

# Gas Phase Detonations: Effective Pressures Acting on the Walls of the Enclosures and Probability of Deflagration-to-Detonation Transition in Pipes, Vessels and Packings

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ACHEMA 2018, Building: CMF Congress Centre, Lecture room: Illusion 2

# Overview

- Brief background info: deflagrative and detonative explosions in gaseous mixtures
- Motivation
- Detonations in pipes
- Detonations in empty vessels (i.e. no turbulence enhancing elements inside)
- Detonations in vessels filled with dry packings
- Detonations in vessels filled with irrigated packing
- Detonations in bubble swarms rising upwards in a liquid
- Particularly dangerous geometries in context with detonations
- Present status of adopting the pipe results in regulation, guidelines, standards etc.

# Gas Phase Explosion (Self-sustaining flame front)

$v_{\text{flame}} < v_{\text{sound}}$   
(typically: 0.5 – 10 m/s)

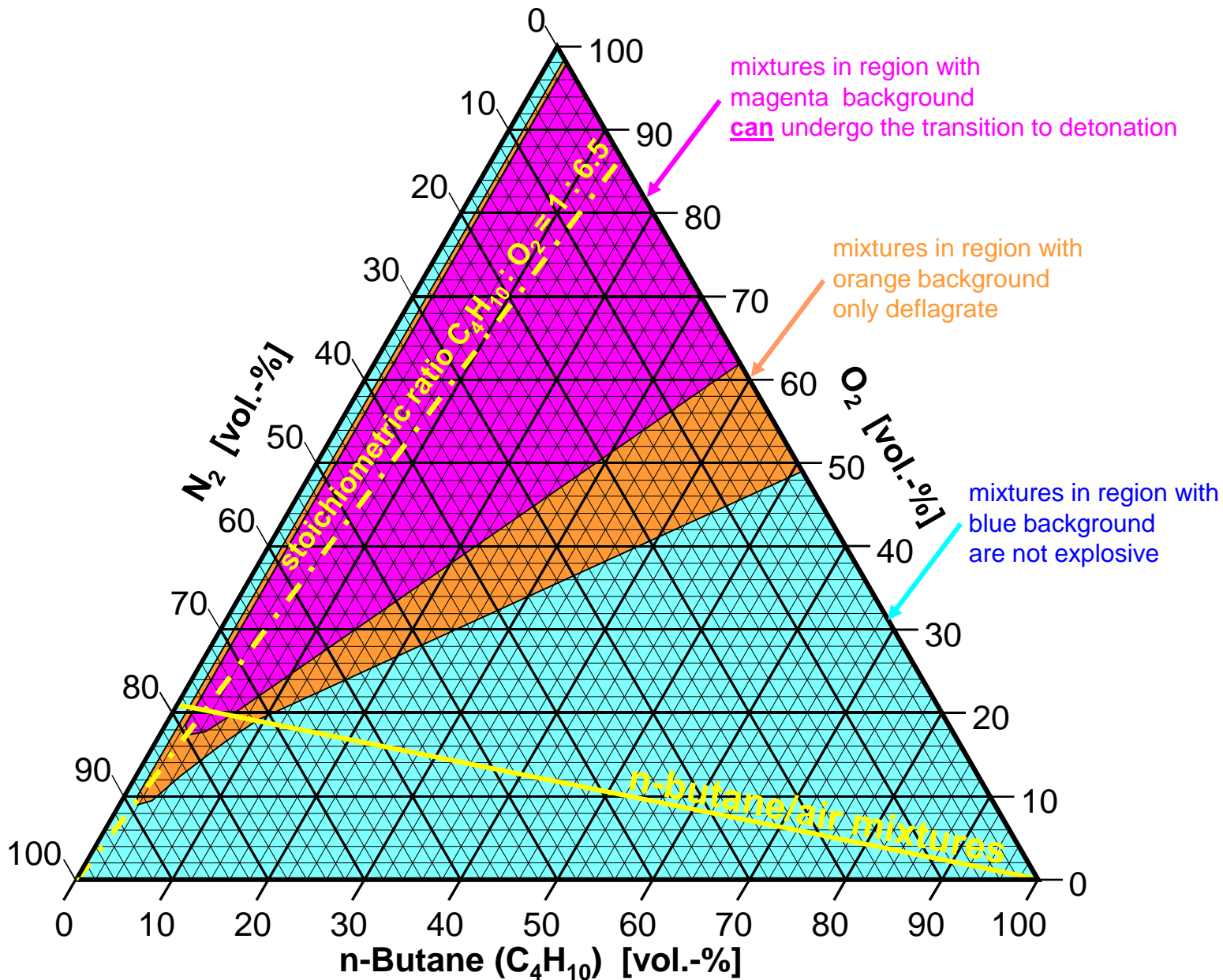
$v_{\text{flame}} > v_{\text{sound}}$   
(typically: 1600 – 2800 m/s)

## Deflagration

## Detonation

occurrence of shock wave:	no	yes
mechanisms for triggering the reaction in the unburnt mixture	<ul style="list-style-type: none"> <li>• transfer of heat from flame front to unburnt mixture</li> <li>• diffusion of radicals from flamefront into unburnt mixture</li> </ul>	adiabatic compression by shock wave heats up gas mixture to $T \gg T_{\text{autoignition}}$ (flame front is coupled to shock front)
propagation speed of pressure $v_{\text{pressure}}$ :	$v_{\text{pressure}} = v_{\text{sound}}$	$v_{\text{pressure}} = v_{\text{flame}} > v_{\text{sound}}$
pressure venting:	possible	not possible ( $v_{\text{flame}} > v_{\text{sound}}$ !!)
explosion pressure ratio $r = p_{\text{ex}}/p_{\text{initial}}$ :	$r \leq 25$	much larger than for deflagrations
influence of geometry of enclosure on $r = p_{\text{ex}}/p_{\text{initial}}$ :	no	yes, substantial
spatial pressure distribution:	same pressure at any location ( $\Rightarrow$ no net force on containment)	substantial differences between pressures at different locations ( huge net forces on containment)

# Example: Deflagrative and potentially detonative explosion regime of n-Butane/O<sub>2</sub>/N<sub>2</sub> at 1 bar abs, 20 °C



# Practical demonstration: Transition from deflagrative to detonative explosion of a gaseous mixture in a long pipe



Deflagration to Detonation transition in almost stoichiometric propane/air-mixture at about  $90 \cdot \phi_i$  distance to point of ignition (=1.8 m), 3 bar abs, 15°C, pipelength = 4 m,  $\phi_i = 20$  mm

4.9 vol.-%  $C_3H_8$ , Versuch 9, slow motion



Versuch9 Propan 4.9 O2 95.1, 3 bar abs,-84000-FPS.wmv

4.9 vol.-%  $C_3H_8$ , Versuch 9, real time



Versuch9 Propan 4.9 O2 95.1, 3 bar abs,-Echtzeit.wmv

4.03 vol.-%  $C_3H_8$ , Versuch 7, slow motion



Versuch7 Propan 4 O2 96, 3 bar abs,100000-FPS.wmv

4.03 vol.-%  $C_3H_8$ , Versuch 7, real time

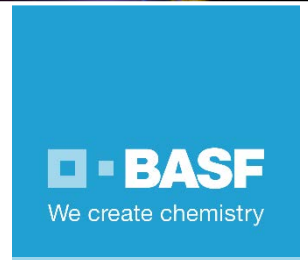
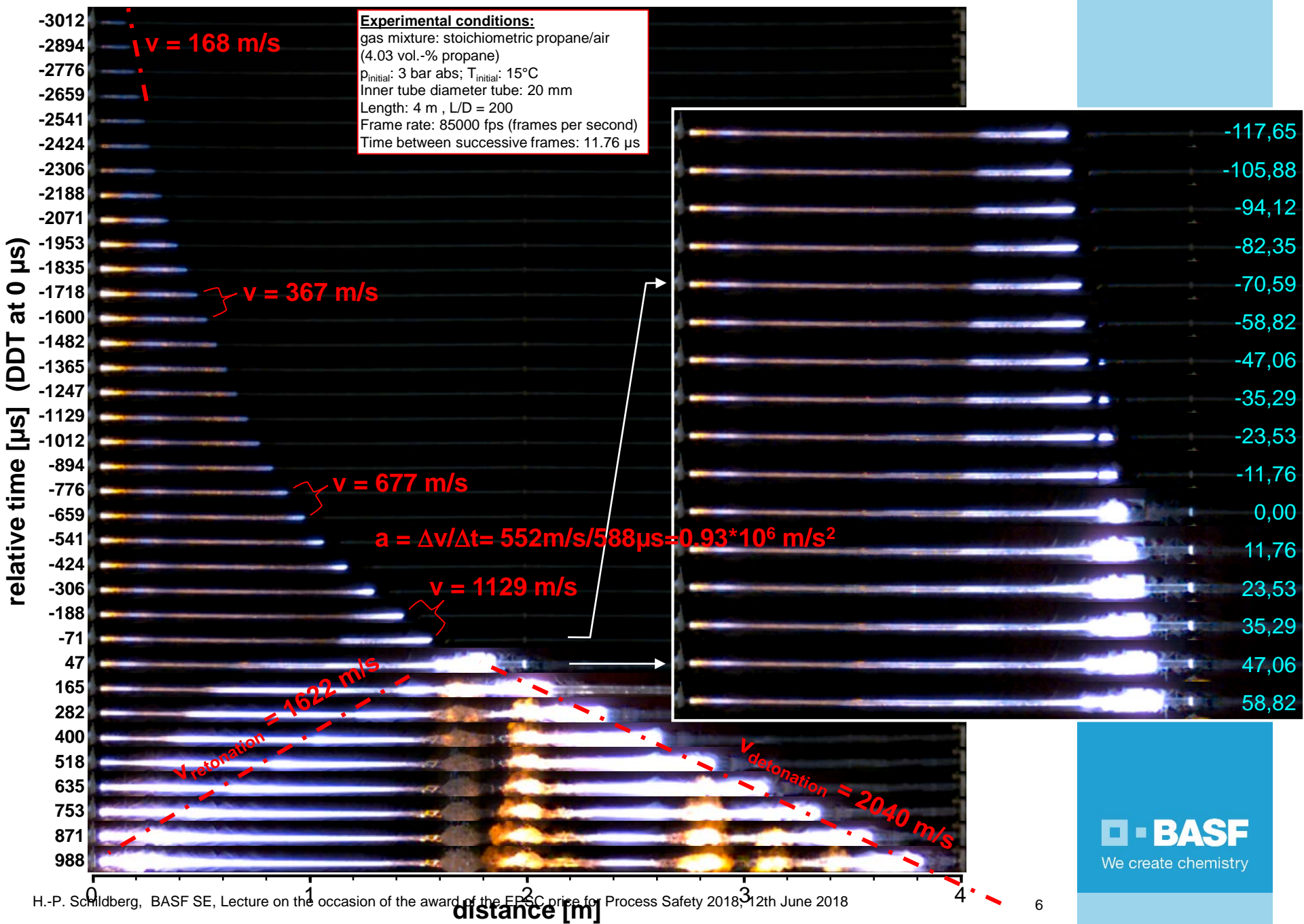


Versuch7 Propan 4 O2 96, 3 bar abs,-Echtzeit.wmv

Note: stoichiometric concentration of propane in air is 4.03 vol.-%



# DDT in propane/air at 3 bar abs, 15 °C (Versuch 9)



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# Motivation

- In chemical process plants **detonable gas mixtures do occur** and effective ignition sources can, in general, not be ruled out with certainty
- The sole safety concept in this case is **explosion pressure proof design** of the affected plant components
- Worldwide there are **no guidelines published** by standardization organizations or interest groups (ISO, NFPA, ASME, CGA, CEN, EIGA, BSI, DIN, VDI) for explosion pressure proof design against the load generated by gas phase detonations
- Scientific literature:
  - **Focussed** mainly on the explosive mixture itself, **not on the interaction mixture-enclosure**
  - pressure/space/time profiles only understood for the two most simple detonative pressure scenarios with lowest pressure generation . **No systematic classification of the remaining scenarios, not to mention their pressure/space/time profiles**



**BASF started research in 2008 aimed at developing a guideline for detonation pressure proof pipe design.**



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# Main results of the work on detonations in pipes

- Detonations in pipes can be described by 8 distinctly different pressure scenarios:
  - 4 Scenarios in “*long*” pipes
  - 4 Scenarios in “*short*” pipes
- 6 scenarios are design-relevant
- An experimental method (“*pipe wall deformation method*”) was established to directly determine the “*static equivalent pressures*” of each detonative scenario
- Once the static equivalent pressures are known, the classical pressure vessel formulae, which can only cope with static loads, can be applied for detonation pressure resistant design
- Results can be generalized to apply to any combustible/O<sub>2</sub>/N<sub>2</sub> mixture by a parameter **R**, whose typical variation over the entire explosion triangle is provided.

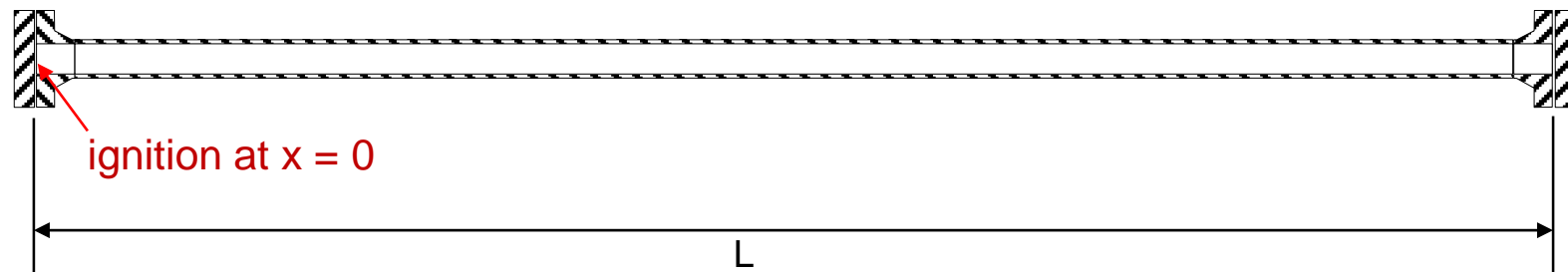
# Publications with Experimental Results

- [1] H.P. Schildberg, J. Smeulers, G. Pape, *Experimental determination of the static equivalent pressure of gas phase detonations in pipes and comparison with numerical models*, Proceedings of ASME **2013** Pressure Vessels and Piping Conference, *Proc. ASME*. 55690, Volume 5: High-Pressure Technology, ISBN: 978-0-7918-5569-0; doi: 10.1115/PVP2013-97677  
(Paper No. PVP2013-97677, pp. V005T05A020; 15 pages; conference from July 14-18, 2013, Paris, France)
- [2] H.P. Schildberg, *Experimental determination of the static equivalent pressure of detonative decompositions of acetylene in long pipes and Chapman-Jouguet pressure ratio*, Proceedings of ASME **2014** Pressure Vessels and Piping Conference, *Proc. ASME*. 46025, Volume 5: High-Pressure Technology, ISBN: 978-0-7918-4602-5; doi: 10.1115/PVP2014-28197  
(Paper No. PVP2014-28197, pp. V005T05A018; 13 pages; conference from July 20-24, 2014, Anaheim, California, USA)
- [3] H.P. Schildberg, *Experimental Determination of the Static Equivalent Pressures of detonative Explosions of Stoichiometric  $H_2/O_2/N_2$ -Mixtures in Long and Short pipes*, Proceedings of the ASME **2015** Pressure Vessels and Piping Conference, *Proc. ASME*. 56987; Volume 5: High-Pressure Technology; Rudy Scavuzzo Student Paper Competition and 23<sup>rd</sup> Annual Student Paper Competition; ASME NDE Division, V005T05A015. July 19, 2015, PVP2015-45286, doi: 10.1115/PVP2015-45286  
(Paper No. PVP2015-45286, 13 pages, conference from July 19-23, 2015, Boston, Massachusetts, USA)
- [4] H.P. Schildberg, *Experimental Determination of the Static Equivalent Pressures of Detonative Explosions of Stoichiometric  $CH_4/O_2/N_2$ -Mixtures and of  $CH_4/O_2$ -Mixtures in Long Pipes*, Proceedings of the ASME **2016** Pressure Vessels and Piping Conference,  
(Paper No. PVP2016-63223, 14 pages, conference from July 17 - 21, 2016, Vancouver, BC, Canada)
- [5] H.P. Schildberg, *Experimental Determination of the Static Equivalent Pressures of Detonative Explosions of Stoichiometric  $C_2H_4/O_2/N_2$ -Mixtures and of  $C_2H_4/O_2$ -Mixtures in Long Pipes and of stoichiometric  $C_6H_{12}/O_2/N_2$  Mixtures in long and short pipes*  
(to be published in Proceedings of the ASME **2018** Pressure Vessels and Piping Conference)

