LIMITS

OF STEADY PROPAGATION OF HYDROGEN DEFLAGRATIONS AND DETONATIONS

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Flame propagation in tubes

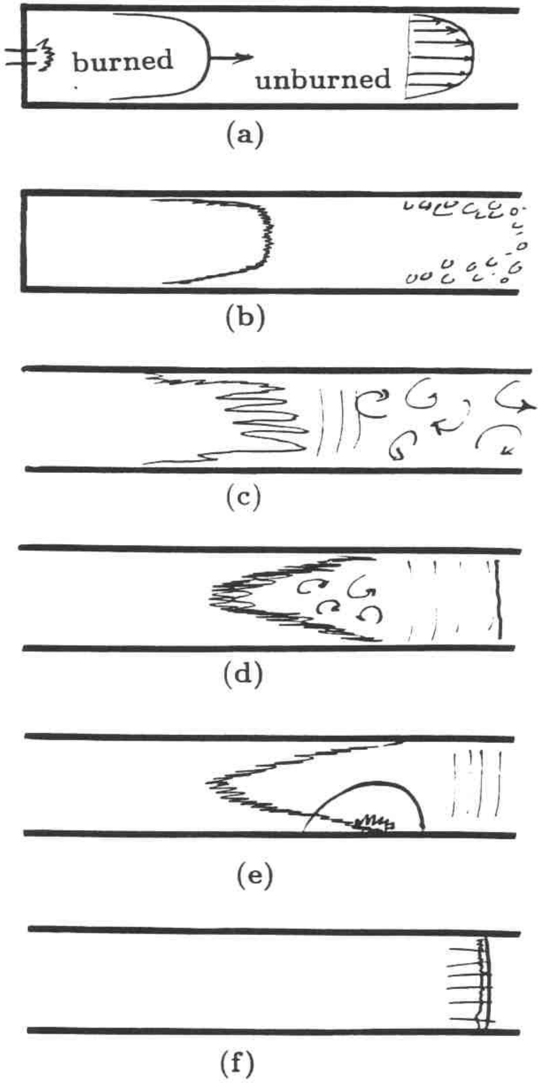
- **Lower limit** ⇒ LAMINAR FLAME (m/s)
- **Upper limit** ⇒ CJ DETONATION (km/s)
- **Between limits** ⇒ spectrum of TURBULENT FLAMES depending on:
  - Initial conditions: pressure, temperature, composition
  - Geometry: size, obstacles, etc.
- **Smooth tubes** ⇒ continuous flame acceleration and abrupt DDT
- **Rough (obstructed) tubes** ⇒ several distinct regimes of steady flame propagation

Experimental Composition Limits

Mixture	Deflagration lean limit [% fuel by vol.]	Detonation lean limit [% fuel by vol.]	Detonation rich limit [% fuel by vol.]	Deflagration rich limit [% fuel by vol.]
$H_2 - O_2$	4.6	15	90	93.9
H_2 – air	4	18.3	59	74
$CO - O_2$	15.5	38	90	93.9
$(CO+H_2)–O_2$	12.5	17.2	91	92
$(CO+H_2)$–air	6.05	19	59	71.8
$NH_3 - O_2$	13.5	25.4	75	79
$C_3H_8 - O_2$	2.4	3.2	37	55
$C_2H_2 - O_2$	2.8	3.5	92	93
$C_4H_{10}O$ – air	1.85	2.8	4.5	36.5

Source:
Kuo, Principles of Combustion, 2005

Progress of DDT event in a smooth tube



a) the initial configuration showing a smooth flame and the laminar flow ahead;

b) first wrinkling of flame and instability of the upstream flow;

c) breakdown into turbulent flow and a corrugated flame;

d) production of pressure waves ahead of the turbulent flame;

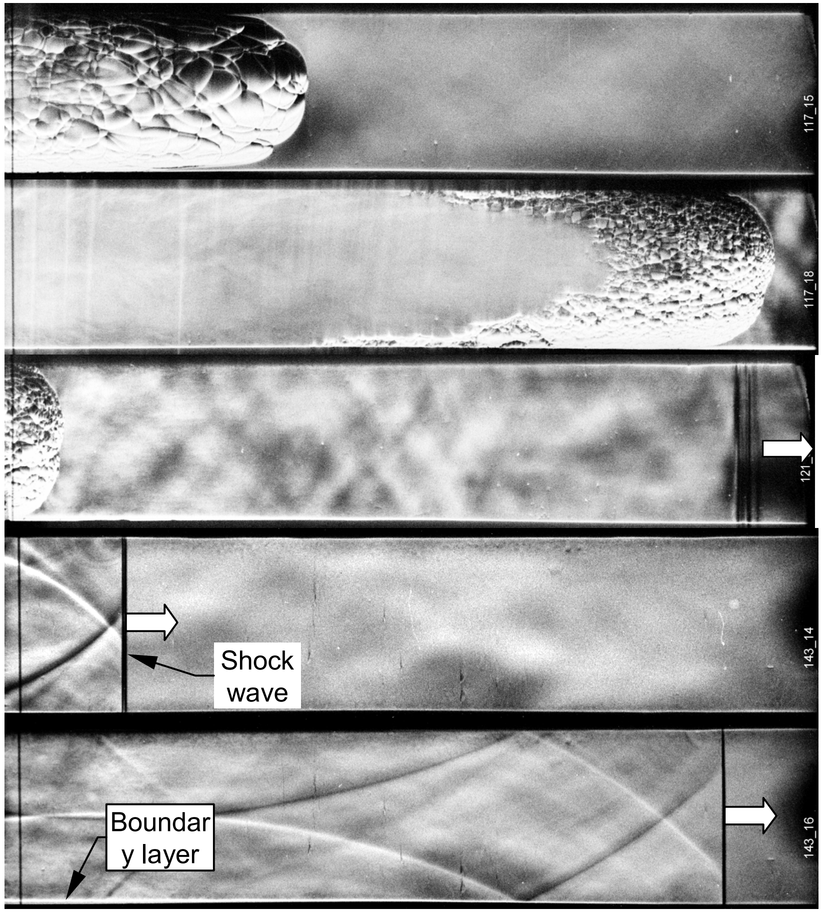
e) local explosion of a vertical structure within the flame;

f) transition to detonation.

(Shepherd&Lee, 1992)

Effect of boundary layer on the flame acceleration and DDT

Premixed flames in smooth closed tube - stoichiometric hydrogen-oxygen



Shadow photograph of early stage of flame propagation

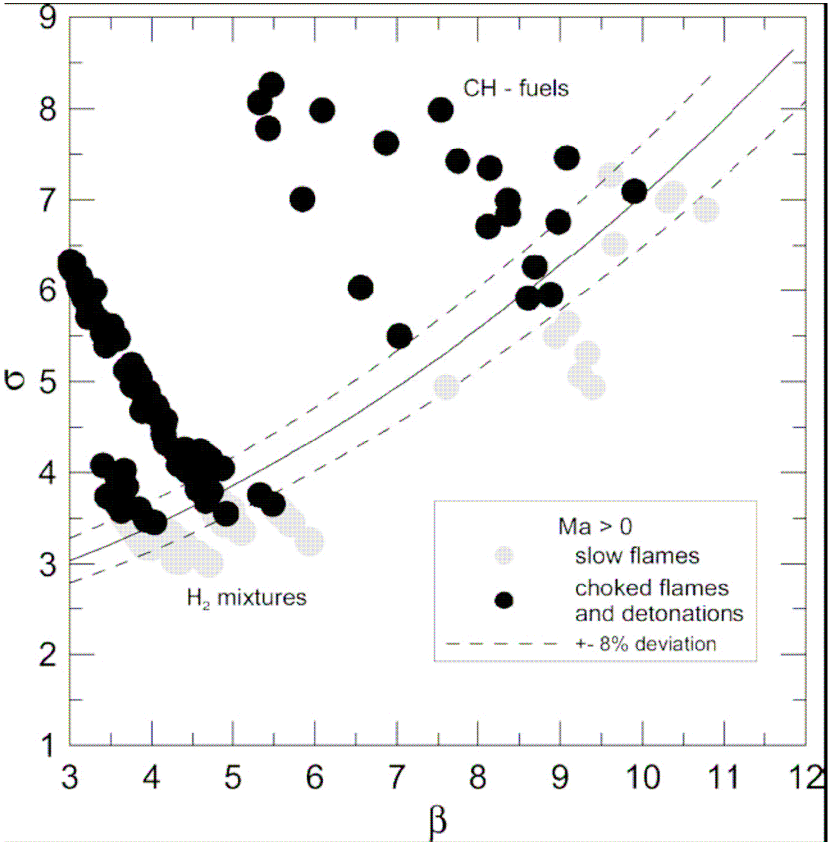
p_0=0.75 bar

at 210-440 mm from ignition

Ignition by electric spark of 20mJ

(Kuznetsov M., Dorofeev S., 2005)

