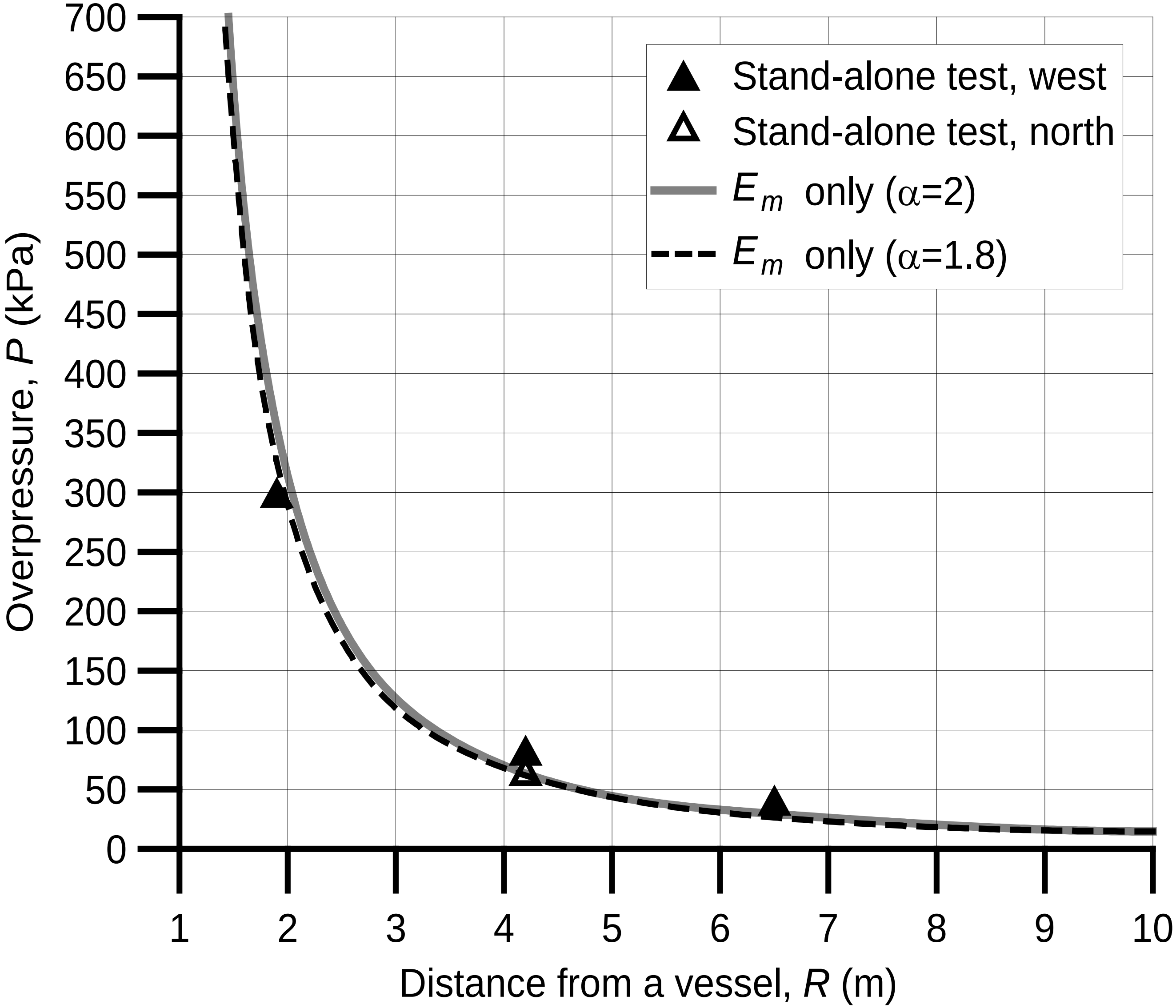
Dimensionless radius

$$\overline{R} = \frac{R \cdot p_0^{1/3}}{(\alpha \cdot E_m)^{1/3}}.$$

Dimensionless impulse

$$\overline{I} = \frac{I \cdot a_0}{(\alpha \cdot E_m)^{1/3} p_0^{2/3}}.$$

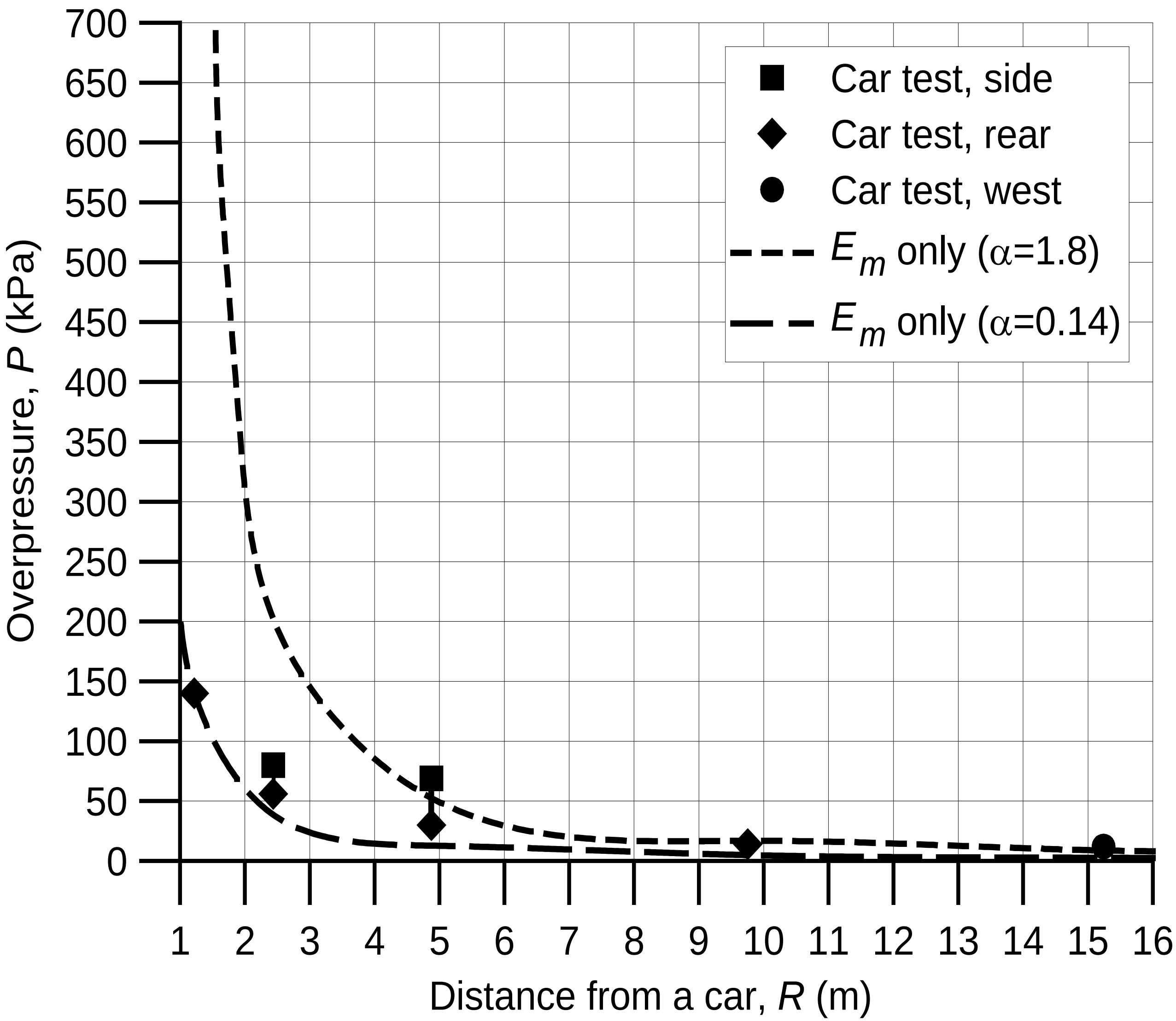
Stand-alone tank: existing methodology



When α=2 (on the ground - hemisphere): Under-prediction at 6.5 m: –26%

When α=1.8 (with some losses to deform ground): under-prediction at 6.5 m: –31%

Under-vehicle tank: existing methodology



When α=1.8:

Unacceptable over-prediction:

1.22 m - 7 times

2.44 m - 1.5 times

9.75 m - 1.2 times

Under-prediction:

15.24 m by 30%

When α=0.14 (tuned to 1st point):

Unacceptable under-prediction:

2.44 m: –31%

4.87 m: –57%

9.75 m: –65%

15.24 m: –78%

Ulster methodology with inclusion of chemical energy (combustion)

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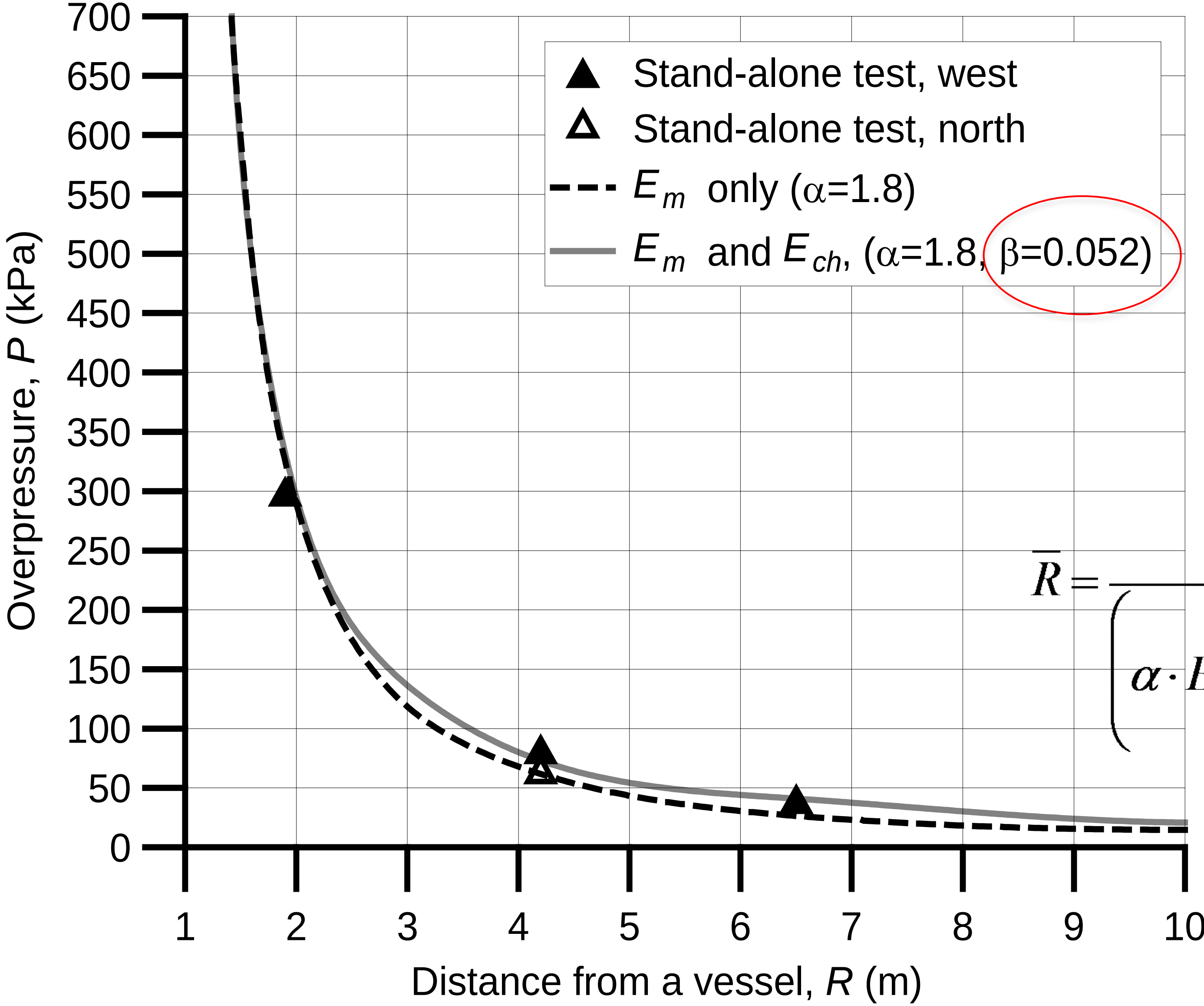
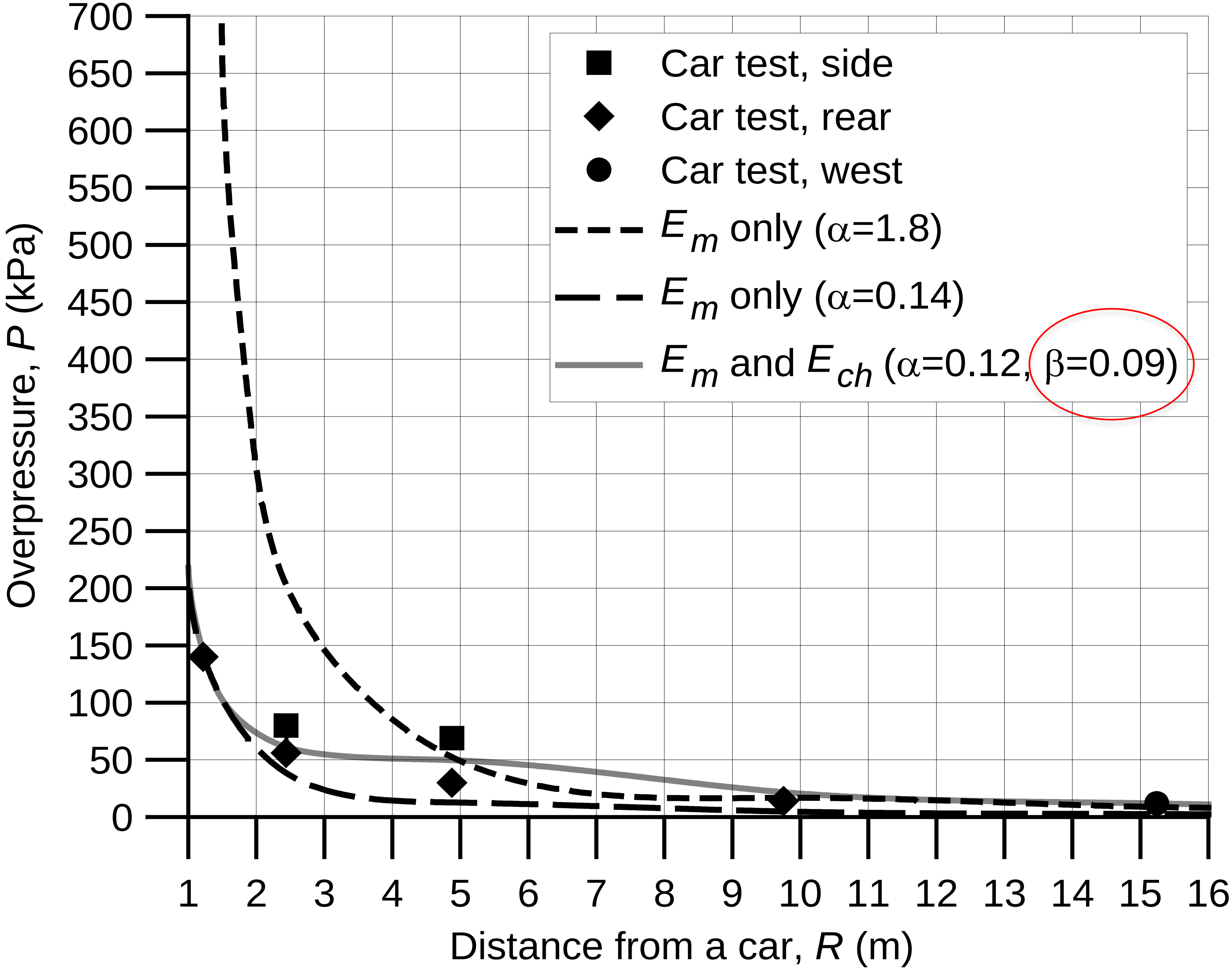
Stand-alone tank: Ulster method