# Publications giving a General Overview

- [7] H.P. Schildberg, Gas phase detonations in pipes: the 8 possible different pressure scenarios and their static equivalent pressures determined by the pipe wall deformation method. (part 1), Chemical Engineering Transactions, 48, 241-246; DOI:10.3303/CET1648041  
(Proceedings of the 15th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, 5.6.-8.6.2016, Freiburg, Germany. Guest Editors: Eddy de Rademaeker, Peter Schmelzer, Copyright © 2016, AIDIC Servizi S.r.l., ISBN 978-88-95608-39-6; ISSN 2283-9216)
- [8] H.P. Schildberg, Gas phase detonations in pipes: the 8 possible different pressure scenarios and their static equivalent pressures determined by the pipe wall deformation method. (part 2), Chemical Engineering Transactions, 48, 247-252; DOI:10.3303/CET1648042  
(Proceedings of the 15th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, 5.6.-8.6.2016, Freiburg, Germany. Guest Editors: Eddy de Rademaeker, Peter Schmelzer Copyright © 2016, AIDIC Servizi S.r.l., ISBN 978-88-95608-39-6; ISSN 2283-9216)
- [9] Technische Regel für Gefahrstoffe 407 (TRGS 407), Tätigkeiten mit Gasen – Gefährdungsbeurteilung, Gemeinsames Ministerialblatt Nr. 12-17 (26.04.2016), p. 328 – 364, ISSN 0939-4729  
Note 1: In the attachment A4 (page 48 – 56 of TRGS 407) the pressure scenarios in long pipes and their static equivalent pressure are for the first time mentioned in a guideline (here only related to detonative decompositions of acetylene).  
Note 2: The TRGS 407 is published by German Bundesministerium für Arbeit und Soziales (Federal Ministry for Work and Social Affairs).  
Note 3: Das Gemeinsame Ministerialblatt (GMBI) ist das amtliche Publikationsorgan der Bundesregierung und wird vom Bundesministerium des Innern seit 1950 herausgegeben. Hier veröffentlichen nahezu alle Bundesministerien die von ihnen erlassenen oder ergänzten Allgemeinen Verwaltungsvorschriften, Verordnungen, Richtlinien, Erlasse, Anordnungen, Rundschreiben und Bekanntmachungen von allgemeiner Bedeutung sowie Stellenausschreibungen einschließlich ihres nachgeordneten Bereichs.

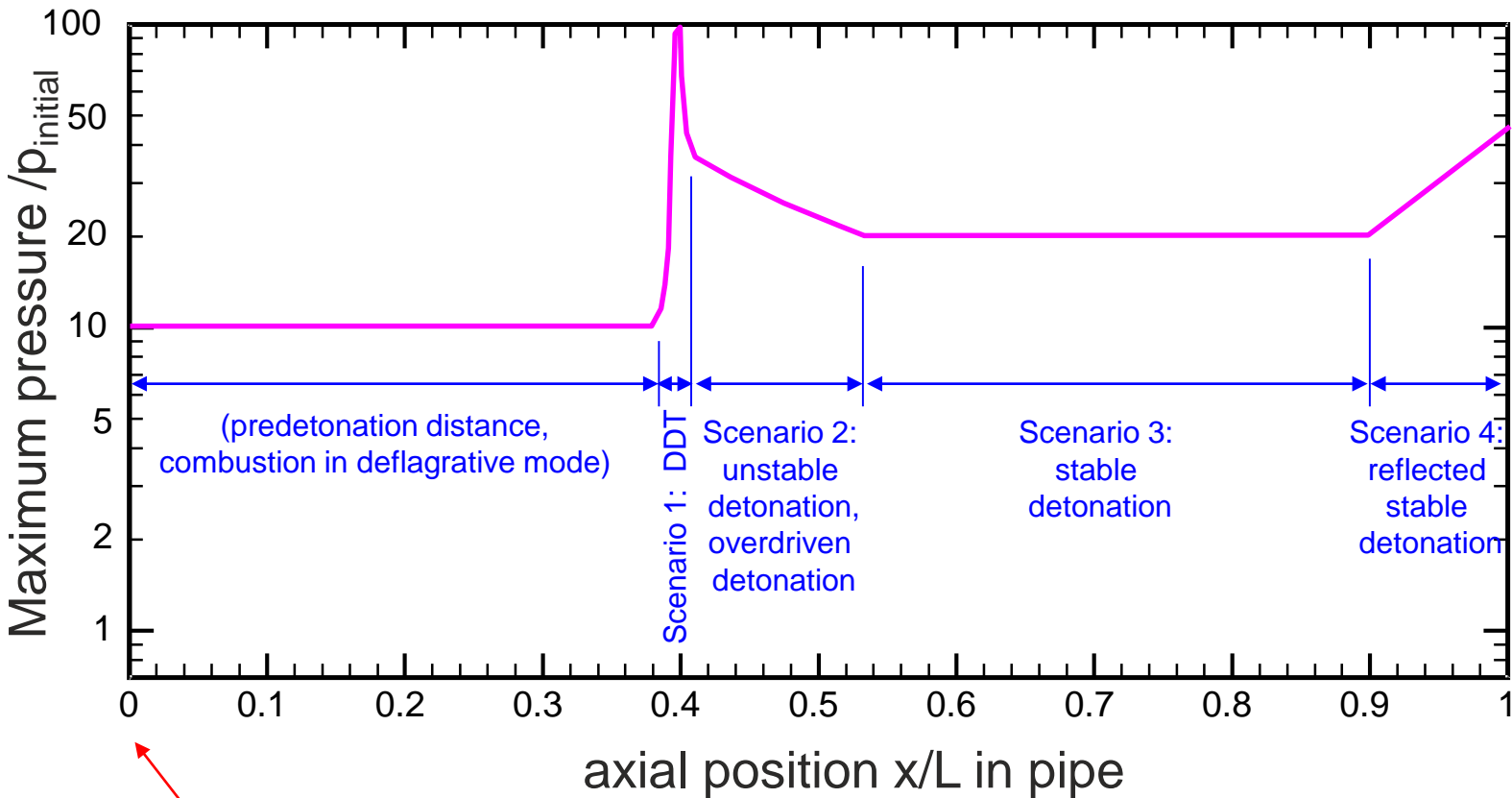
# Help to visualize the different detonative pressure scenarios



**1<sup>st</sup> step:** trigger an explosion with transition to detonation inside a pipe

**2<sup>nd</sup> step:** record the maximum pressure ratios found in the pipe at any axial position during the course of the explosion

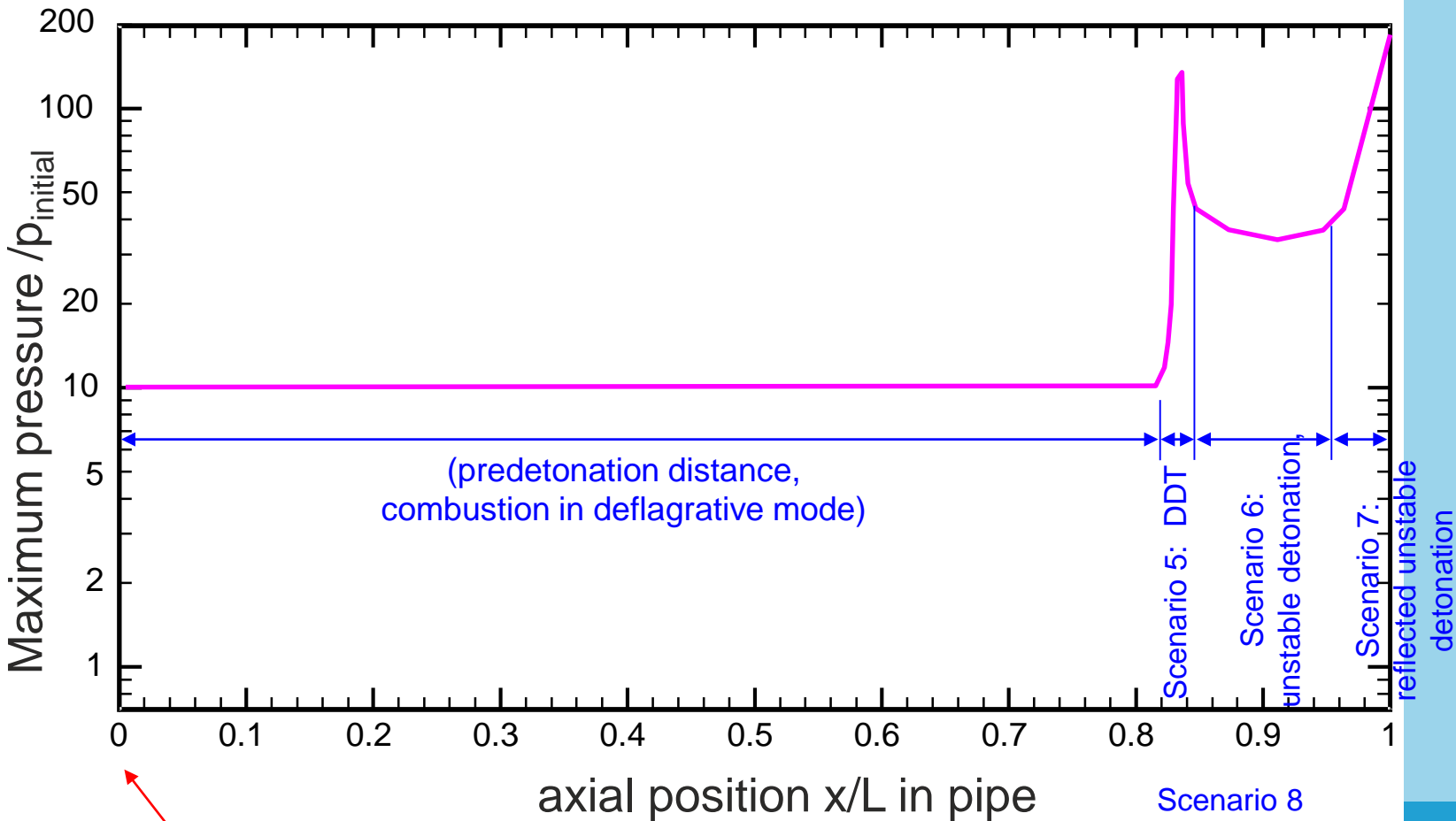
# Maximum pressure ratios found in a long pipe at different axial positions in the course of an explosion involving a transition from deflagration to detonation (schematic)



ignition at  $x = 0$

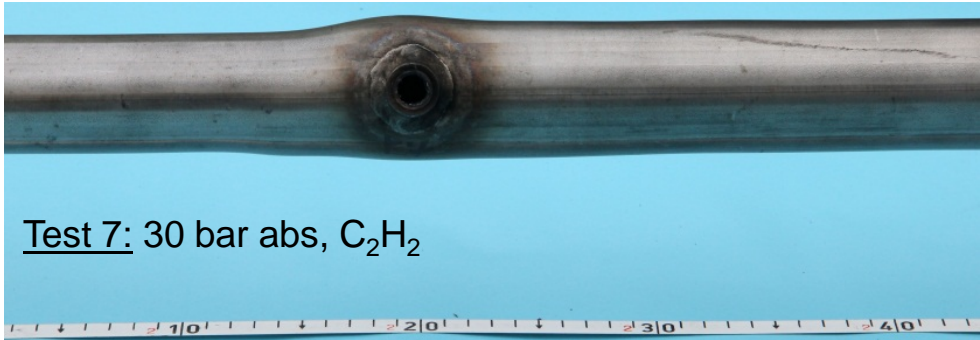


# Maximum pressure ratios found in a short pipe at different axial positions in the course of an explosion involving a transition from deflagration to detonation (schematic)

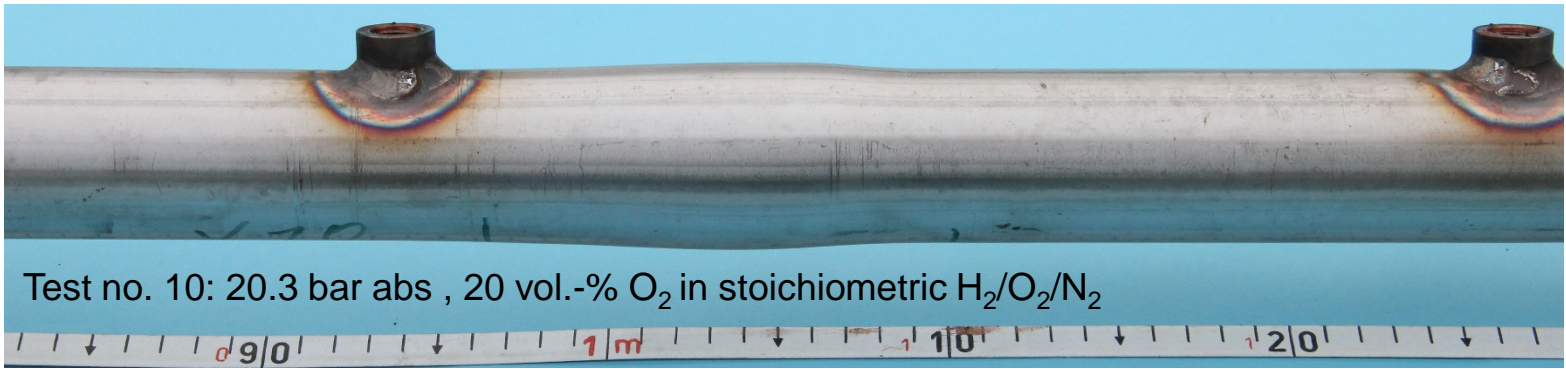


Scenario 8  
(not displayed in the above sketch):  
Coalescence of 5 and 7 under  
omission of 6, i. e. DDT occurs  
directly ahead of blind flange

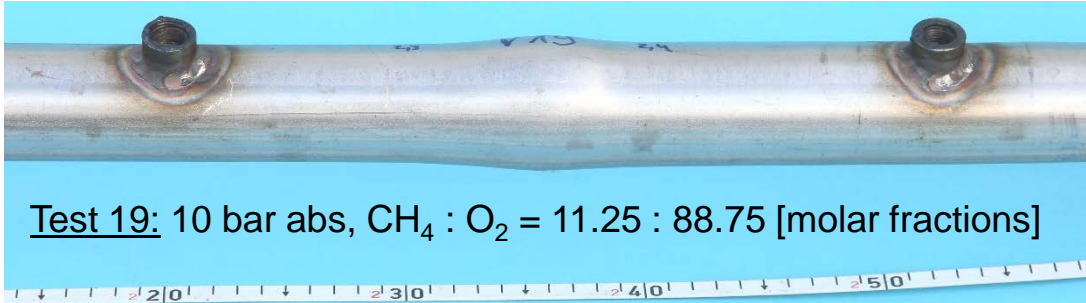
# Example: bulging in long pipes at DDT (scenario 1)