Regimes of flame propagation leading to DDT



Zel'dovich number:

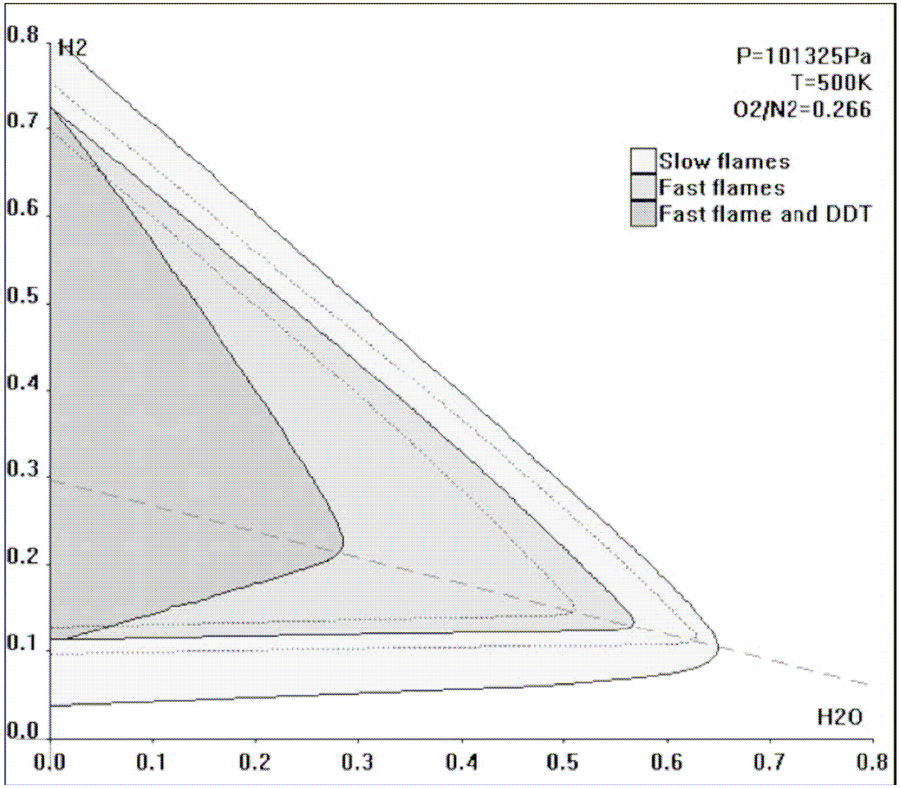
$$\beta = \frac{E_a(T_b - T_u)}{RT_b^2}$$

Expansion ratio:

$$\sigma = \frac{\rho_u}{\rho_b}$$

Source: S.Dorofeev et al., *Journal of Loss Prevention in the Process Industries 14 (2001) 583–589*

Regimes of flame propagation leading to DDT

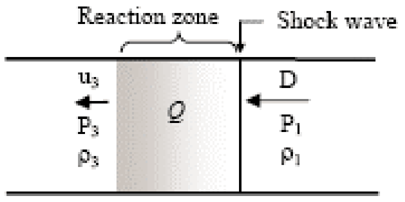


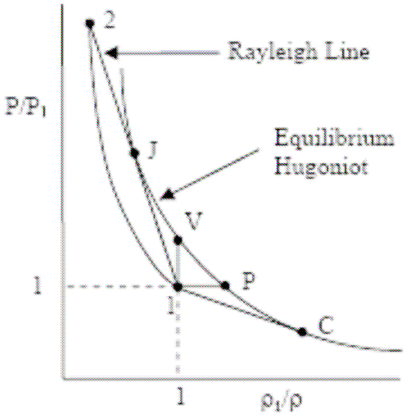
Explosion limits for H2/air/H2O mixtures at T=500 K and p=1 atm. Range of uncertainty of fast flame boundary is shown by dotted lines

Source: S.Dorofeev et al., *Journal of Loss Prevention in the Process Industries 14 (2001) 583–589*

CJ Detonation

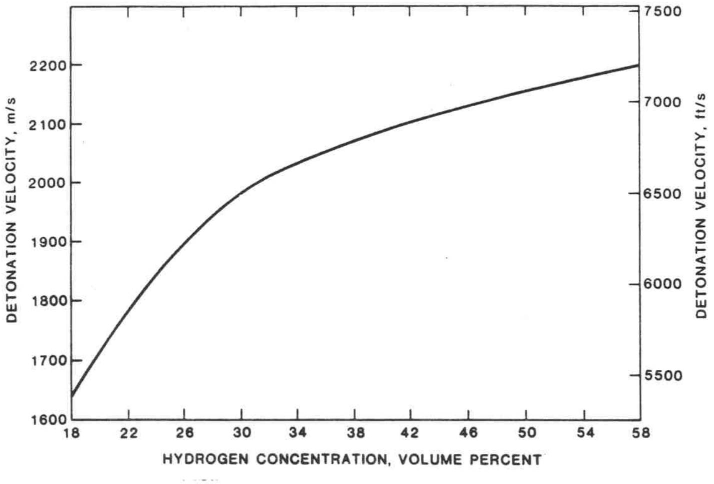
Fuel		% vol.	U_{CJ} [m/s]	P_{CJ} [bar]	T_{CJ} [K]	P_{vN} [bar]	T_{vN} [K]
Fuel –air mixtures							
hydrogen	H_2	29.6	1971	15.6	2949	27.7	1532
acetylene	C_2H_2	7.75	1867	19.1	3113	34.8	1674
ethylene	C_2H_4	6.54	1825	18.4	2926	33.5	1592
ethane	C_2H_6	5.66	1825	18.0	2816	33.0	1542
propane	C_3H_8	4.03	1801	18.3	2823	33.6	1543
butane	C_4H_{10}	3.13	1800	18.4	2828	34.4	1554
methane	CH_4	9.48	1804	17.2	2781	31.2	1530
octane	C_8H_{18}	1.62	1796	18.6	2832	30.3	1541
Fuel – oxygen mixtures							
hydrogen	H_2	66.7	2842	18.9	3683	33.1	1770
acetylene	C_2H_2	28.6	2425	33.9	4213	64.5	2239
ethylene	C_2H_4	25.0	2376	33.5	3938	64.1	2037
ethane	C_2H_6	22.2	2373	34	3803	65.6	1933
propane	C_3H_8	16.7	2360	36.3	3830	70.4	1931
butane	C_4H_{10}	13.3	2358	39.1	3854	76.3	1987
methane	CH_4	33.3	2394	29.4	3728	55.6	1907
octane	C_8H_{18}	7.4	2343	39.9	3868	78.3	1932

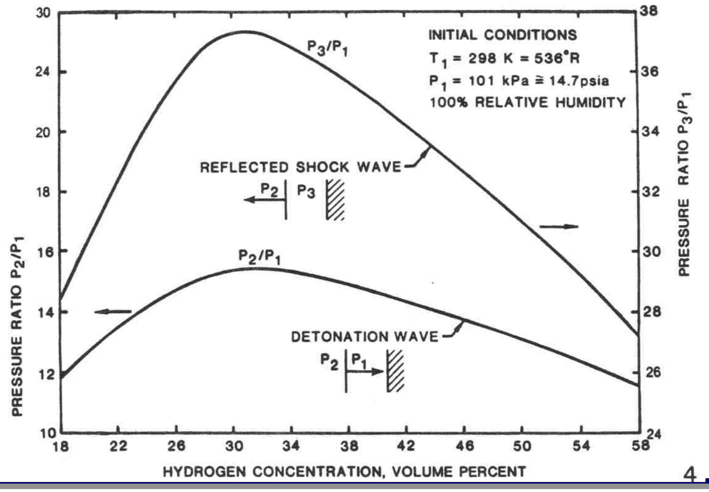


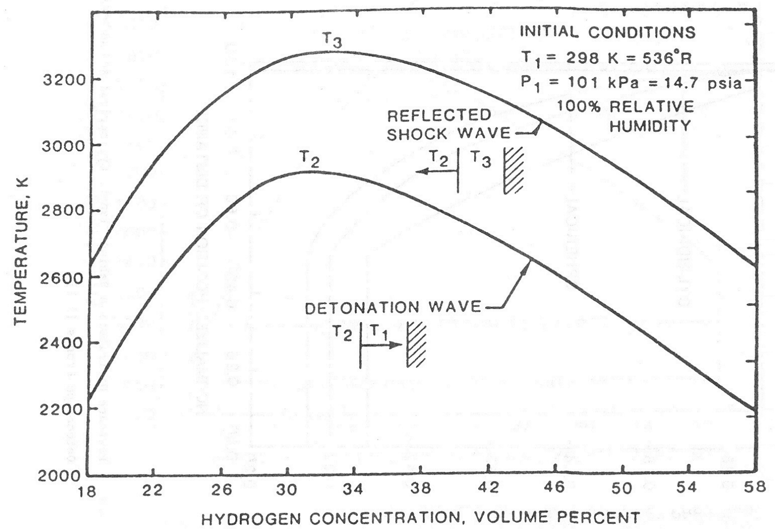


CJ Detonation

Hydrogen-Air CJ Detonation Parameters







- Velocity
- Pressure
- Temperature

Are simple to calcutale from equilibrium codes:

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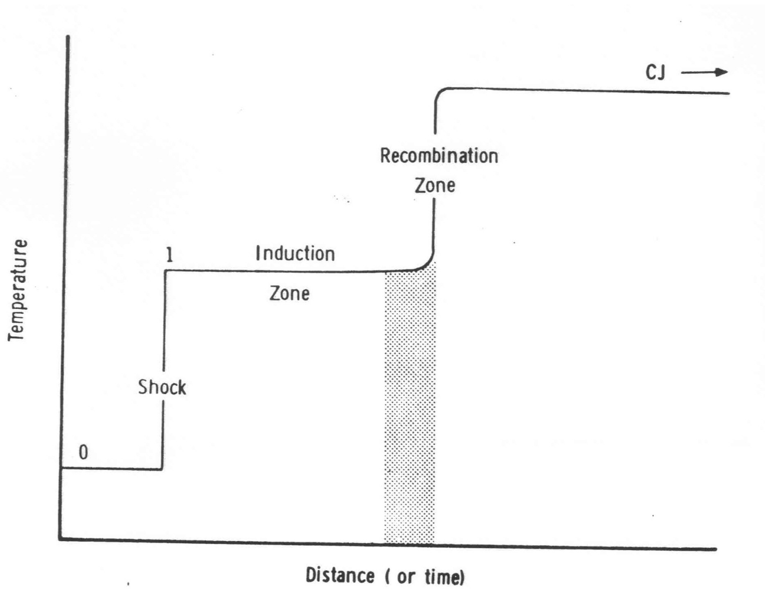
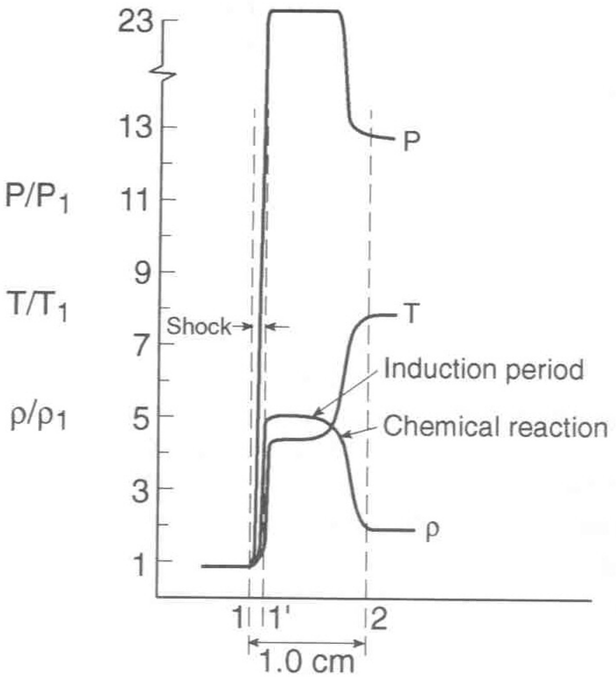
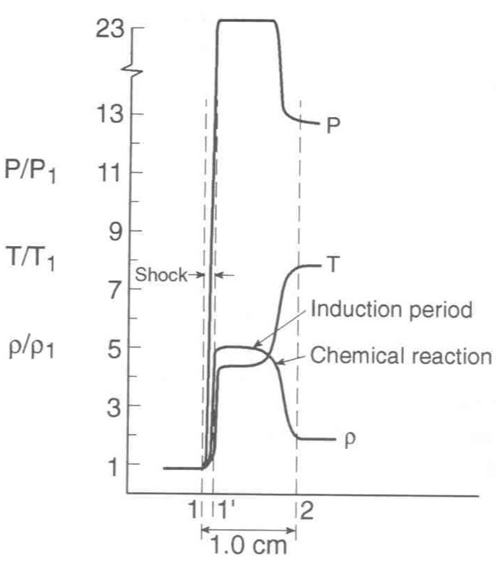
ZND Detonation





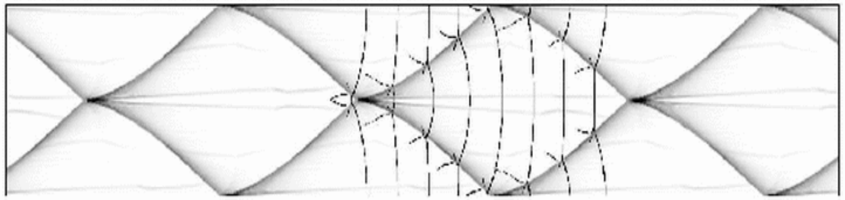
ZND Detonation

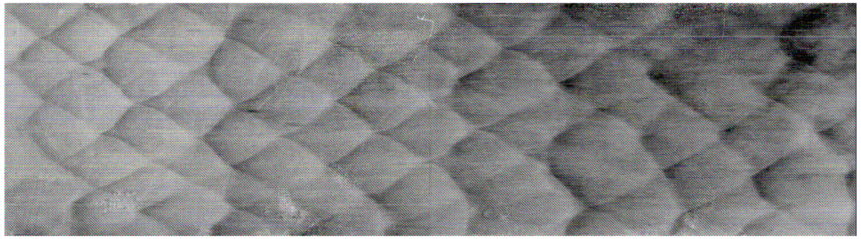
Calculated values of the physical parameters of ZND model for various hydrogen and propane detonations (Glassman I., Combustion, 1996)

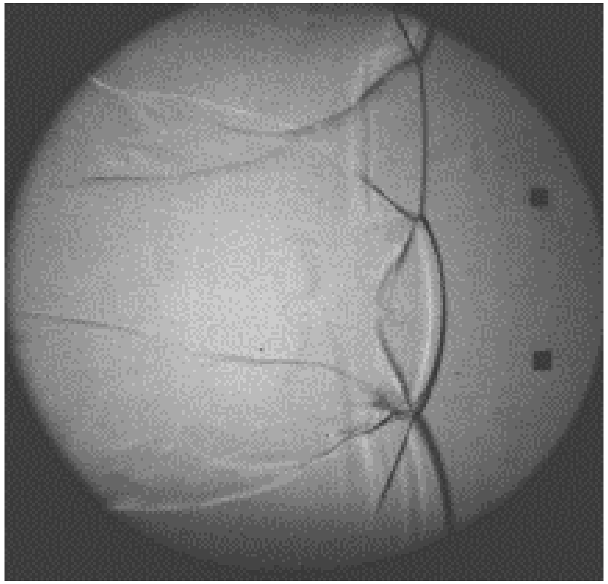


	1	1’	2
H2 – air (Φ = 1.2)			
M	4.86	0.41	1.00
U [m/s]	2033	377	1129
P [bar]	1	28	16
T [K]	298	1546	2976
ρ/ρ_1	1.00	5.39	1.80
H2 – O2 (Φ = 1.1)			
M	5.29	0.40	1.00
U [m/s]	2920	524	1589
P [bar]	1	33	19
T [K]	298	1773	3680
ρ/ρ_1	1.00	5.57	1.84