New dimensionless radius

$$\overline{R} = \frac{R \cdot p_0^{1/3}}{\left(\alpha \cdot E_m + \beta \cdot E_{ch} \cdot \left(\frac{R_{shk}}{R_{com}}\right)^3\right)^{1/3}}.$$

Under-vehicle tank: Ulster method



Deterministic separation distance from a blast wave

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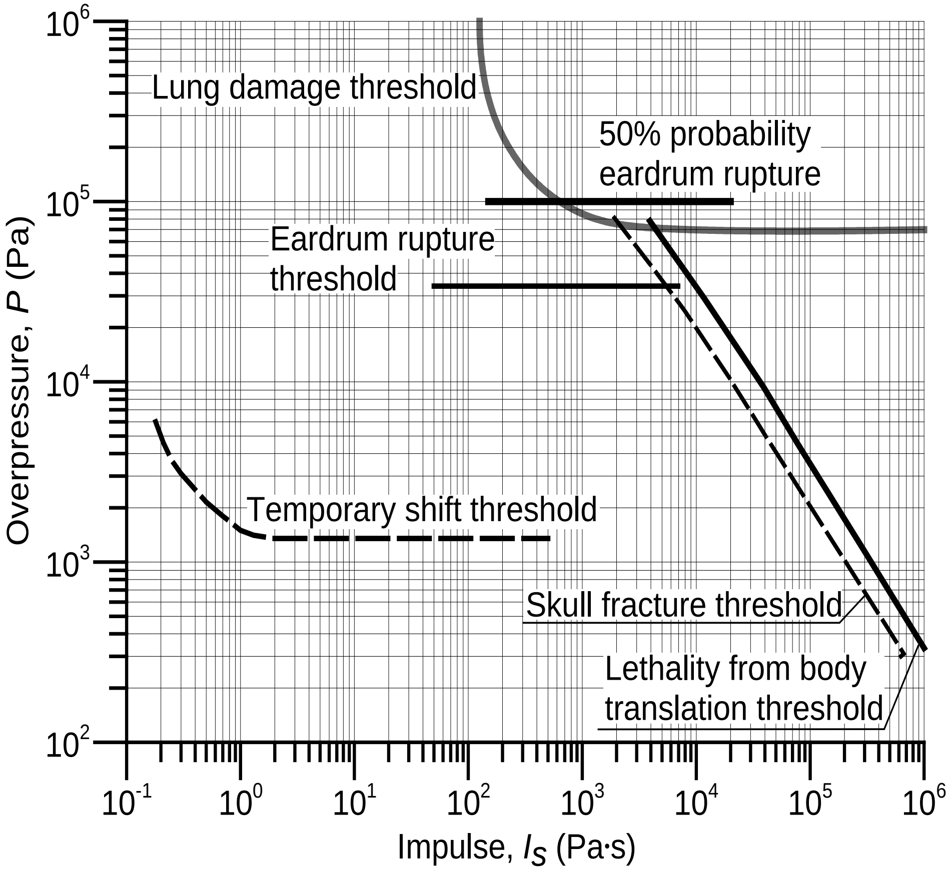
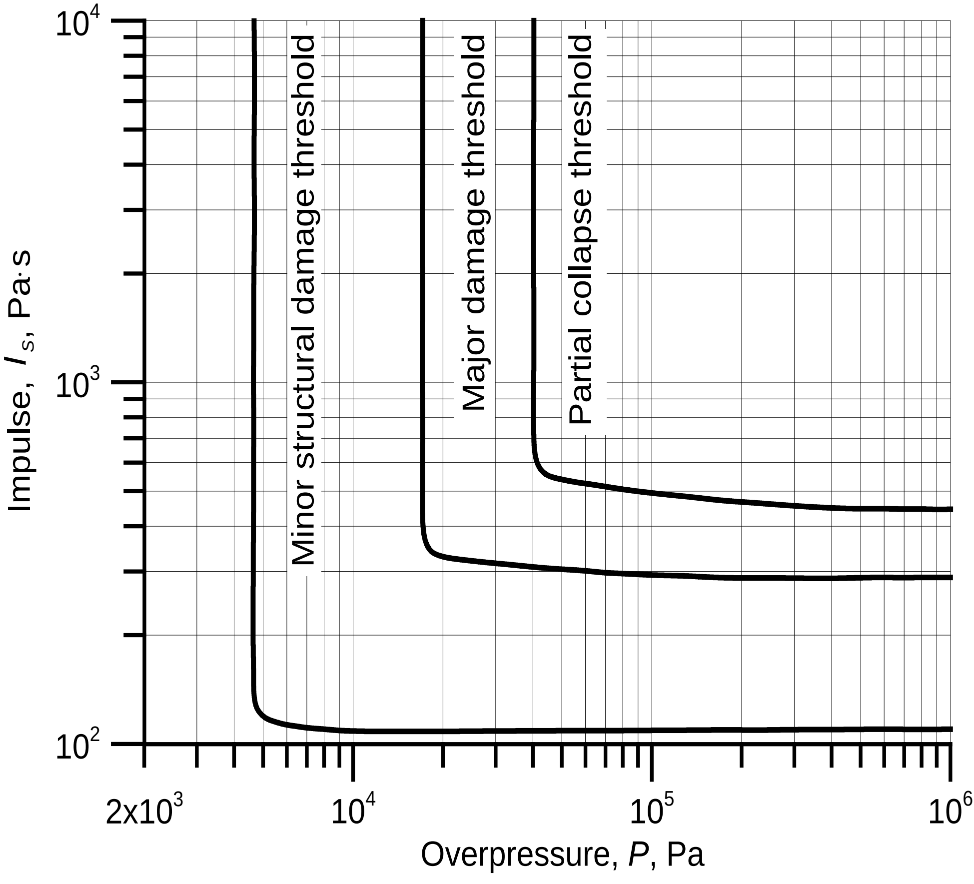
Harm criteria