Test 7: 30 bar abs, C<sub>2</sub>H<sub>2</sub>



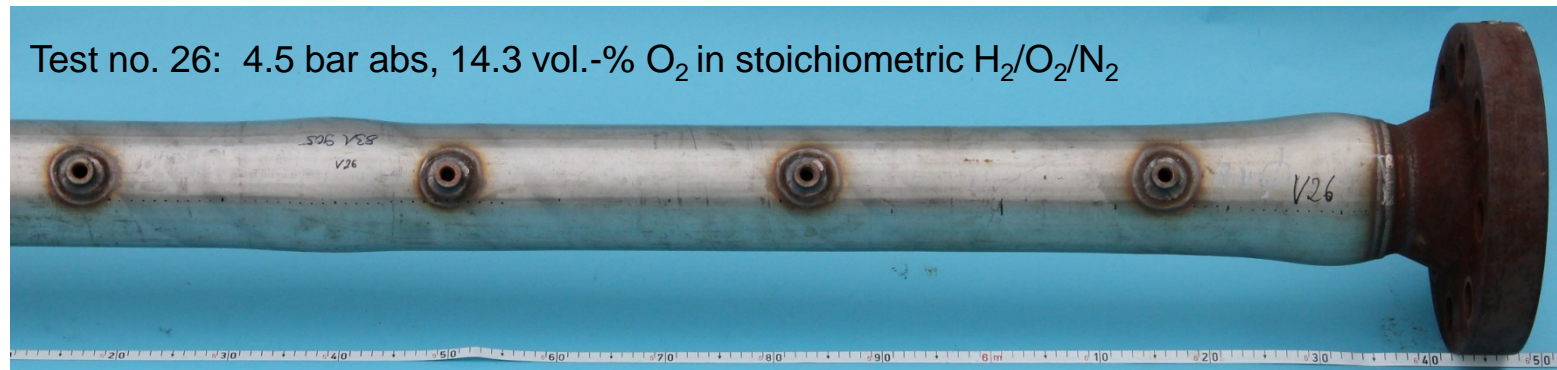
Test no. 10: 20.3 bar abs , 20 vol.-% O<sub>2</sub> in stoichiometric H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub>



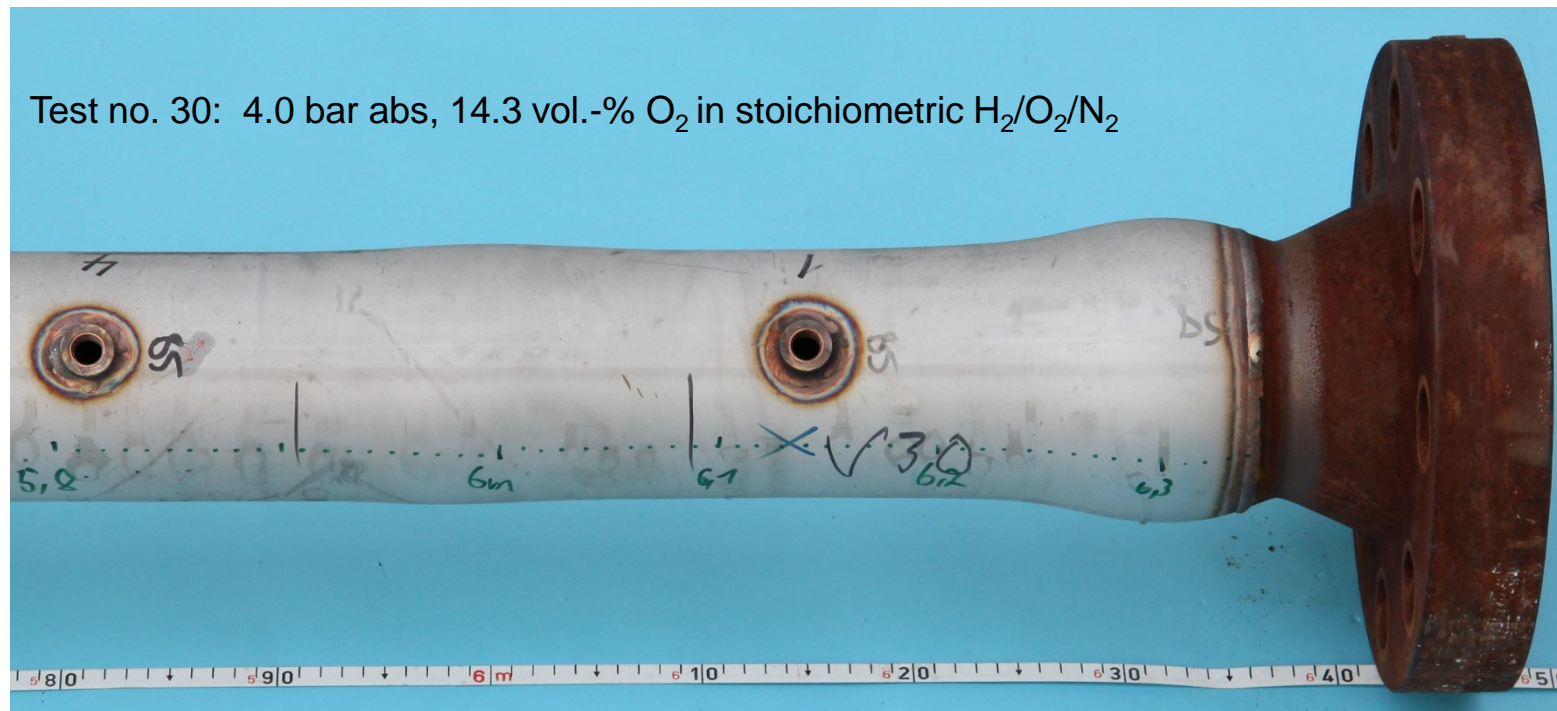
Test 19: 10 bar abs, CH<sub>4</sub> : O<sub>2</sub> = 11.25 : 88.75 [molar fractions]

# Example: bulging in short pipes (scenario 5 and 7)

Test no. 26: 4.5 bar abs, 14.3 vol.-% O<sub>2</sub> in stoichiometric H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub>



Test no. 30: 4.0 bar abs, 14.3 vol.-% O<sub>2</sub> in stoichiometric H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub>





# Example: bulging in short pipes (scenario 8)

## Test no. 28:

4.5 bar abs,  
14.05 vol.-% O<sub>2</sub>  
in stoichiometric  
H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub>



## Test no. 29:

4.63 bar abs,  
14.175 vol.-% O<sub>2</sub>  
in stoichiometric  
H<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub>



# Static equivalent pressures for the 8 detonative pressure scenarios in pipes

Type of pressure scenario			Static equivalent pressures for any detonable gas mixture
no.	pipe	name	
1	long pipe	DDT	$p_{stat\_DDT\_long} = R \cdot p_{stat\_stable}$
2		unstable detonation	(irrelevant for pipe design)
3		stable detonation	$p_{stat\_stable} = \alpha \cdot p_{CJ\_r} \cdot p_{initial}$
4		reflected stable detonation	$p_{stat\_reflected\_stable} = 2.4 \cdot p_{stat\_stable}$
5	short pipe	DDT	$p_{stat\_DDT\_short} = 1.5 \cdot p_{stat\_DDT\_long}$ $= 1.5 \cdot R \cdot p_{stat\_stable}$
6		unstable detonation	(irrelevant for pipe design)
7		reflected unstable detonation	$p_{stat\_reflected\_instable} = 1.5 \cdot 2 \cdot p_{stat\_reflected\_stable}$ $= 1.5 \cdot 2 \cdot 2.4 \cdot p_{stat\_stable}$
8		coincidence of DDT and reflection	$p_{stat\_coincidence\_DDT\_reflection} = 2.4 \cdot p_{stat\_DDT\_short}$ $= 2.4 \cdot 1.5 \cdot p_{stat\_DDT\_long}$ $= 2.4 \cdot 1.5 \cdot R \cdot p_{stat\_stable}$

} Factor **R** depends on reactivity of gas mixture

} Formulae for  $p_{stat}$  are valid for any other explosive gas mixture at any  $p_{initial}$  and  $T_{initial}$ .

} Short pipe scenario can be predicted based on long pipe scenarios 1 and 3

## Note:

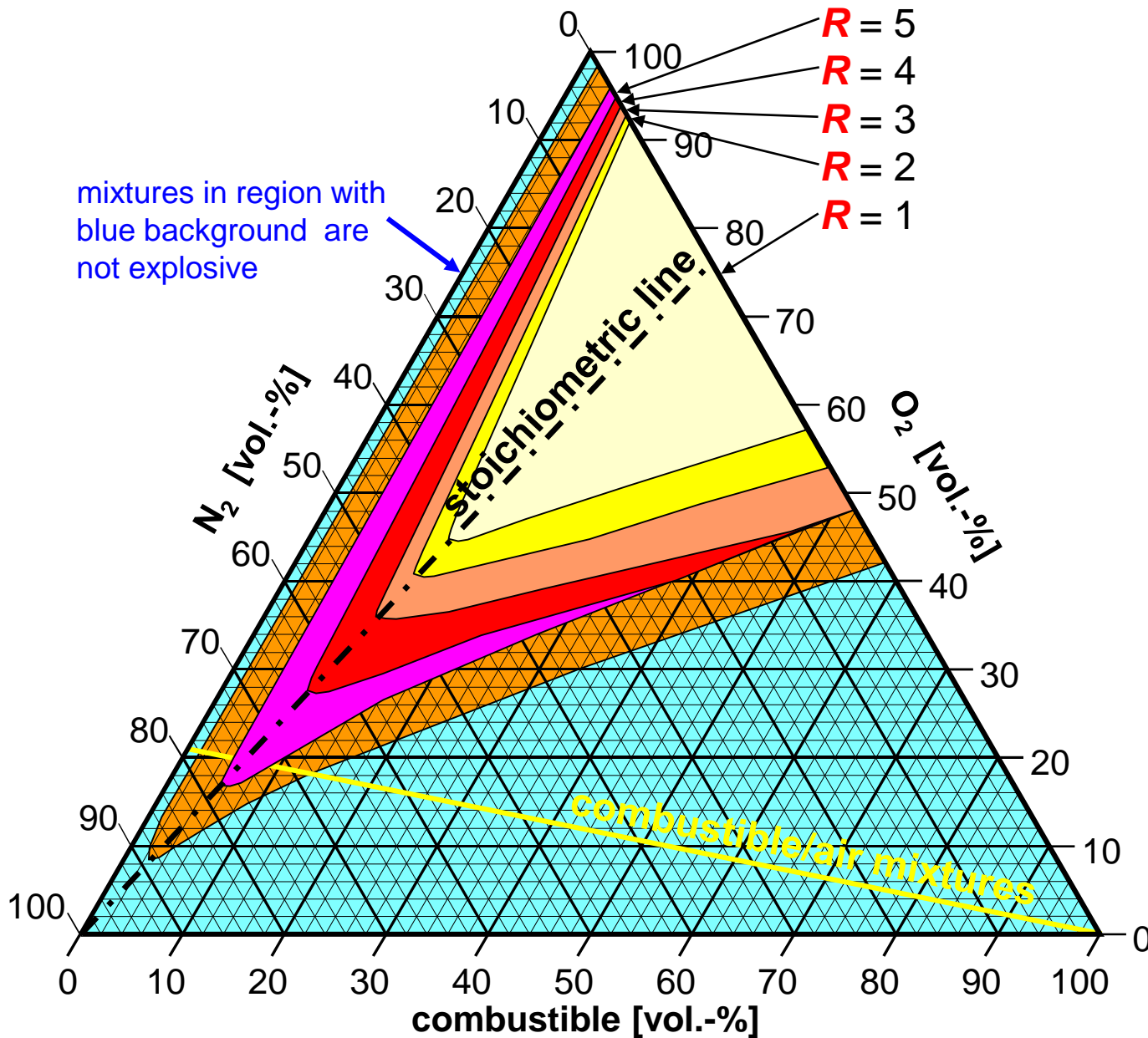
- $\alpha = 0.7$  (valid in general)
- $p_{CJ\_r}$  of the mixture can be calculated (based on combustion enthalpy, mean molar mass and  $c_p/c_v$ -values)
- 2.4 applies for reflection of the stable detonation and is assumed to also apply for reflection of instable detonations and DDT's
- **R** must be determined experimentally (ratio between effective load at DDT and effective load for stable deto.)
- justification for using factors 1.5 and 2 -> next slide

# Example: static equivalent pressures measured for detonations of stoichiometric Ethylene/air mixtures at 15°C

Type of pressure scenario			$p_{\text{stat}}$ (expressed as multiple of $p_{\text{initial}}$ )
no.	pipe	name	
1	long pipe	DDT	64.6
2		unstable detonation	-
3		stable detonation	13.2
4		reflected stable detonation	33
5	short pipe	DDT	81.8
6		unstable detonation	-
7		reflected unstable detonation	128
8		coincidence of DDT and reflection	232



# Variation of R over the explosive range of a ternary mixture of type combustible/O<sub>2</sub>/N<sub>2</sub> (tentative)



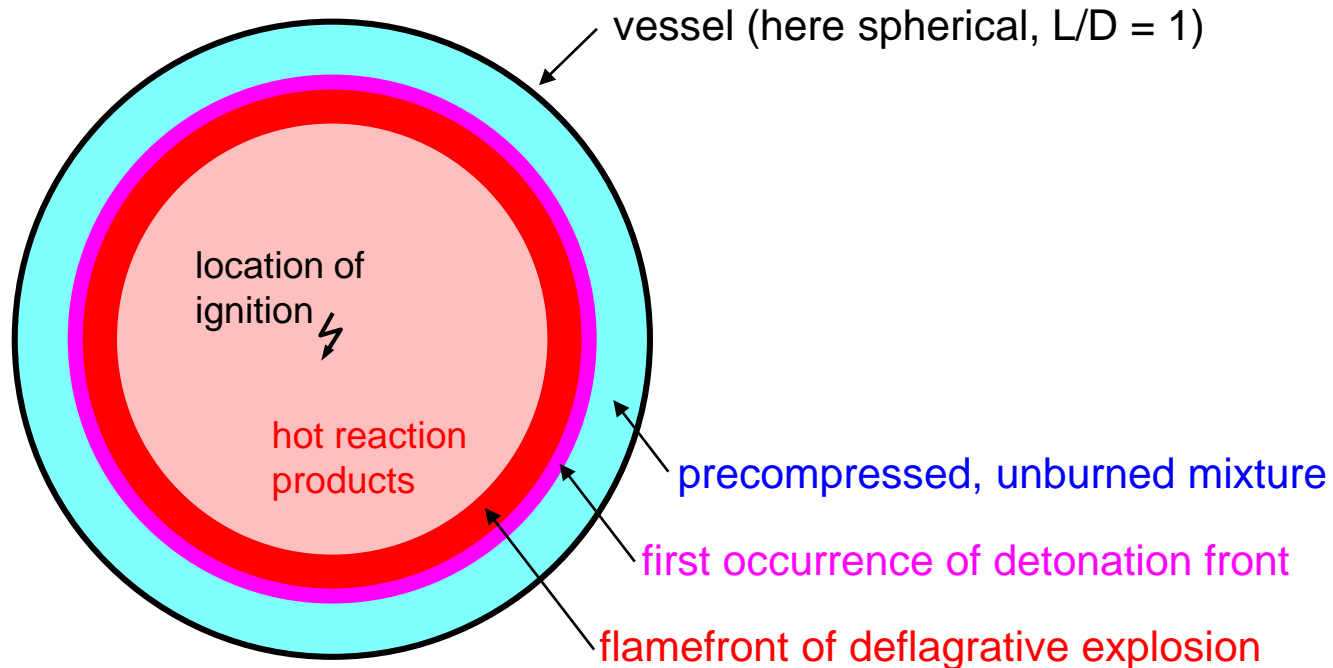
mixtures in region with blue background are not explosive