Detonation wave structure

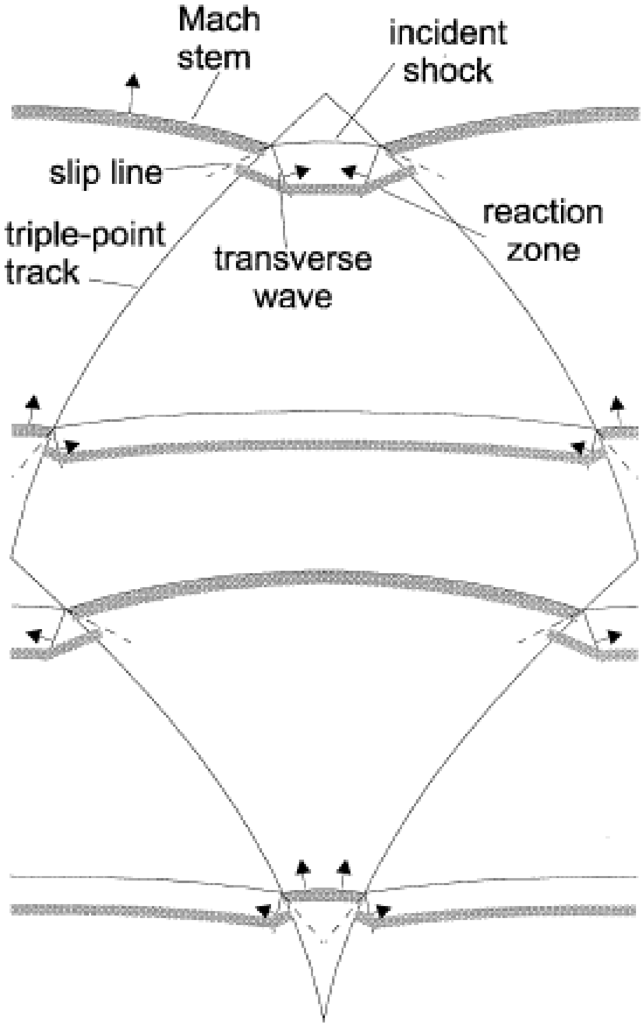






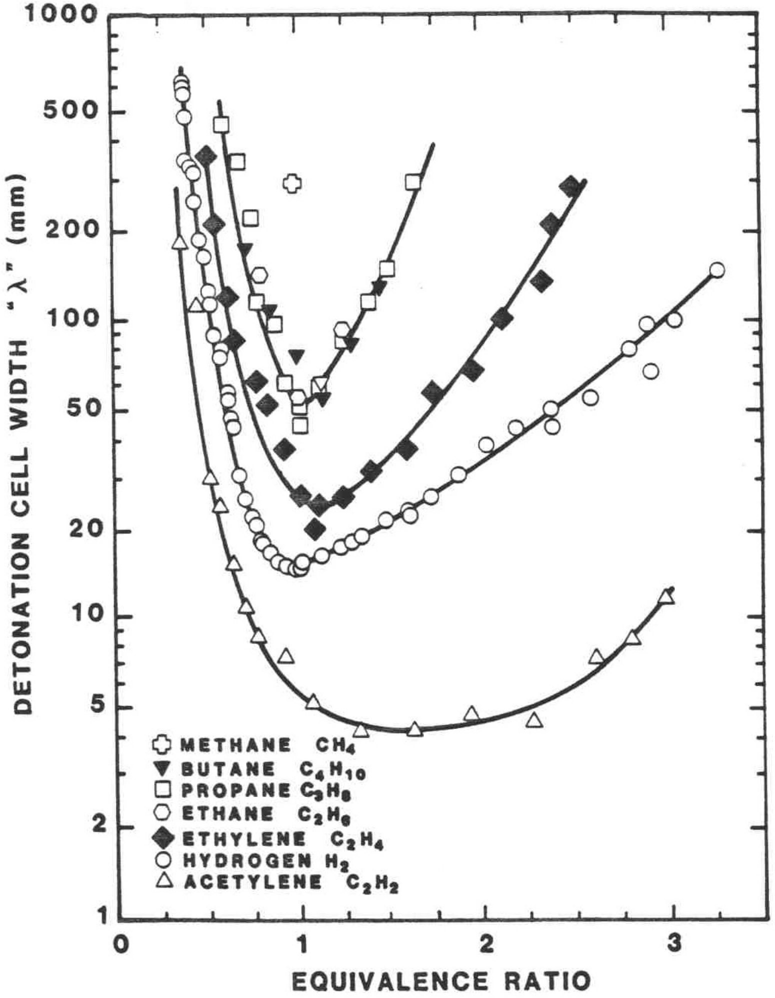
2H2+O2+17Ar at 20kPa

(Austin&Shepherd)