On human



On building



Separation from a vehicle

- **Car** with on-board hydrogen tank of **205 L** volume and **35.7 MPa** storage pressure (for test No.2: derived by the inverse problem method parameters α=*0.12* and β=*0.09*):
  - Eardrum rupture – **10.4 m**
  - Minor damage to building – **3.5 m**
  - Partial demolition – **0.57 m**
- **Scooter** with on-board hydrogen tank of **12 L** volume and **70 MPa** storage pressure:
  - Eardrum rupture – **4.3 m**
  - Minor damage to building – **0.45 m**

Separation from a tank at RS

Harm criteria	Storage volume	
	10 m^3	1 m^3
Eardrum rupture	49 m	22.8 m
Skull fracture	8.5 m	2.4 m
Lung damage	7.9 m	3.7 m
Lethality (body translation)	5.2 m	1.6 m
Minor damage to building	191 m	40 m
50-75% of building demolition	36.7 m	5.9 m

Increase fire resistance of tanks (until fire is finished or is taken under control)!

Concluding remarks

- The existing methodology to calculate a blast wave decay from a high pressure gas tank rupture (physical explosion) is presented, poor predictive capabilities are revealed especially for under-vehicle tank fire test.
- A new model accounting for contribution of hydrogen combustion to the blast wave strength is developed and validated against two available tests.
- The model can be applied as a hydrogen safety engineering tool to calculate deterministic separation distance from a vehicle when an on-board storage tank or a stand-alone tank rupture in a fire (using published information on harm effects).
- More experiments are needed for rupture in a fire of stand-alone and under-vehicle tanks.

Acknowledgment to EPSRC for funding SUPERGEN HFC Hub project and EPSRC Challenge "Integrated safety strategies for hydrogen storage…" project, and FCH JU for funding the HyResponse project (www.hyresponse.eu)

MSc in Hydrogen Safety Engineering (distance learning course):
http://www.ulster.ac.uk/elearning/programmes/view/course/10139

Fundamentals of Hydrogen Safety Engineering (free eBook, http://bookboon.com, search "hydrogen", available since October 2012)