- R = 5
- R = 4
- R = 3
- R = 2
- R = 1

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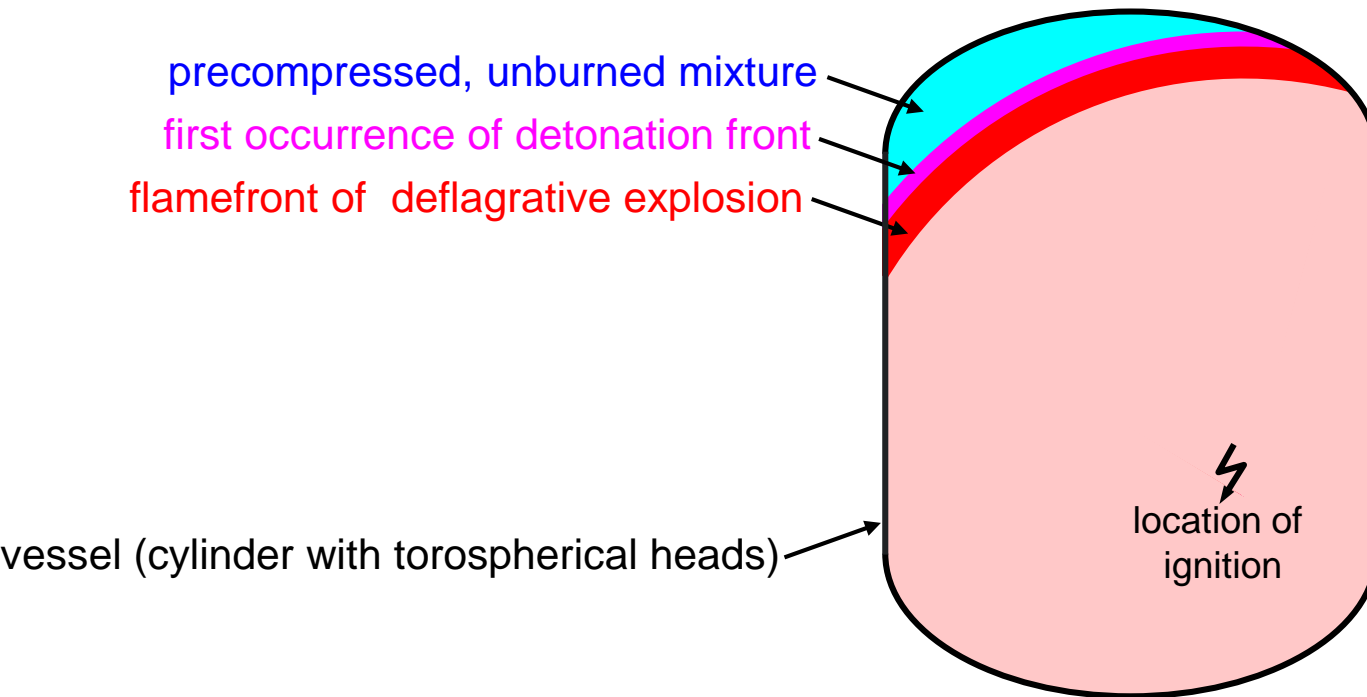
# Fundamental problem when deflagration to detonation transitions occur in empty vessels



If there is a transition from deflagration to detonation in the vessel, precompression will almost always occur, because the diameter is usually not much larger than the predetonation distance. The precompression factor may attain the highest possible value, i. e. the deflagration pressure ratio.

Note that the detonation propagates faster than the speed of sound in the reaction gases, i.e. pressure relief into the central section of the vessel occurs after the wall has „seen“ the detonative pressure peak

# Schematic sketch of an explosion with DDT inside a vessel



If a DDT occurs at this time instant, maximum pressure loads can be expected, because the unreacted mixture is almost precompressed to  $r \cdot p_{\text{initial}}$   
( $r$  denotes the deflagration pressure ratio,  $p_{\text{initial}}$  the pressure in the vessel at the moment of ignition)

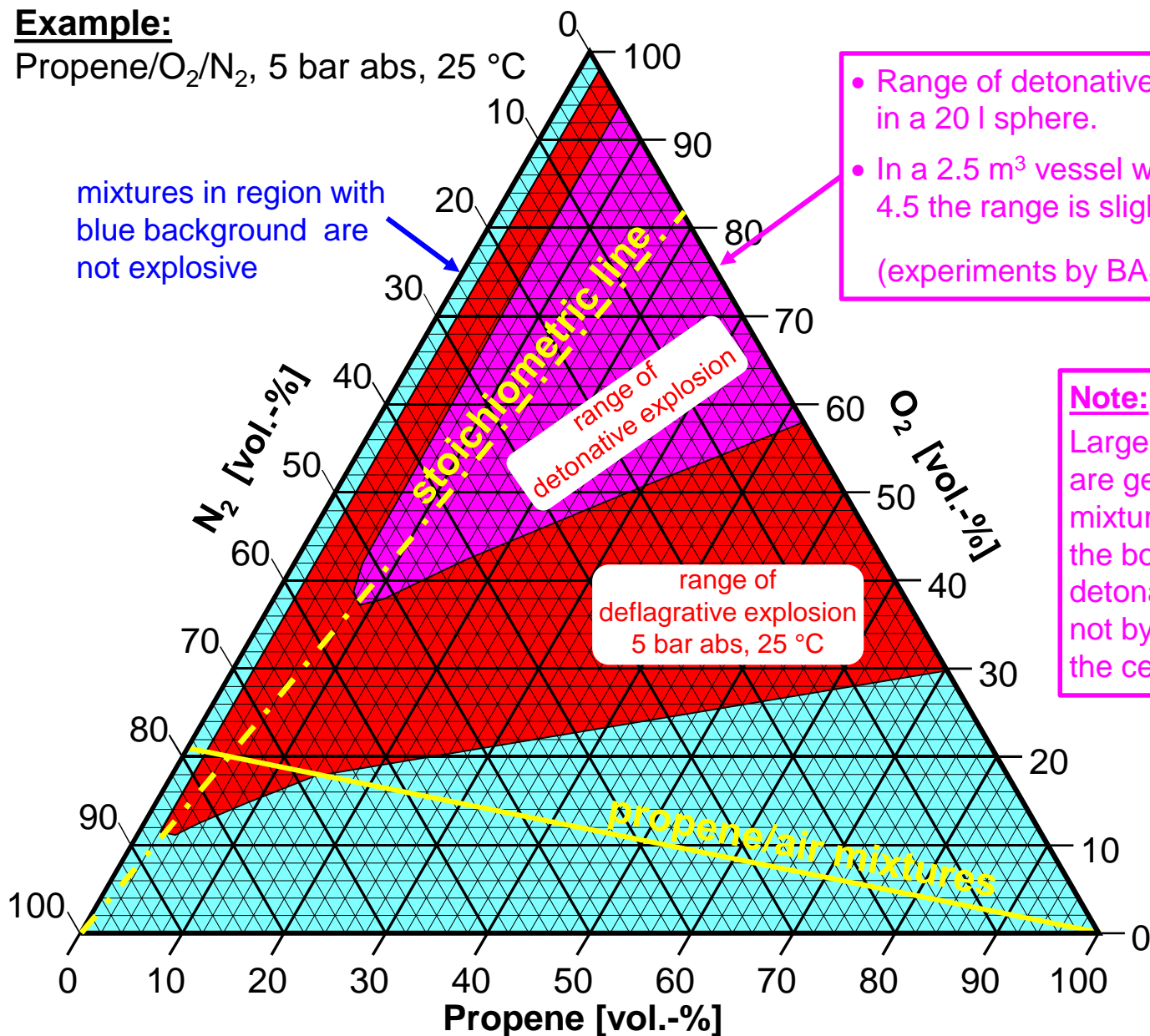
Note that the detonation propagates faster than the speed of sound in the reaction gases, i.e. pressure relief into the lower section of the vessel occurs after the wall in the upper left section has „seen“ the detonative pressure peak

# Mixtures which undergo a DDT inside vessels

## Example:

Propene/O<sub>2</sub>/N<sub>2</sub>, 5 bar abs, 25 °C

mixtures in region with blue background are not explosive

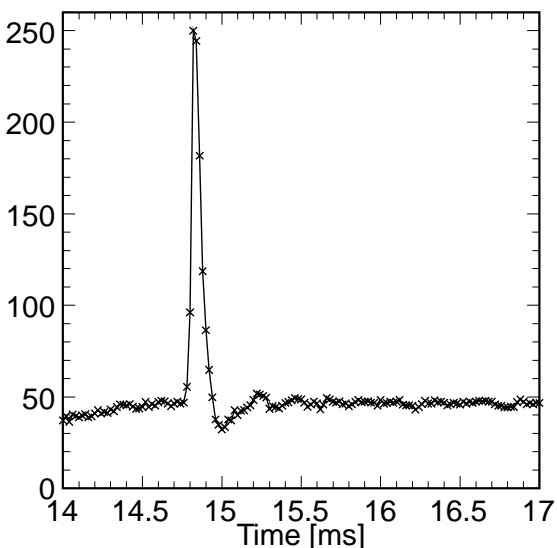
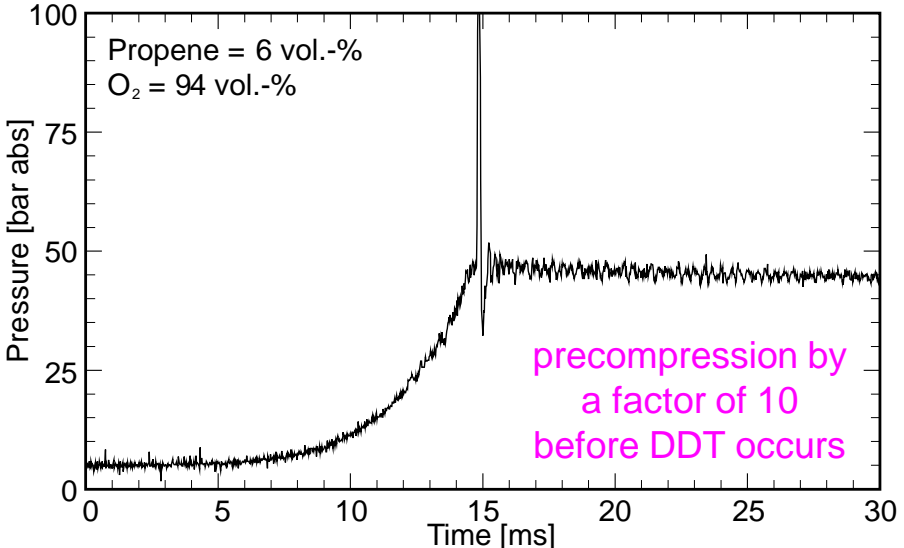
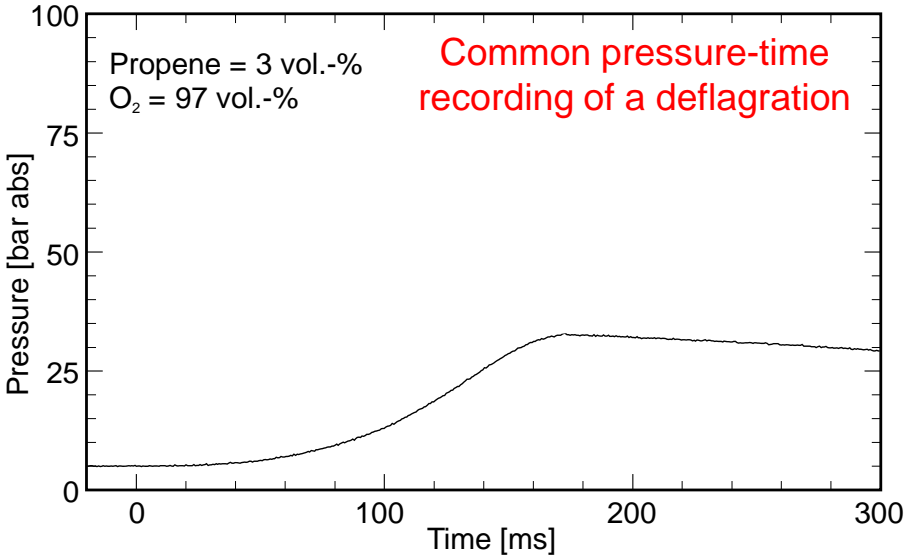


- Range of detonative explosions in a 20 l sphere.
- In a 2.5 m<sup>3</sup> vessel with L/D  $\cong$  4.5 the range is slightly larger.  
(experiments by BASF)

## Note:

Largest pressures are generated by mixtures close to the border of the detonative range, not by mixtures in the center !!!!!

# Pressure/Time recordings of explosions of Propene/O<sub>2</sub>-mixtures at 5 bar abs, 20°C in a 20 l sphere (1/2)

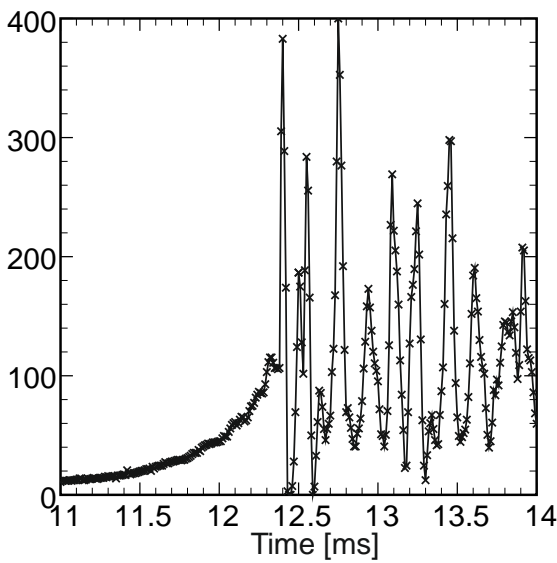
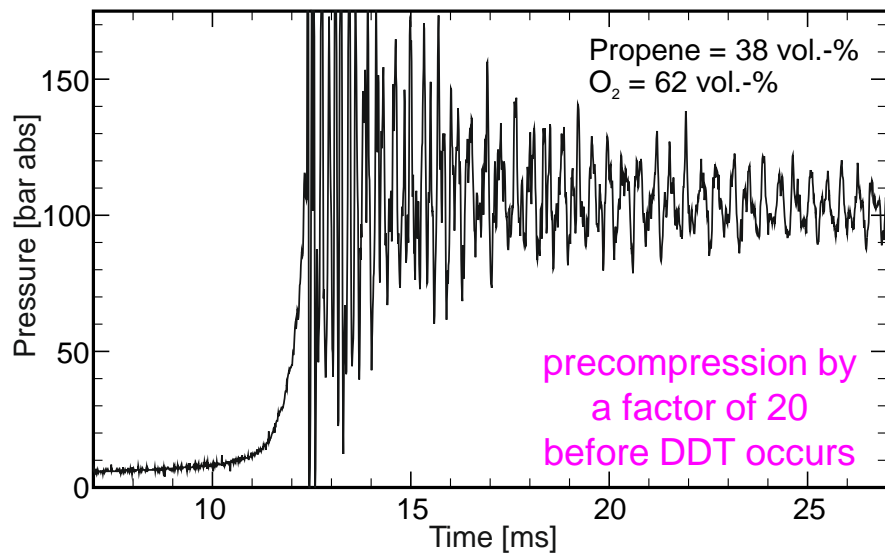
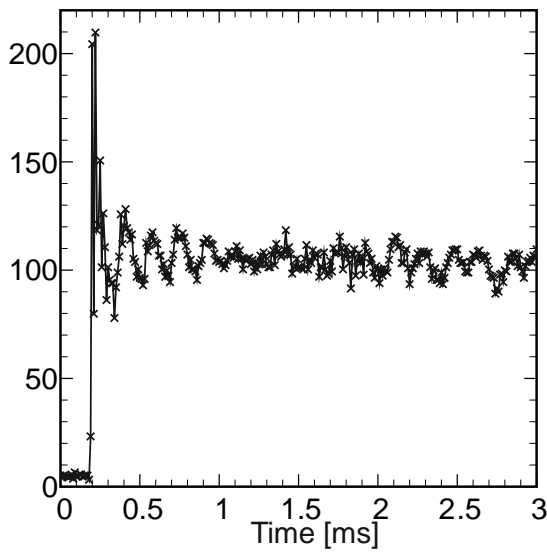
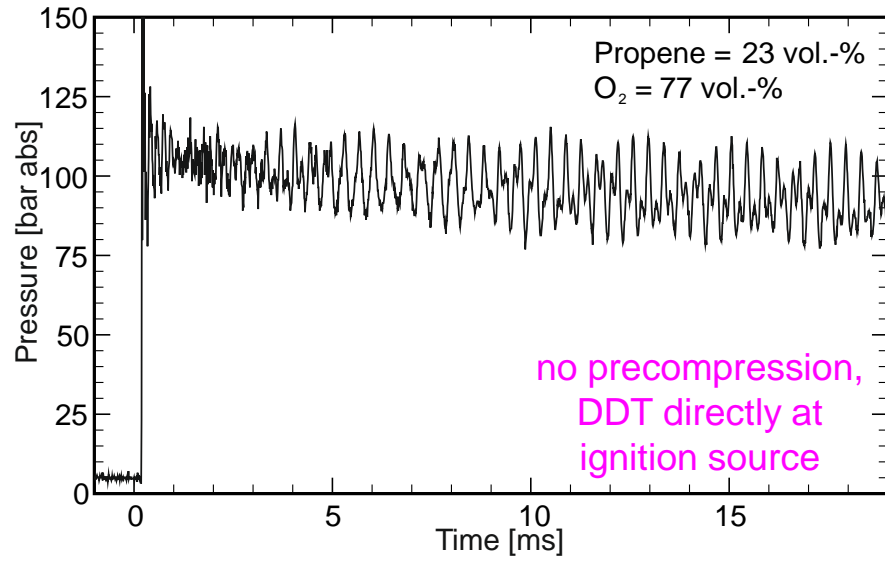