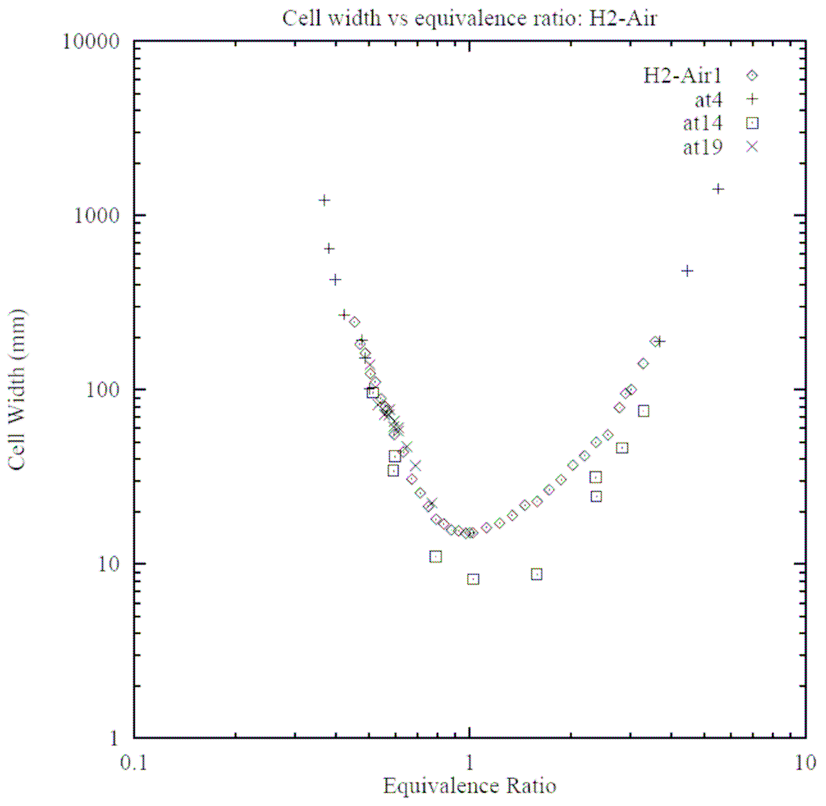
Detonation cell size

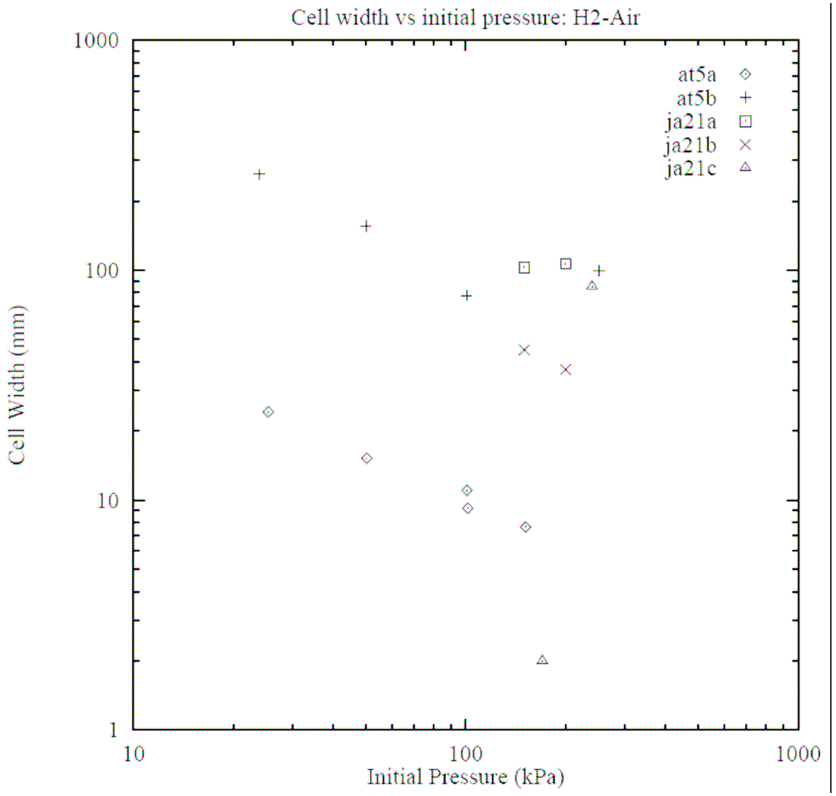
Fuel-air mixtures



Detonation cell size

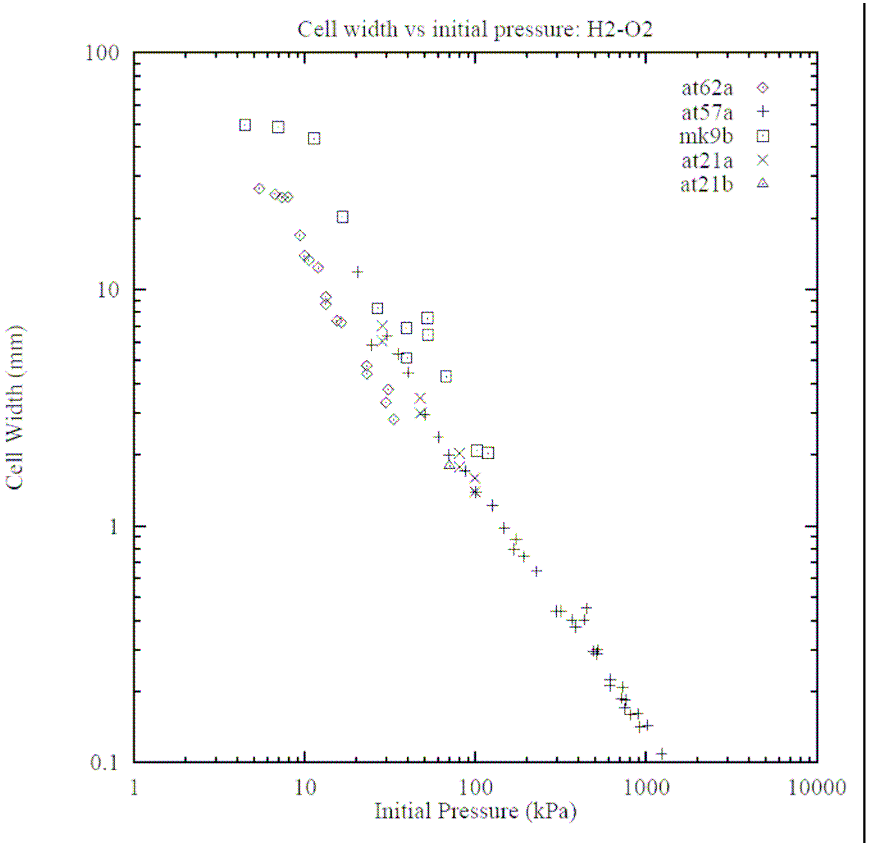
hydrogen-air mixtures





Detonation cell size

hydrogen-oxygen mixtures

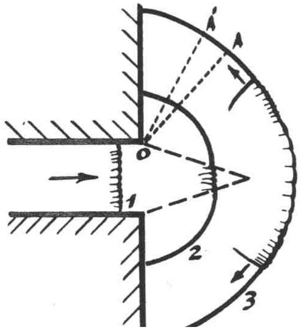


Detonation limits

- propagation limit: $d_{tube} > d_f$

$$d_f = \lambda/\pi$$

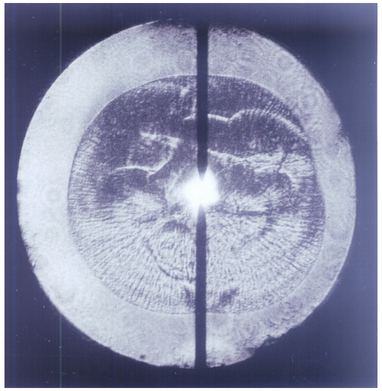
- critical tube diameter for diffraction: $d_{tube} > d_c$



Tube: $d_c = 13\,\lambda$

Square channel: $l_c = 10\,\lambda$

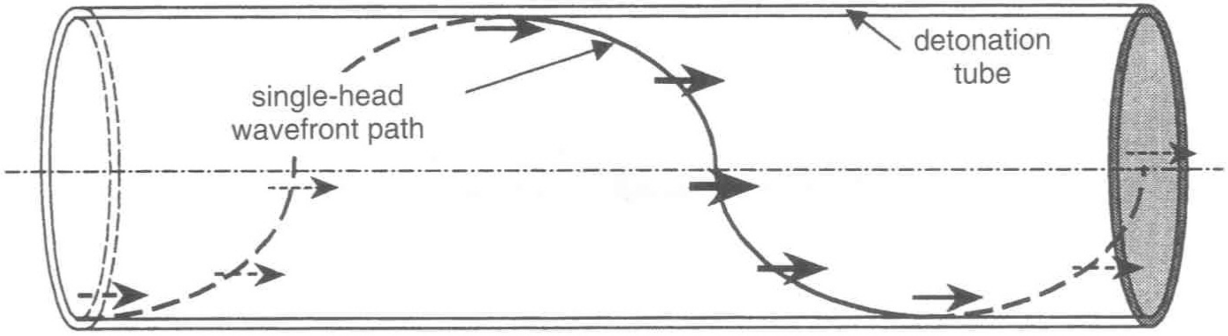
- Critical energy for direct initiation: $E > E_c$



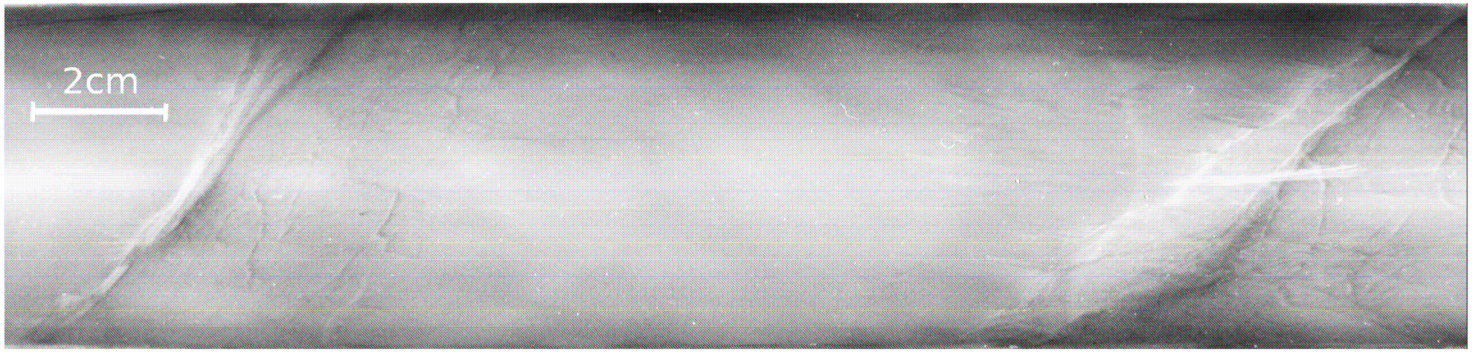
$$E_c = 430\rho_0 U_{CJ}^2 \lambda^3$$

Detonation propagation limits

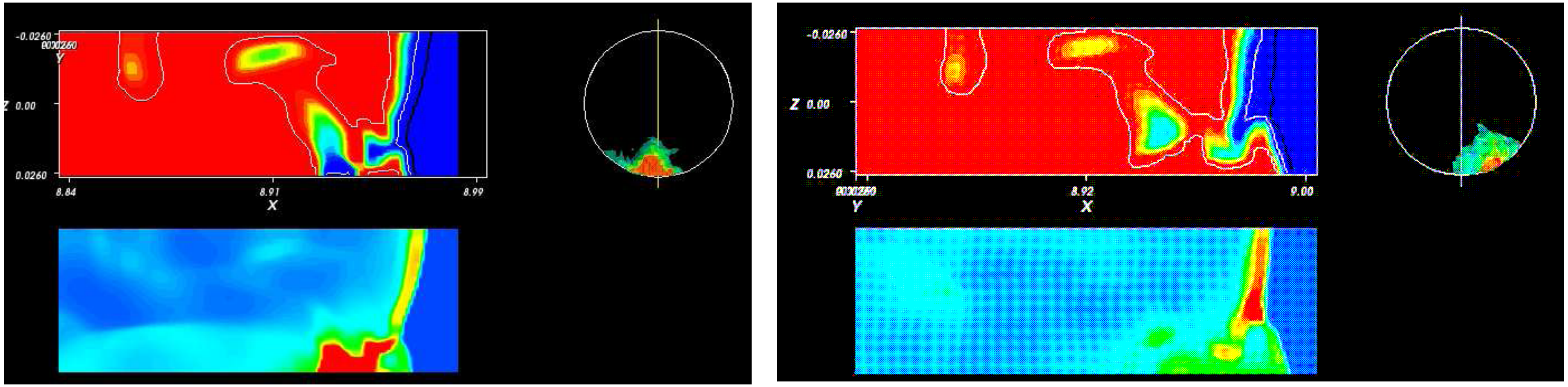
- single spin (head)