Reference: "The course of the explosions of combustible/O<sub>2</sub>/N<sub>2</sub> mixtures in vessel-like geometry", H.-P. Schildberg, Forschung im Ingenieurwesen (2009) 73, 33-65, DOI 10.1007/s10010-009-0091-6





# Pressure/Time recordings of explosions of Propene/O<sub>2</sub>-mixtures at 5 bar abs, 20°C in a 20 l sphere (2/2)



# Fundamental questions when quantifying hazards associated with potential detonations in vessels

- Under what conditions (mixture composition,  $p_{\text{initial}}$ ,  $T_{\text{initial}}$ , volume,  $L/D$ ) do we have to assume that a DDT occurs?
- What is the largest conceivable value of the static equivalent pressure  $p_{\text{stat}}$  ?  
(it should be larger than  $p_{\text{stat}}$  of the pipe scenario no. 8).

Hint: In vessels having dimensions as used in the process industry the width of the detonative peaks hitting the wall will be much less than half of the cycle time of the fundamental oscillation modes. This helps to reduce  $p_{\text{stat}}$ . But excitation is usually unsymmetric and thereby triggers all higher harmonics, which have much smaller cycle times.

- How to cope with the massive net forces acting on the vessel, which cause the vessel to be displaced?

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# Typical packings used in the process industry

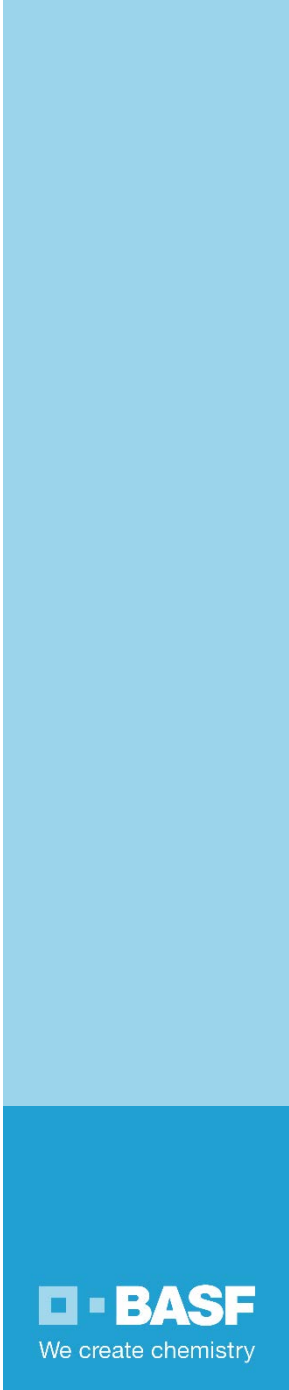
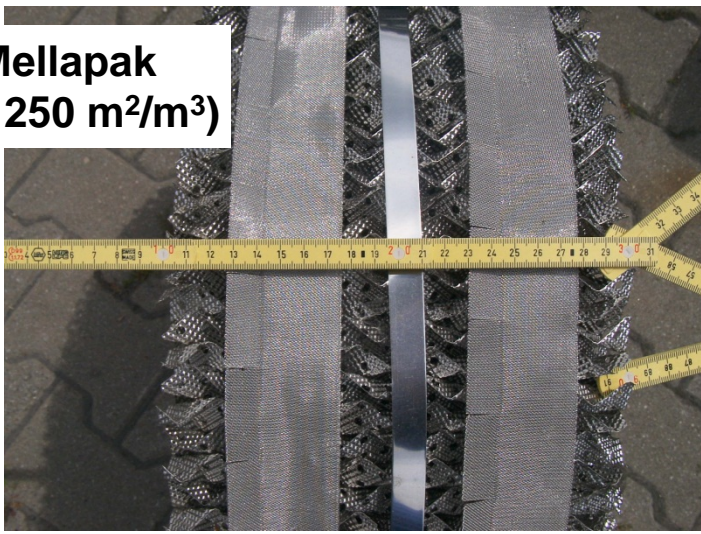
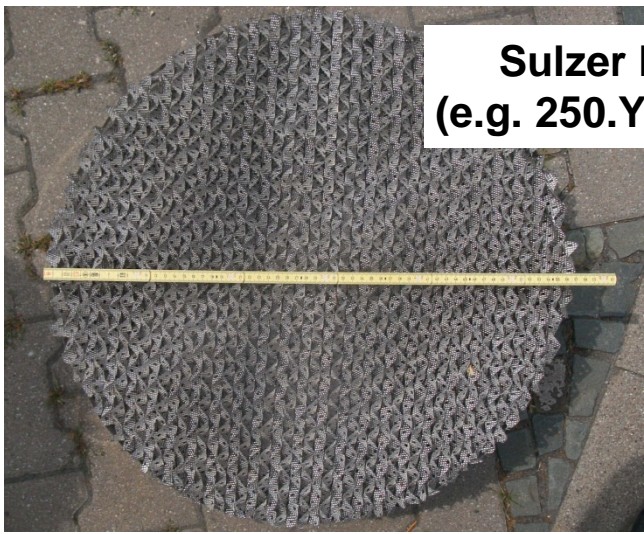
**Raschig Rings, L/D = 1,  
typical: 15 mm ≤ L ≤ 50 mm**



**Pall Rings, L/D = 1,  
typical: 15 mm ≤ L ≤ 50 mm**

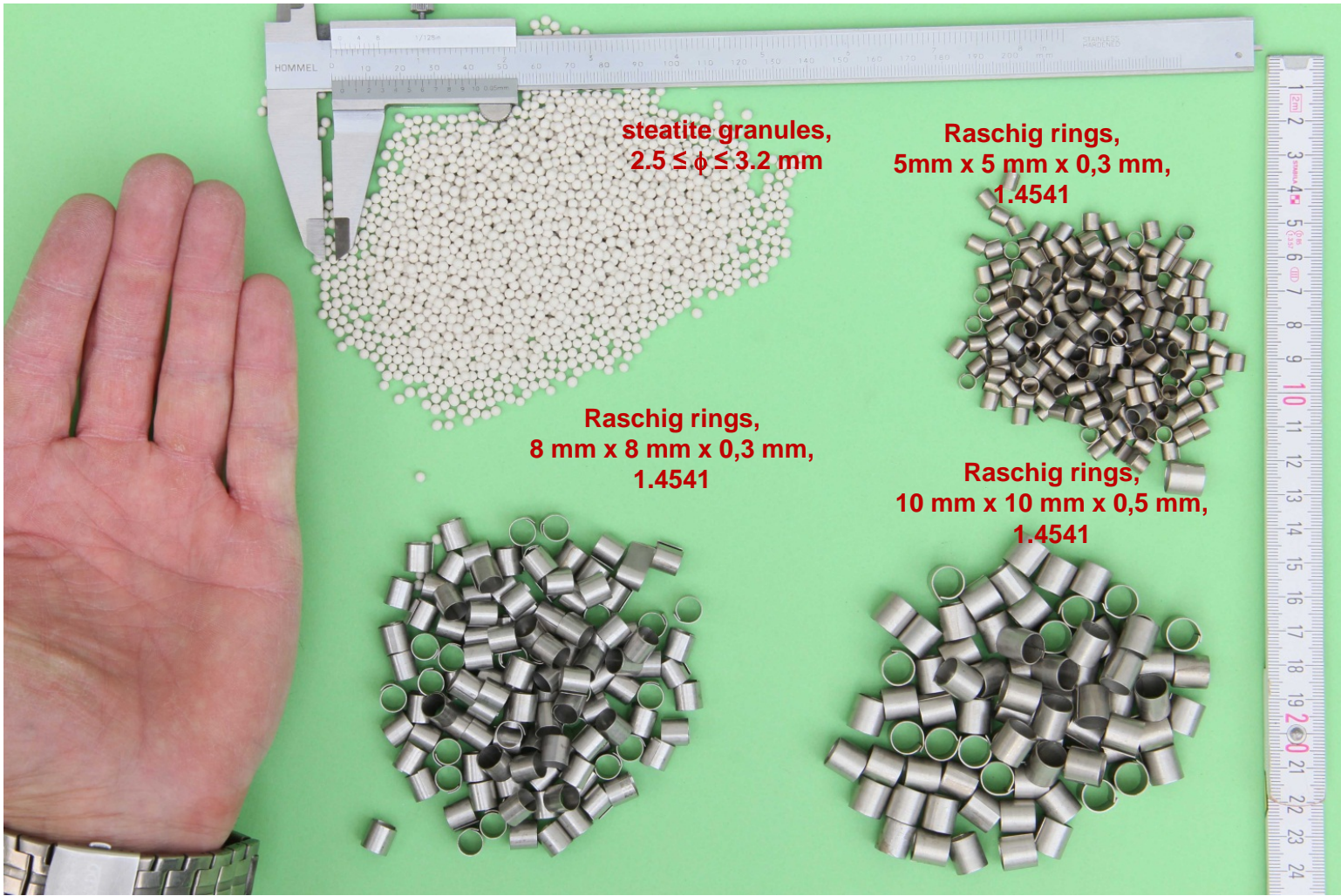


**Sulzer Mellapak  
(e.g. 250.Y, 250 m<sup>2</sup>/m<sup>3</sup>)**





# Typical packings used in small-scale equipment



# Typical applications of vessels filled with dry packings

- Vessels acting as demisters
- Vessel acting as flame arrestors  
(e.g. for self decomposable gases like Acetylene or Ethylene Oxide)
- Vessels acting as static mixers



# Fundamental questions pertaining to the course of explosions in vessels with dry packings

- Can mixtures, which explode in deflagrative manner in empty vessels, transition to detonation in packed vessels?

Yes! Example: hydrocarbon/air mixtures do not transition to detonation in empty vessels, but will do in a packing, if the packing diameter is larger than 1/3 of the detonation cell size of the mixture.

- If a DDT occurs:

- Can we specify a predetonation distance as function of the dimensions of the packing elements?

Yes! Example: stoichiometric hydrocarbon/air mixtures at 20 °C and 1 bar abs <math>p\_{\text{initial}} < 5 \text{ bar abs}</math> have a predetonation distance of about  $100 \cdot \phi_i$  in straight pipes ( $\phi_i$  is the inner pipe diameter). In packings this distance is much smaller ( $\phi_i$  denotes the packing diameter).

- How large is the maximum precompression factor relative to the maximum precompression factor in the empty vessel?

(specific BASF know how)

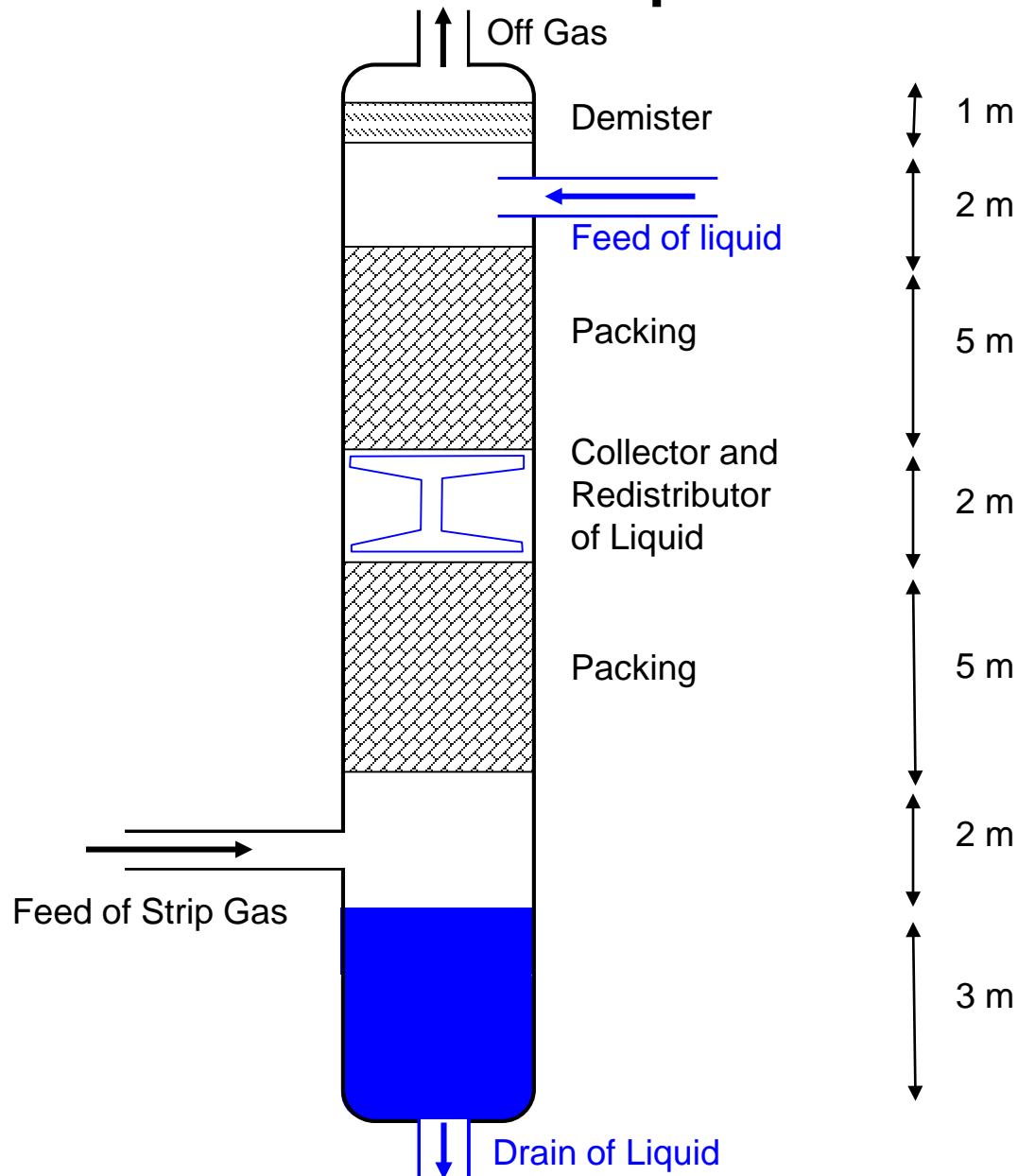
- How large is the static equivalent pressure acting on the wall of the vessel compared to a detonation in an empty vessel?