Single spin detonation



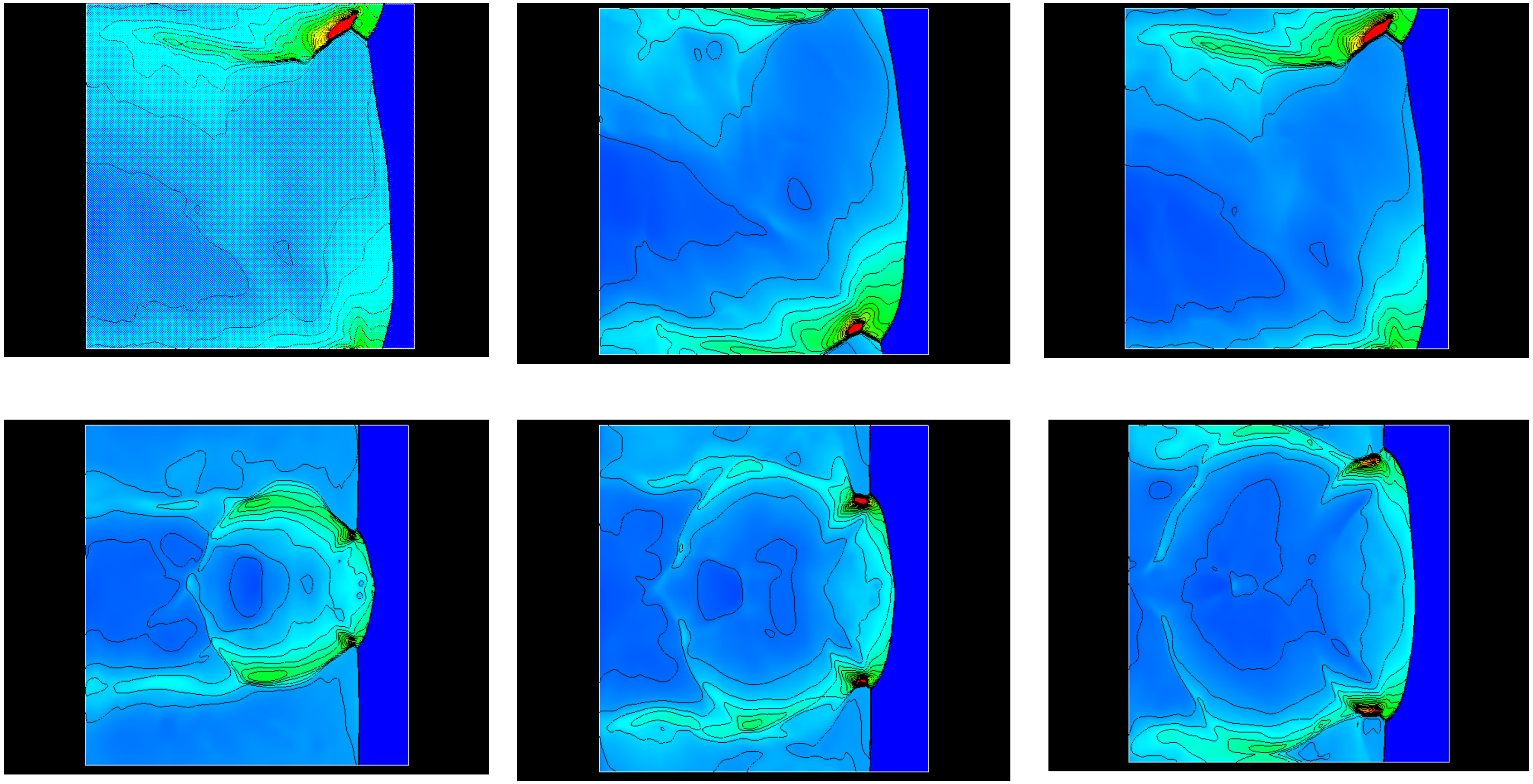
Experimental soot traces for $CH_4 + 2O_2$ mixture at P0 = 50mbar.



CH_4/O_2 spinning detonation simulation

Source: F.Virot et al., 21st ICDERS, Poitiers, 2007

Single spin detonation

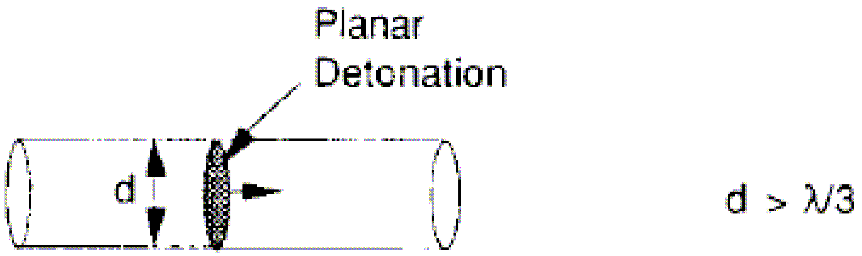


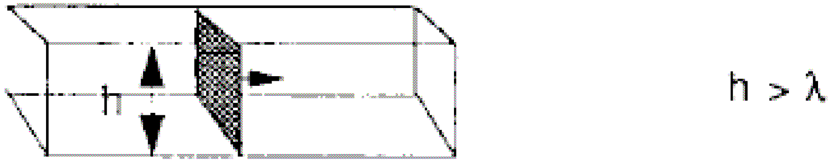
Comparison of pressure contours on the wall

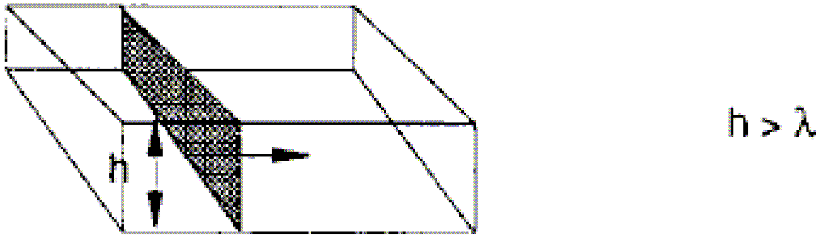
Source: N.Tsuboi et al., 21st ICDERS, Poitiers, 2007