(specific BASF know how)

# Overview

- Brief background info: deflagrative and detonative explosions in gaseous mixtures
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# General application of an irrigated packing: distillation column or desorption tower



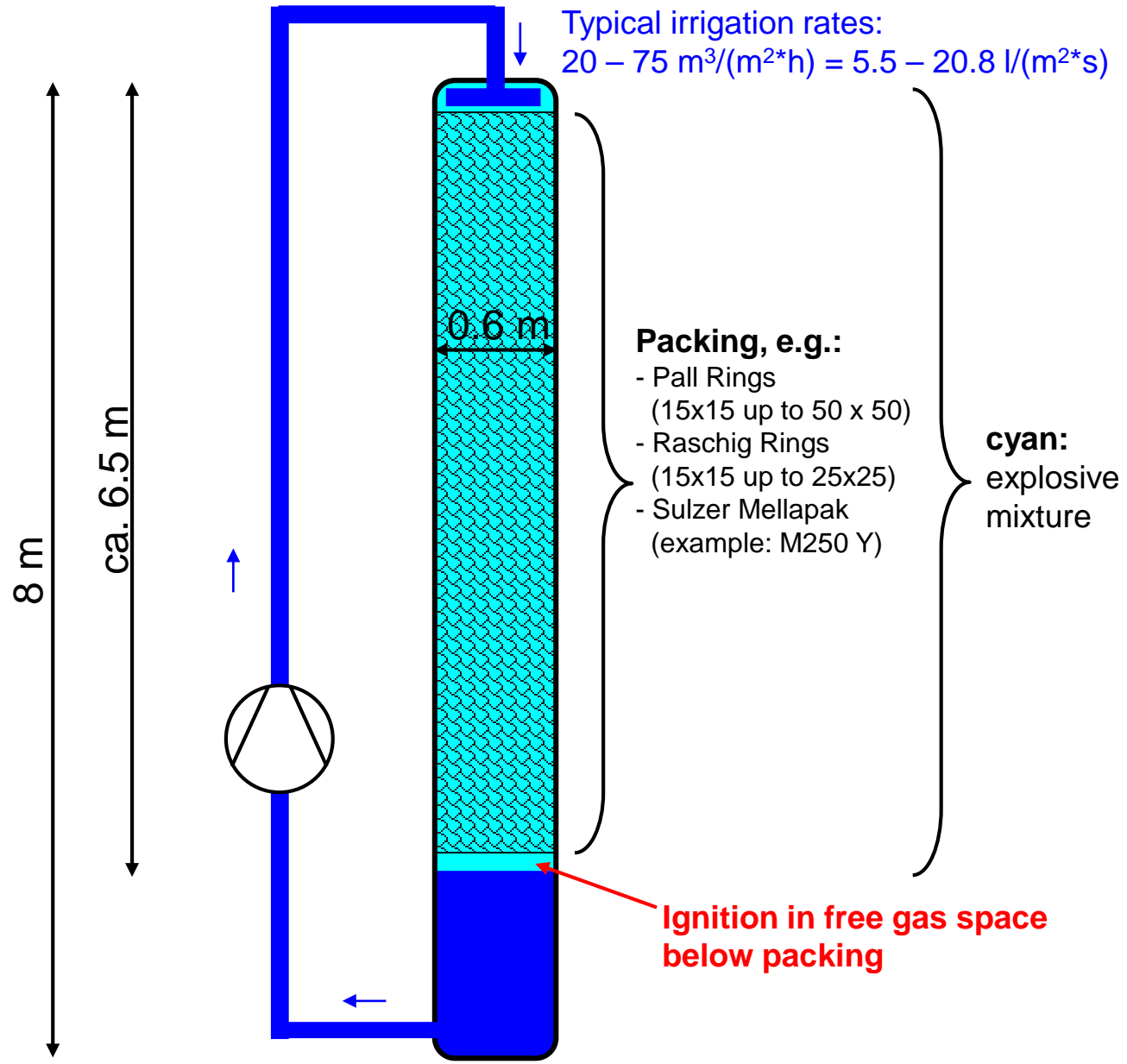
# Fundamental questions pertaining to the course of explosions in vessels with irrigated packings

- Can a DDT, which would happen inside the dry packing, be suppressed by the irrigation?
- If the DDT can be suppressed:
  - What is the required irrigation rate as function of  $p_{\text{initial}}$ ?
  - What is the required irrigation rate as function of the diameter of the packing elements?

## Answers

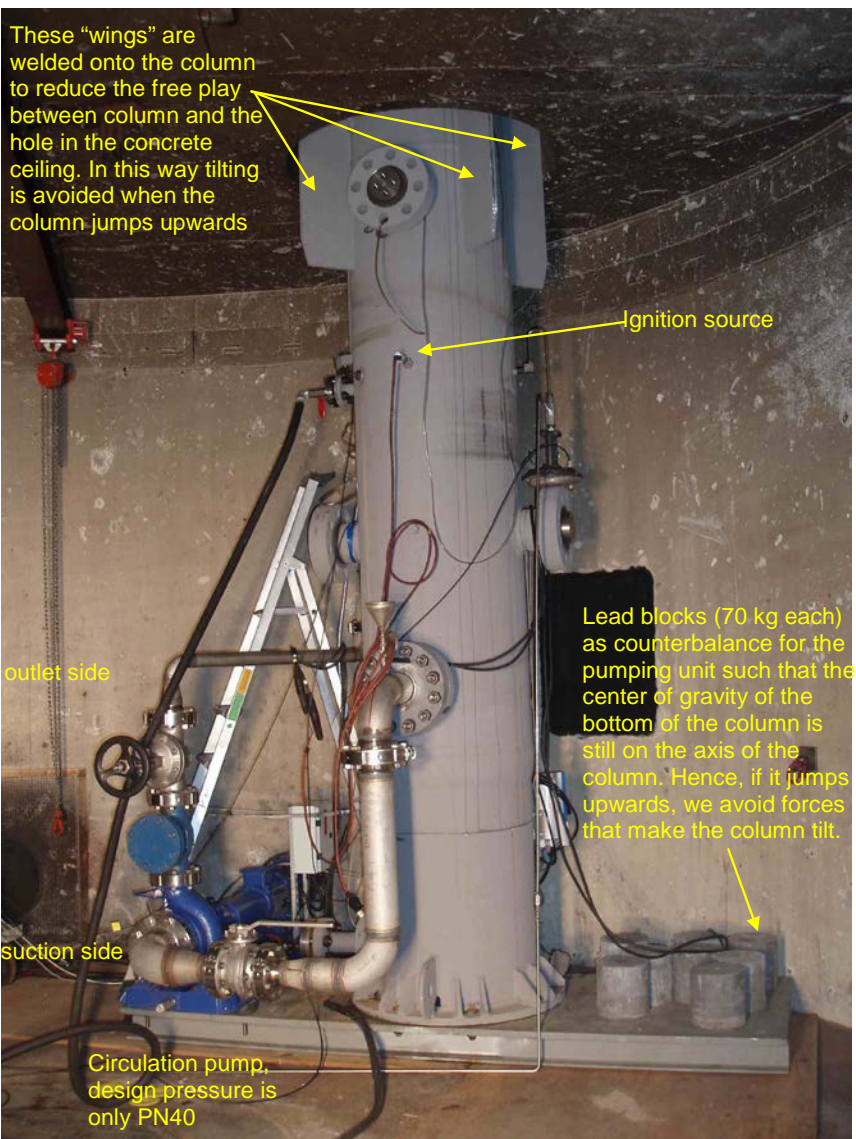
- Answers do very much depend on the process conditions of the system under investigation
- Number of investigated systems is still too small to generalize the results

# Vessel geometry used by BASF for experiments



# Example: PN250 column, 8 m long, installed in bunker K348 for testing suppression of DDT by irrigation

Lower part of the column in the test room of the bunker K348



Upper part of the column, protruding about 4 m over the ceiling of K348



View on the sparger for water mounted under the upper blind flange



(here with rust, picture taken after test no. 4)



# Example: Tests without and with detonation in PN250 column filled with 50x50 Pall Rings



Acetylene:  $p_{\text{initial}} = 8 \text{ bar abs}$   
irrigation rate:   
Pall rings: 50mm x 50mm

**no DDT !!!**



Acetylene:  $p_{\text{initial}} = 12 \text{ bar abs}$   
irrigation rate:   
Pall rings: 50mm x 50mm

**DDT !!!**

File: 0-V1-Kolonne-PN250-8bar C2H2, 6m3-m2-h.avi

0-V2-Kolonne-PN250-12bar C2H2, 6m3-m2-h.AVI



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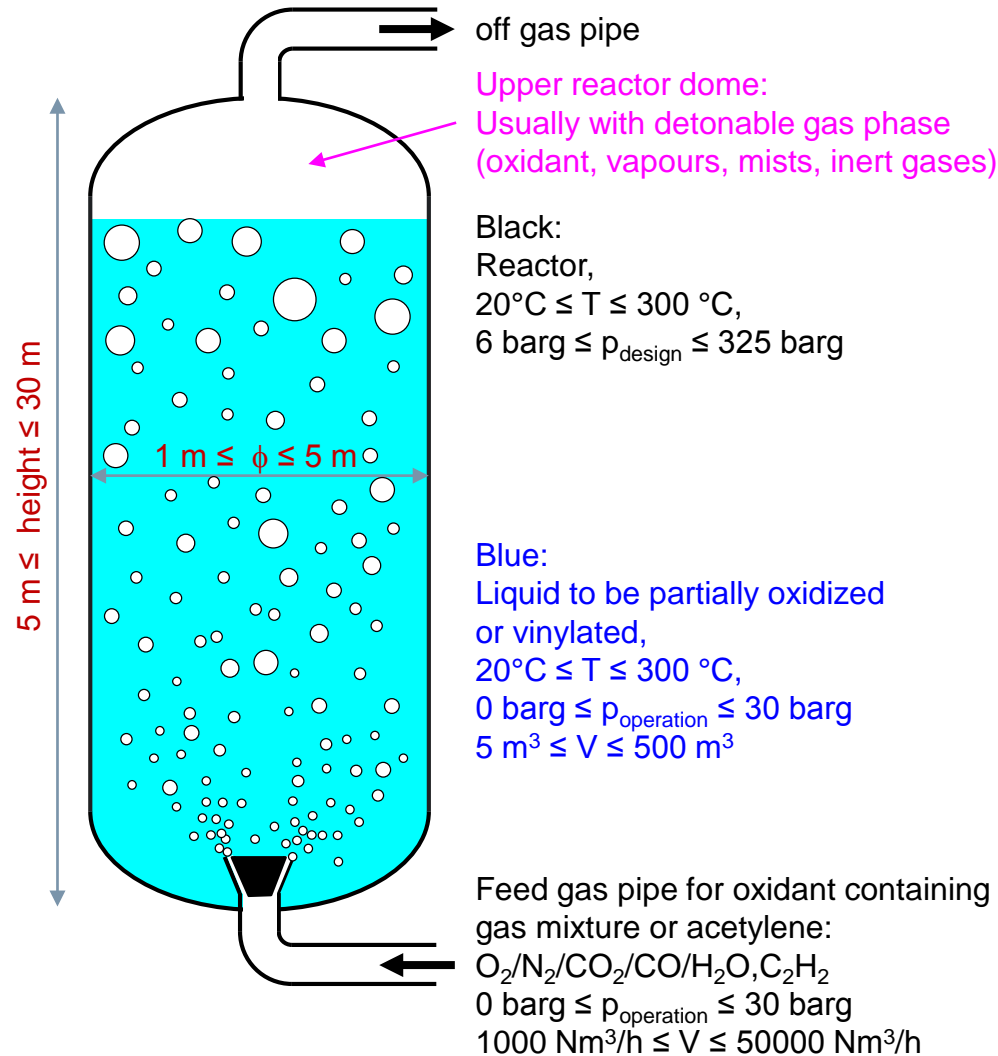
# Schematic sketch of a gas-liquid partial oxidation or vinylation process (injection from bottom)

## Characteristics of process:

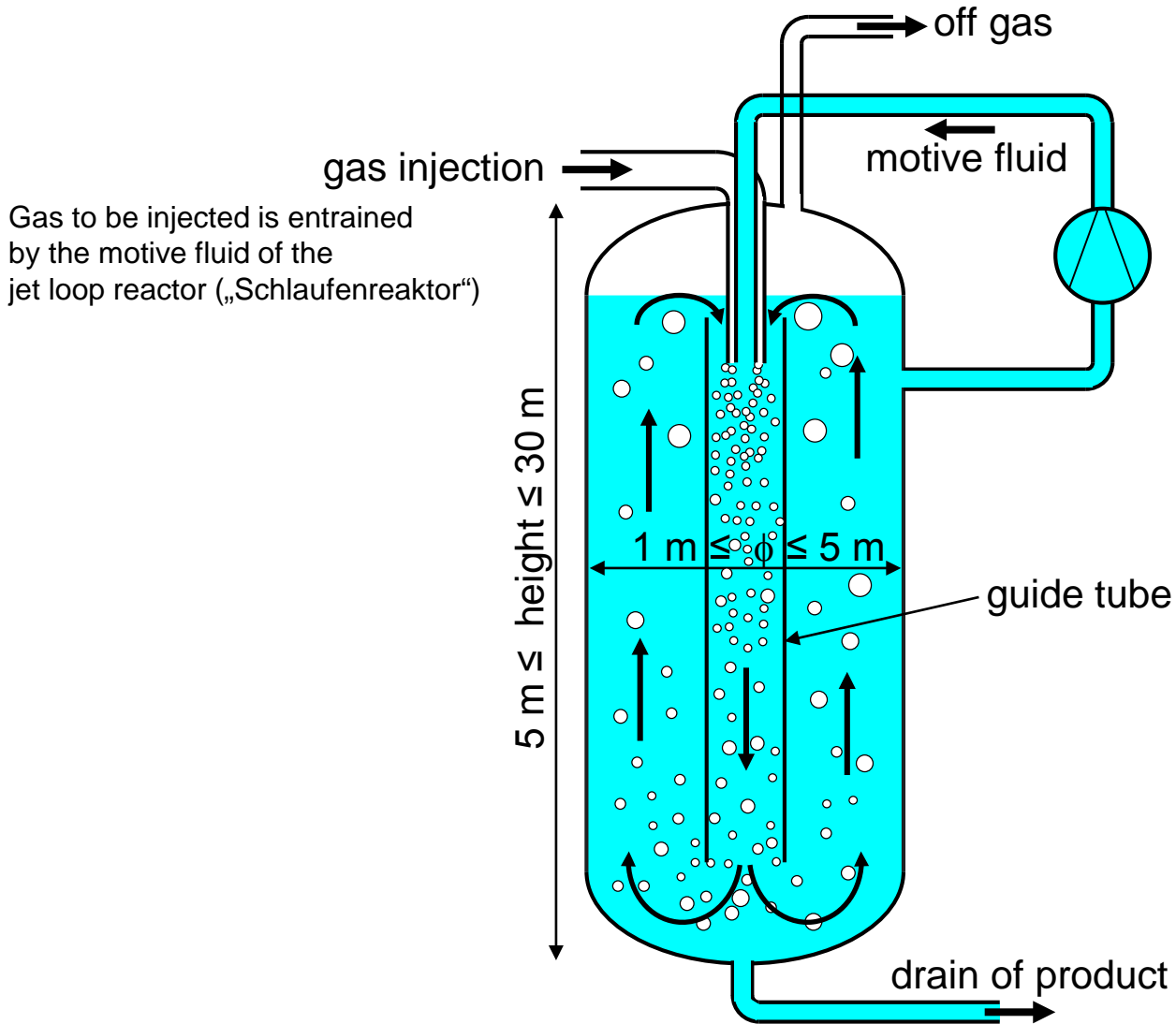
- Large hold-up of organic liquid
- Injection of a gaseous oxidant or gas mixture containing the oxidant
- 5 to 20 % of the liquid are taken by gas bubbles
- Large fraction of the bubbles can be in the **explosive range** due to vapour of the organic liquid (in case of reaction breakdown all bubbles can become explosive)
- Gas space in reactor dome is usually in **explosive range** due to organic vapour and/or organic mist
- Ignition sources can not be excluded (mostly: chemical ignitors)

## Note:

Explosive range encompasses the purely deflagrative regime and the potentially detonative regime



# Schematic sketch of a gas-liquid partial oxidation or vinylation process (injection from top with motive fluid)



# Typical applications with the risk of bubble swarm detonations triggered by detonation in head space of reactor

- Partial oxidation reactions of organic liquids with air,  $O_2$  or  $N_2O$
- Vinylation reactions of organic liquids

# Fundamental questions pertaining to the course of bubble swarm detonation triggered by detonation in the head space of the reactor

- Can the bubbles be ignited by adiabatic compression generated by the shockwave in the liquid?  
(Assumption: shock wave is triggered by gas phase detonation in head space)
- If ignition occurs:
  - Can there really be a DDT inside the bubbles?
  - How large is the static equivalent pressure acting on the wall?
  - Will all conceivable courses of the explosion in the bubbles (homogeneous runaway reaction, deflagration, detonation) lead to the same static equivalent pressure acting on the wall?

# Research data not suited to assess bubble swarm detonation triggered by detonation in head space

No.	Parameter	Reactors used in	
		published research	process industry
<b>geometric data</b>			
1	dimensions of reactors	$L \leq 1 \text{ m}$ ; $\phi_i \leq 0.2 \text{ m}$ (lab scale)	$L \leq 15 \text{ m}$ ; $\phi_i \leq 6 \text{ m}$
2	volumetric gas fraction in liquid	very small (mostly single bubbles)	1 to 20 vol.-%
3	bubble diameter	$\leq 20 \text{ mm}$	$\leq 200 \text{ mm}$
<b>experimental results</b>			
4	ignitability of bubbles containing explosive mixture	yes	(unknown)
5	pressure at wall caused by exploding bubbles	negligible	(unknown)
6	water hammer	negligible	(conceivable)

Due to large differences in (1), (2) and (3), the results from lab scale tests are **not suited** to assess real scale scenarios!!

(e.g. liquid in real reactors has much higher compressibility (due to higher gas fraction) and will be accelerated to much higher speed (combined effect of higher gas fraction and larger length of reactor))

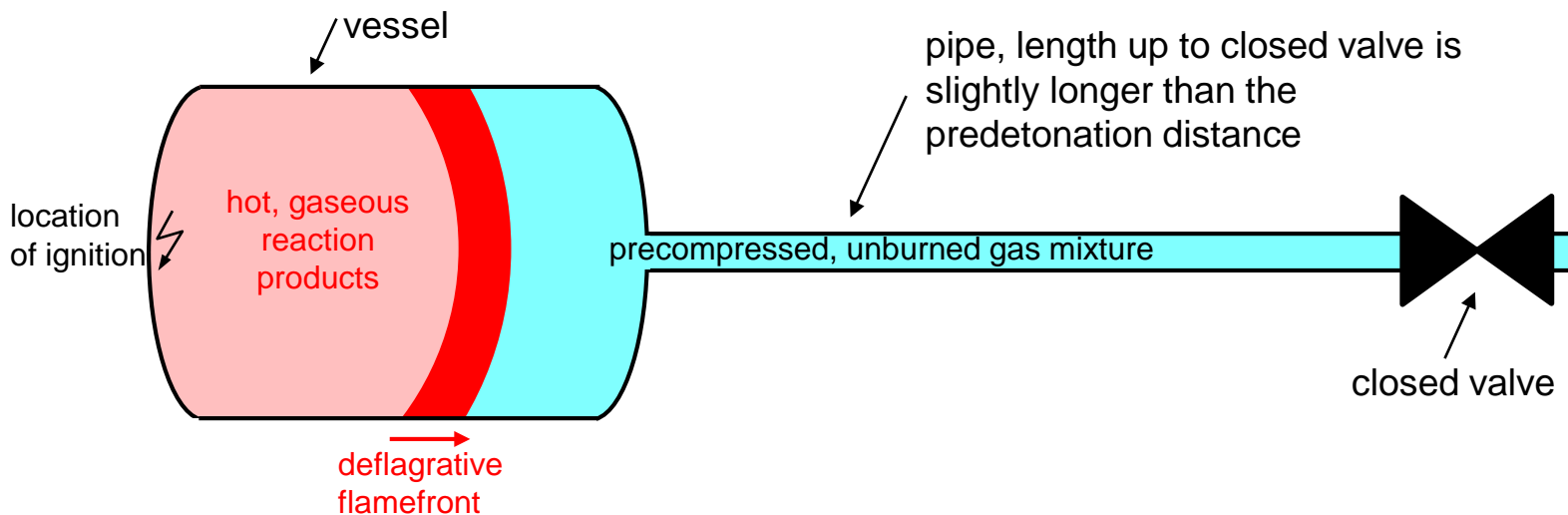


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# Problem with short pipe connected to large vessel



- Many gas mixtures only deflagrate in vessel-geometry but undergo transition to detonation in pipe geometry
- Usually: volume of vessel  $\gg$  volume of short pipe

At the moment when the deflagrative flame front reaches the point where the pipe is tied in, the unburned mixture in the pipe is precompressed by a factor equal to the deflagration pressure ratio (typically 4 to 25).

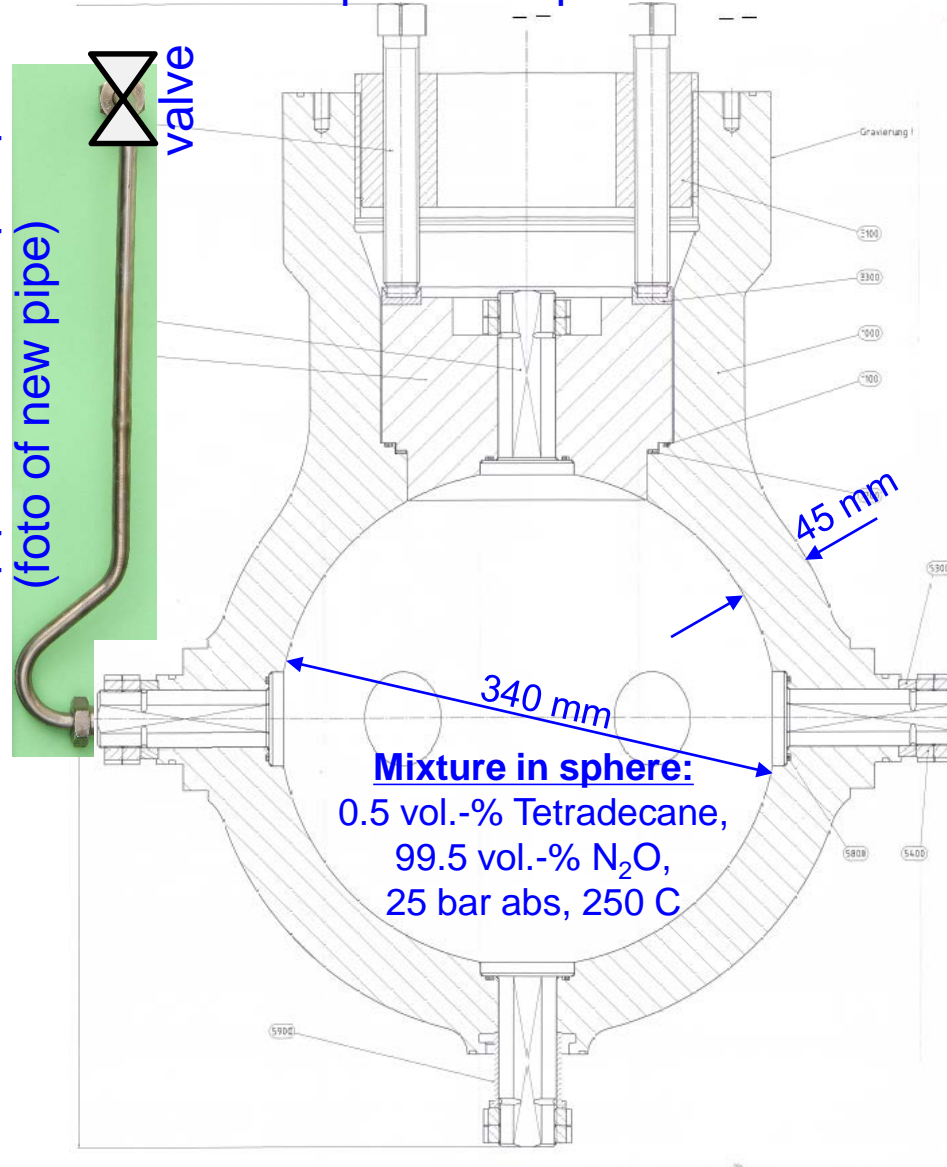
When, upon further propagation, the flame transitions to detonation, the **resulting pressures are extremely large**

# Example 1: 20 l sphere with 45 cm pipe ( $\phi_i = 6$ mm)

20 l sphere used for explosion experiments



10x2 pipe to vacuum pump  
(foto of new pipe)

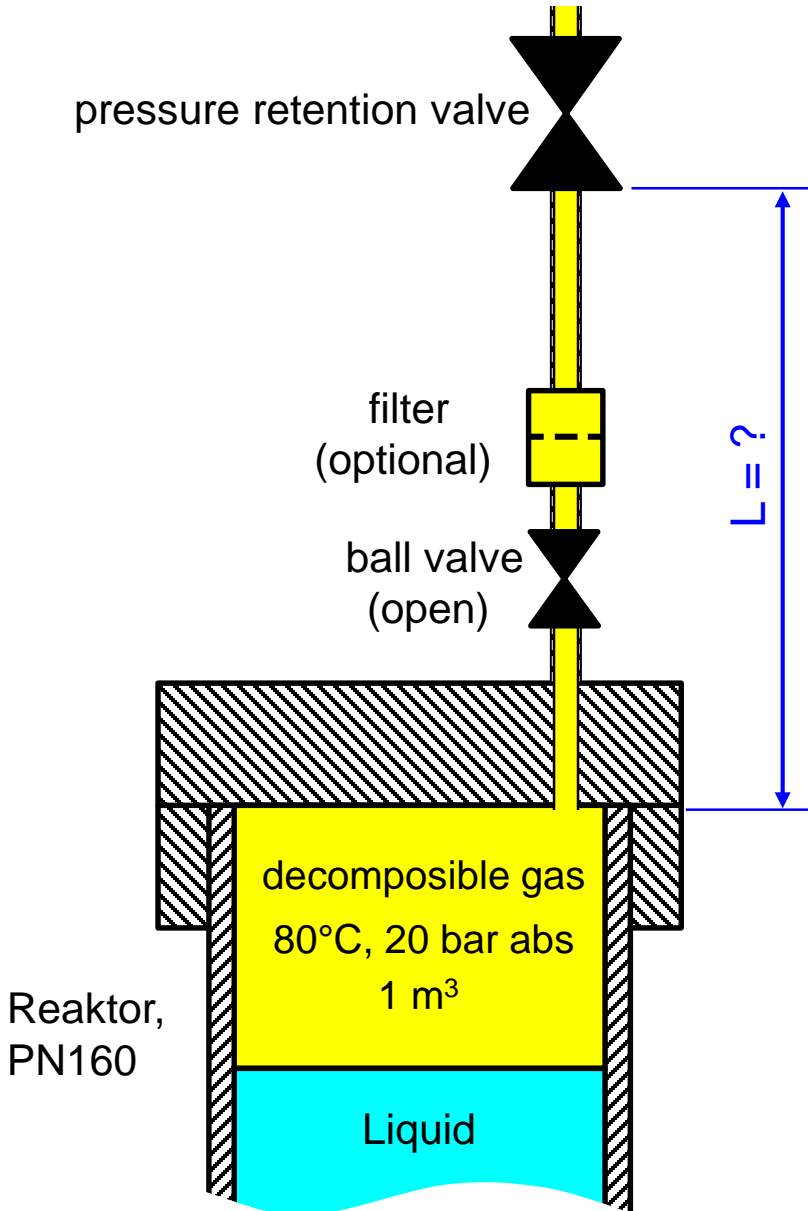


**Mixture in sphere:**  
0.5 vol.-% Tetradecane,  
99.5 vol.-% N<sub>2</sub>O,  
25 bar abs, 250 C

10x2 pipe ruptured at location of DDT, thereafter the curved part molt.

(hydraulic burst pressure of pipe is about 3480 bar; pipe material: 1.4541; deflagration pressure ratio of the mixture was only ca. 5 at  $T_{initial} = 250$  C)

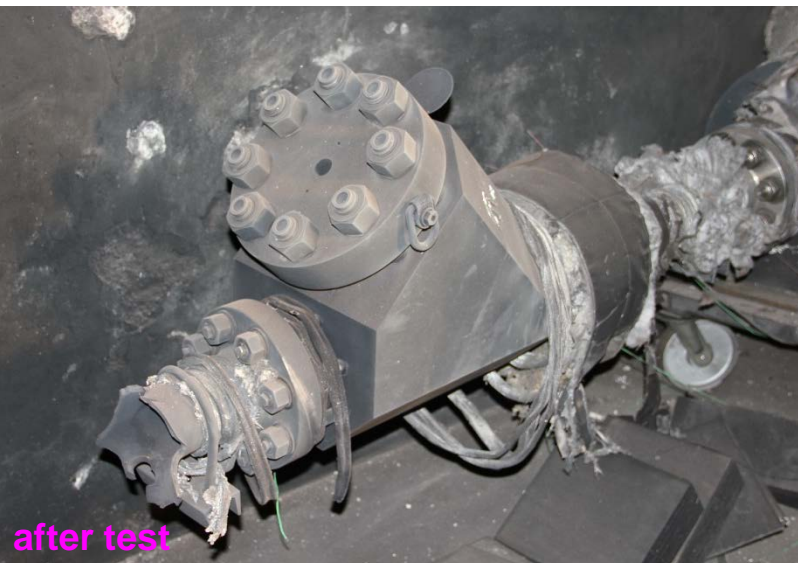
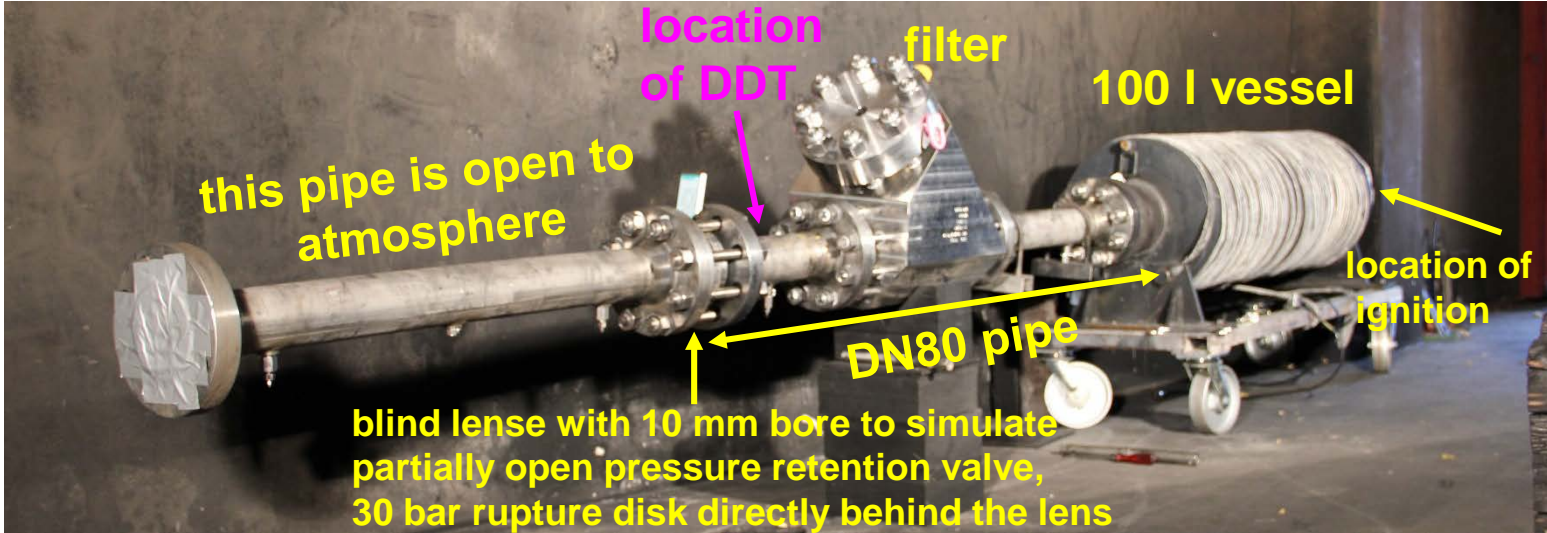
# Example 2: 1 m<sup>3</sup> vessel with DN80 pipe