Detonation limits

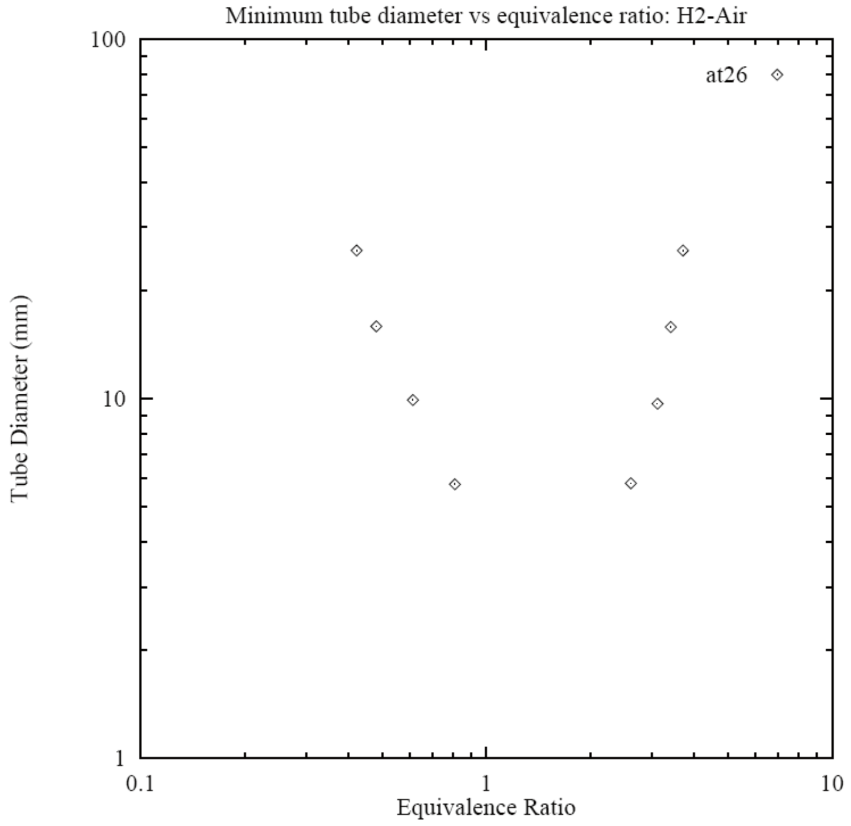
- propagation limit

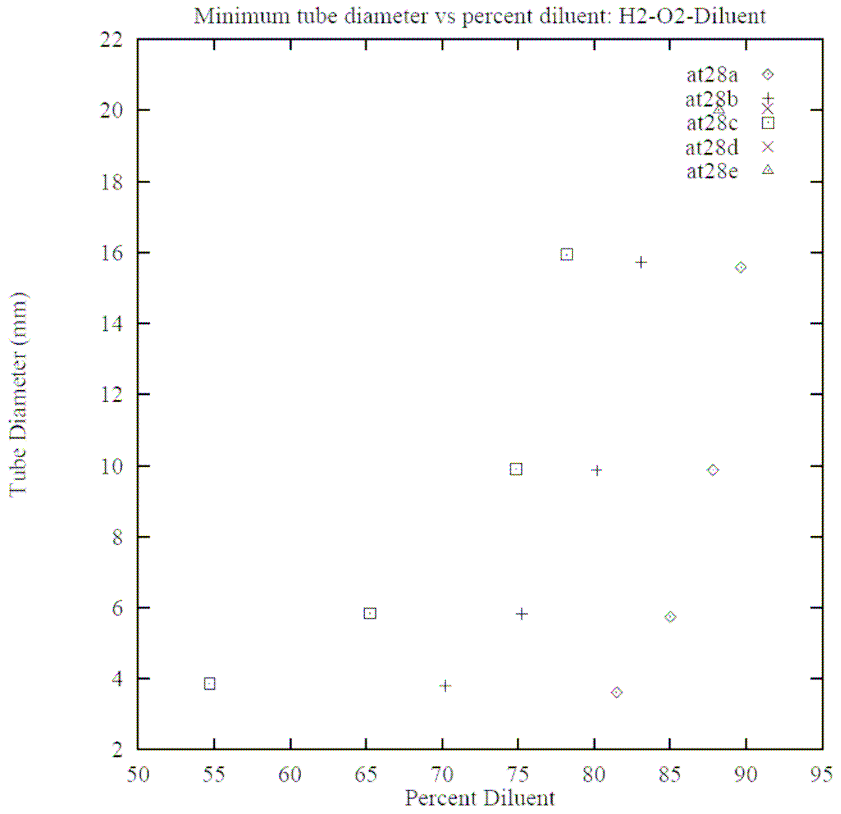






Minimum tube diameter



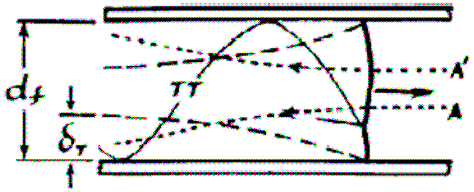


at28a: T = 298 K, P = 100 kPa, Φ = 1, 80-90% Ar; at28b: T = 298 K, P = 100 kPa, Φ = 1, 70-80% He; at28c: T = 298 K, P = 100 kPa, Φ = 1, 55-75% N2; at28d: T = 298 K, P = 100 kPa, Φ = 1, 90% Ar;

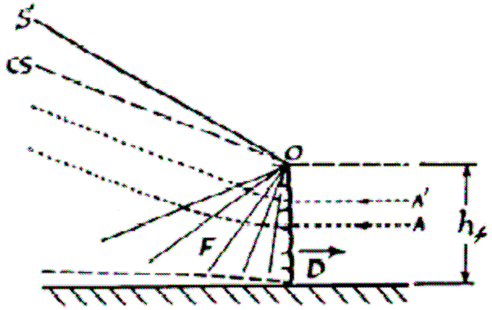
at28e: T = 298 K, P = 100 kPa, Φ = 1, 86% He

Detonation propagation geometries

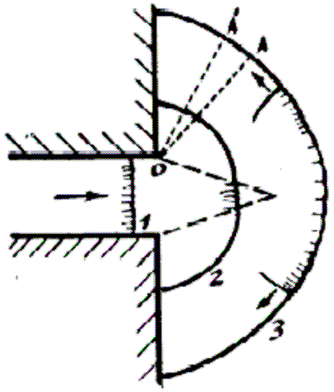
- Confined



- Unconfined



- Diffraction



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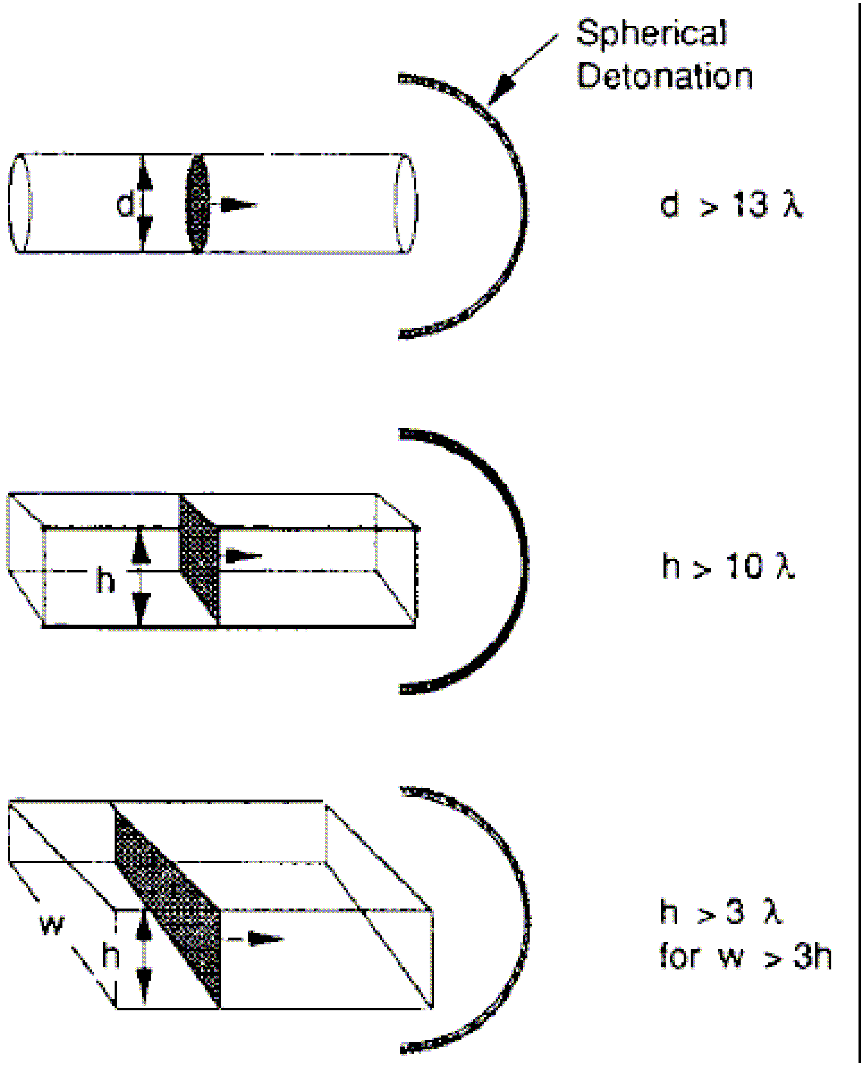
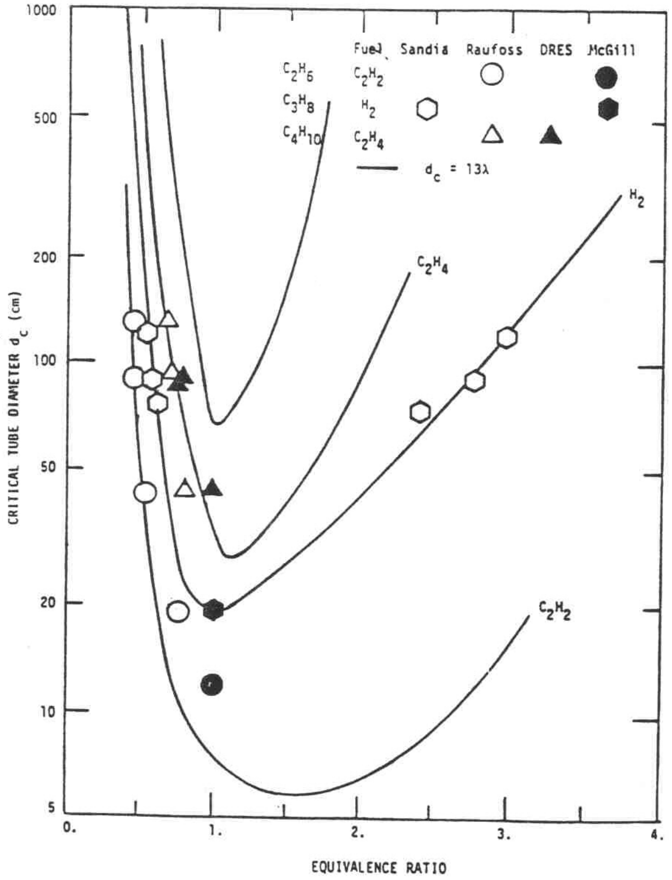
Detonation critical tube diameter