## Question:

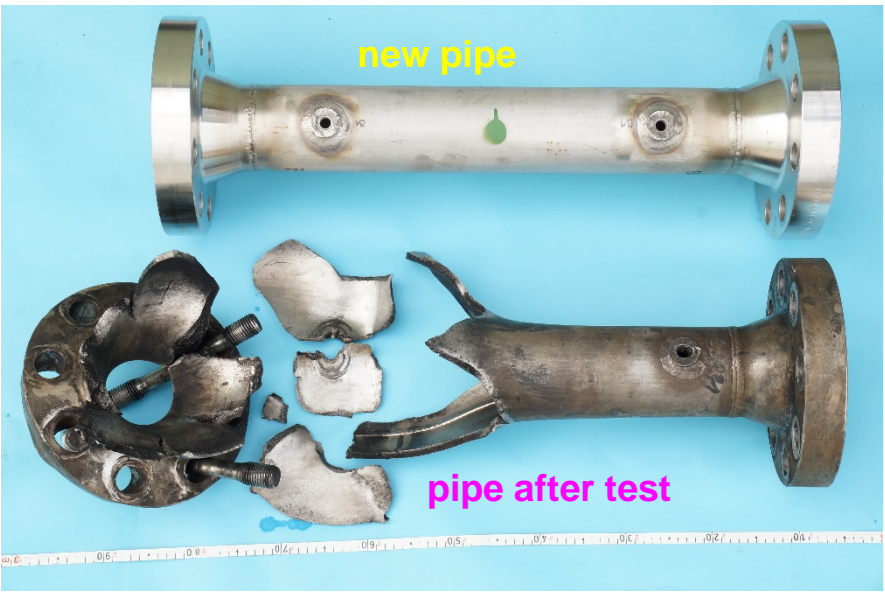
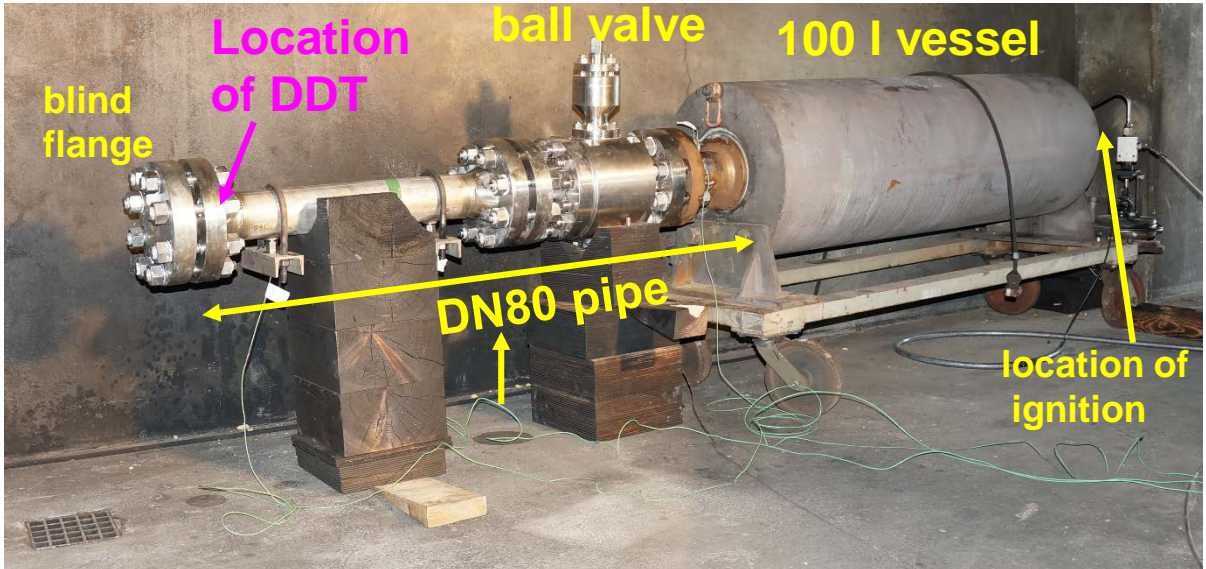
What is the maximum permissible length L of the DN80 pipe such that a deflagrative decomposition starting in the headspace of the reactor does not transition to detonation in the pipe ?

# Example 2: result of a real-scale test





# Example 2: result of a real-scale test



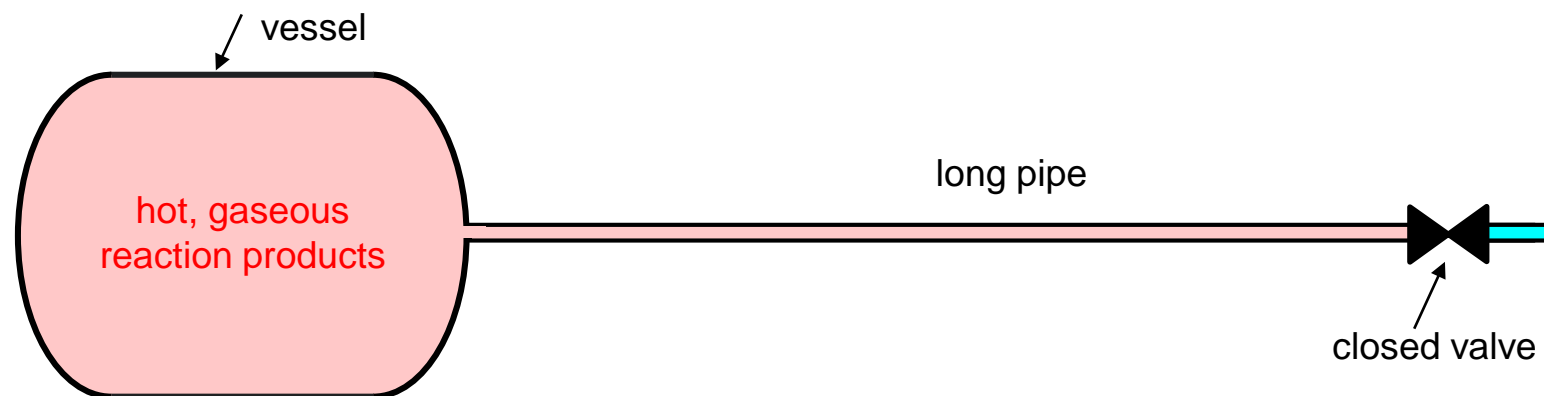
**BASF**  
We create chemistry

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# Problem with long pipe connected to a large vessel



- Explosive mixture present in vessel and pipe explodes in deflagrative or detonative manner. The resulting pressures are sustained by the equipment.
- Usually: volume of vessel  $\gg$  volume of long pipe

The cooling rates in the pipe are much faster than in the vessel.

⇒ Hot reaction gases (2400 K to 3000 K) flow from the vessel into the pipe.

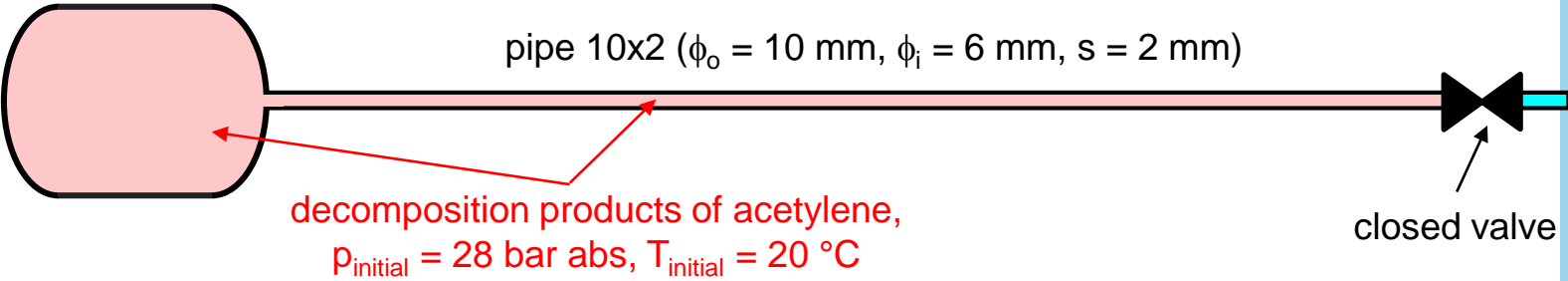
⇒ Excessive heating of pipe at point where connected to vessel

⇒ Rupture of pipe at that point because yield strength  $R_{p0.2}$  drops to very low values

Note: Let  $n$  denote the number of moles in the pipe directly after the explosion has terminated. Then the pipe will typically receive  $9 \cdot n$  hot moles from the vessel within a short time span after completion of the explosion.

# Example 1: vessel with long pipe

4.5 l vessel,  
 $\phi_i = 90 \text{ mm}$ ,  $L = 700 \text{ mm}$



**Case 1:** pipe length is 1.5 m: no rupture

**Case 2:** pipe length is 4.3 m: rupture



## Example 2: 275 l vessel with 82.5x14.2 pipe

275 l vessel

pipe 82.5x14.2 ( $\phi_o = 82.5$  mm,  $\phi_i = 54.1$ ,  $s = 14.26$  mm)

decomposition products of ethylene,  
 $p_{\text{initial}} = 220$  bar abs,  $T_{\text{initial}} = 300$  °C

flow direction to  
other vessels

- Ignition occurred in vessel (decomposition reaction is slow)
- About 60 s after ignition: pipe ruptured at flange where it was connected to the vessel due to excessive heating

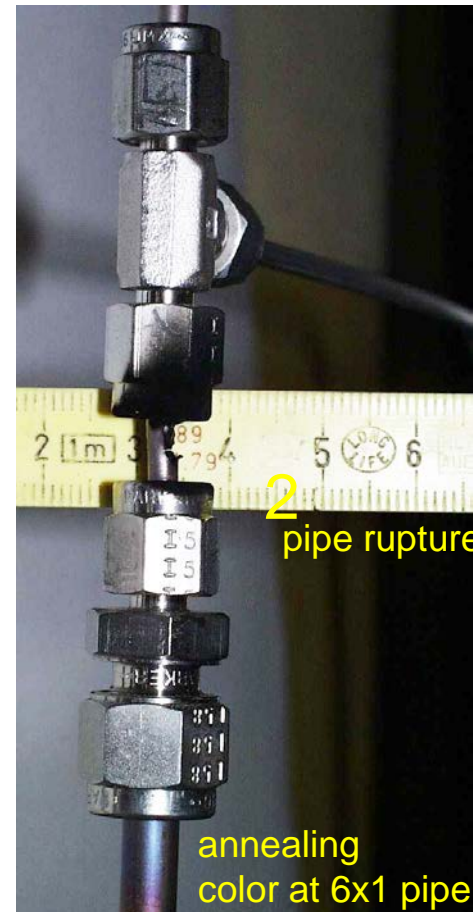
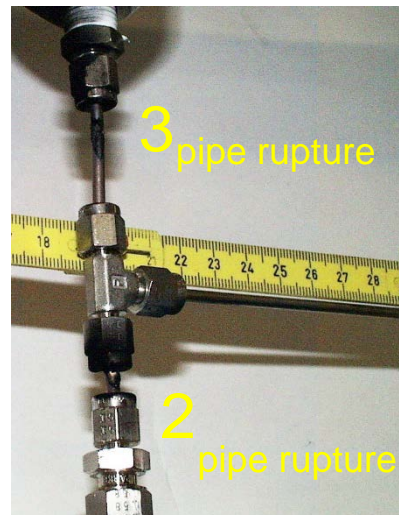
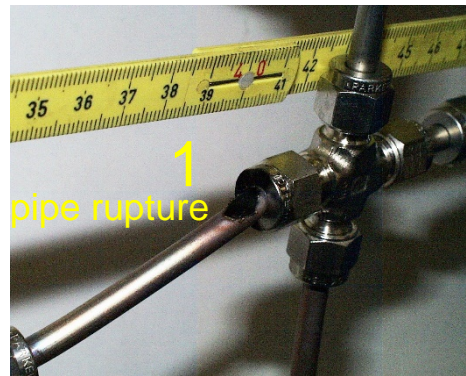
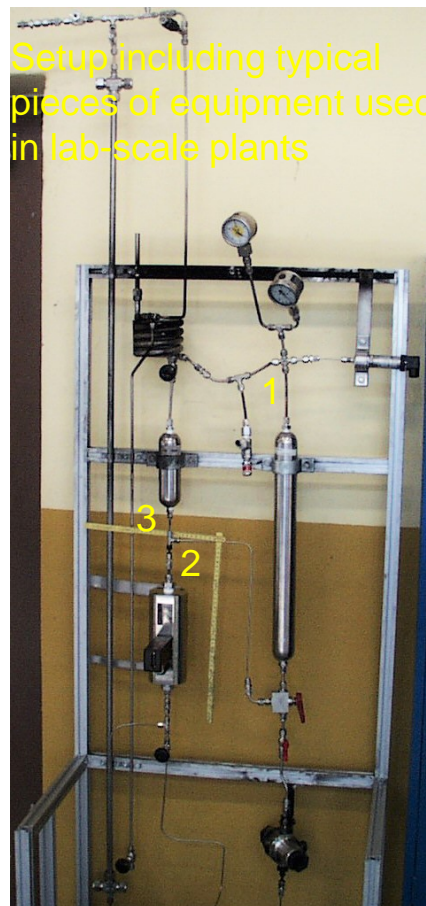
# Example 3: laboratory setups with small Swagelock pipes and Whitey-bombs

**Test conditions:** decomposition of acetylene,  $p_{\text{initial}} = 28 \text{ bar abs}$ ,  $T_{\text{initial}} = 20 \text{ }^\circ\text{C}$

**Pipes:** 3.16 x 0.5, 6 x 1

**Vessels:** Whitey bombs with 0.1 to 1 l, design pressures ca. 200 to 300 bar

After the decomposition reaction has terminated, flow of hot reaction products sets in from somewhere to somewhere and wall sections under high thermal load rupture.



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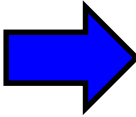
# State of adopting the pipe results in regulation, guidelines, standards etc

## ■ Germany: TRGS 407, Anhang 4

- long pipe scenarios for C<sub>2</sub>H<sub>2</sub>-Detonations included
- a pipe is considered as detonation pressure resistant only on basis of the wall thickness, not on basis of its official design pressure.

## ■ ASME: In 2015 a working group was established to develop a new ASME code case on detonation pressure resistant pipe design. Work has been postponed so far due to work overload.

## ■ NFPA: NFPA 67 “*Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems*” is going to be revised shortly, in particular chapters 5 to 8 dealing with principles of detonations in pipes. Members of BASF Corporation take part.



## ■ Still much work to be done to make the pipe results “penetrate” the existing guidelines.

## ■ Possibly: Extra chapter to be included in DIN EN 13480 *Metallic industrial piping – Part 3: Design and calculation*





The Chemical Company