- critical tube diameter for diffraction to unconfined space

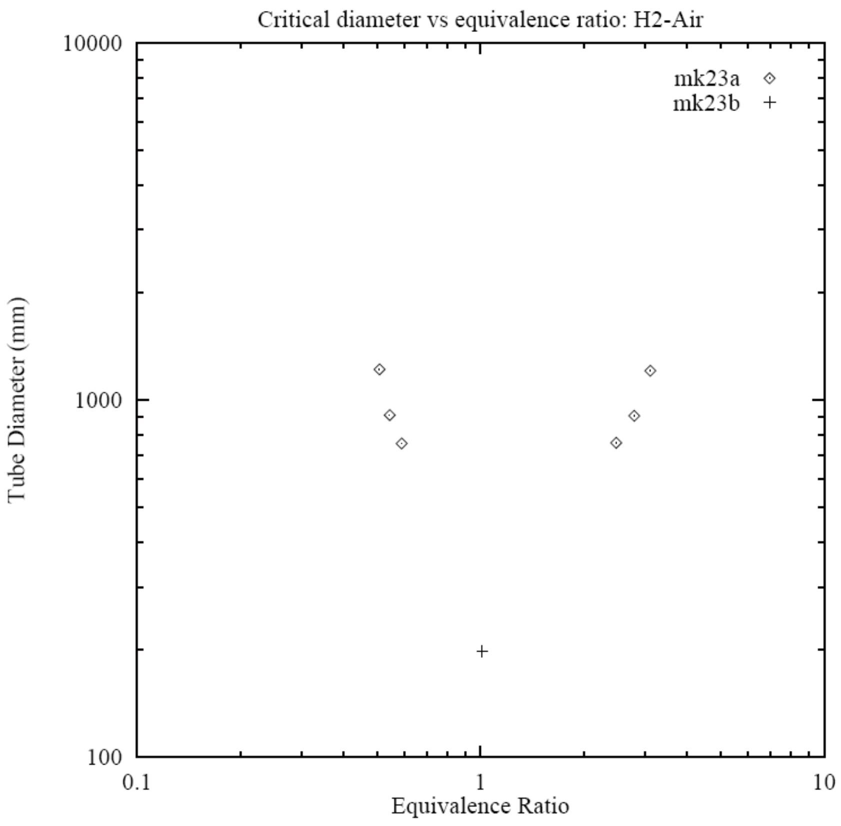


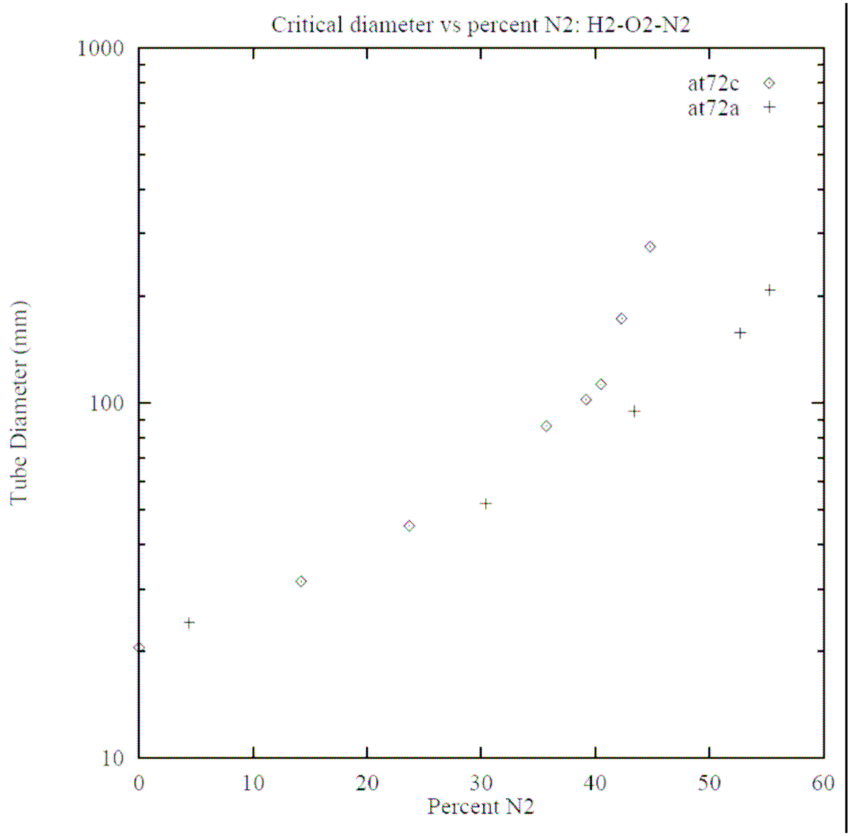
Critical tube diameter

Fuel-Air Mixtures ($T_o = 300$ K, $P_o = 1$ atn

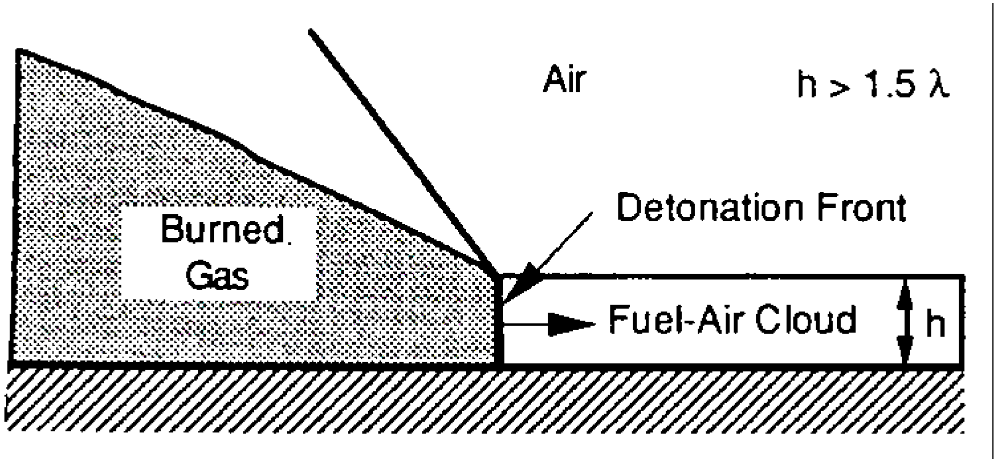


Critical tube diameter



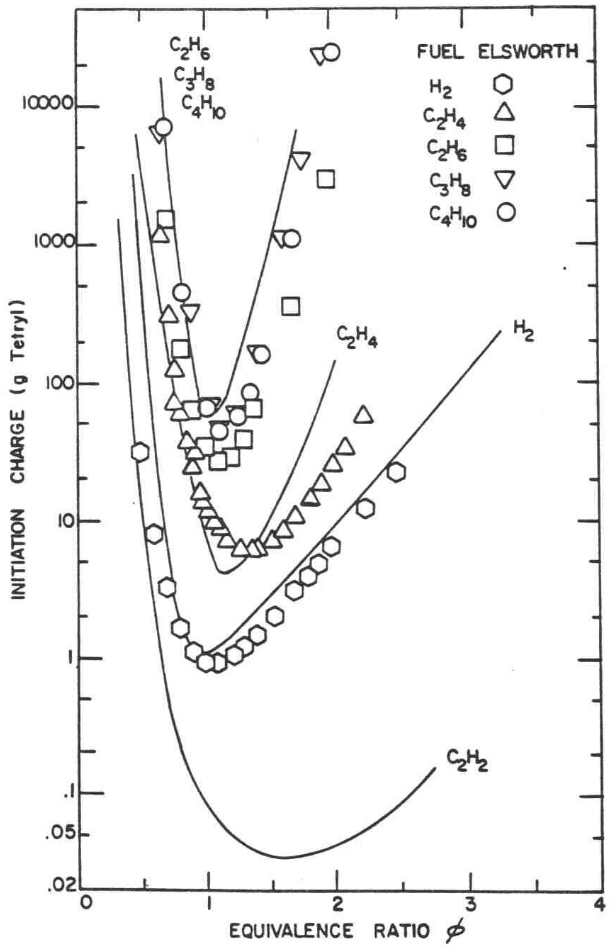


Critical mixture layer

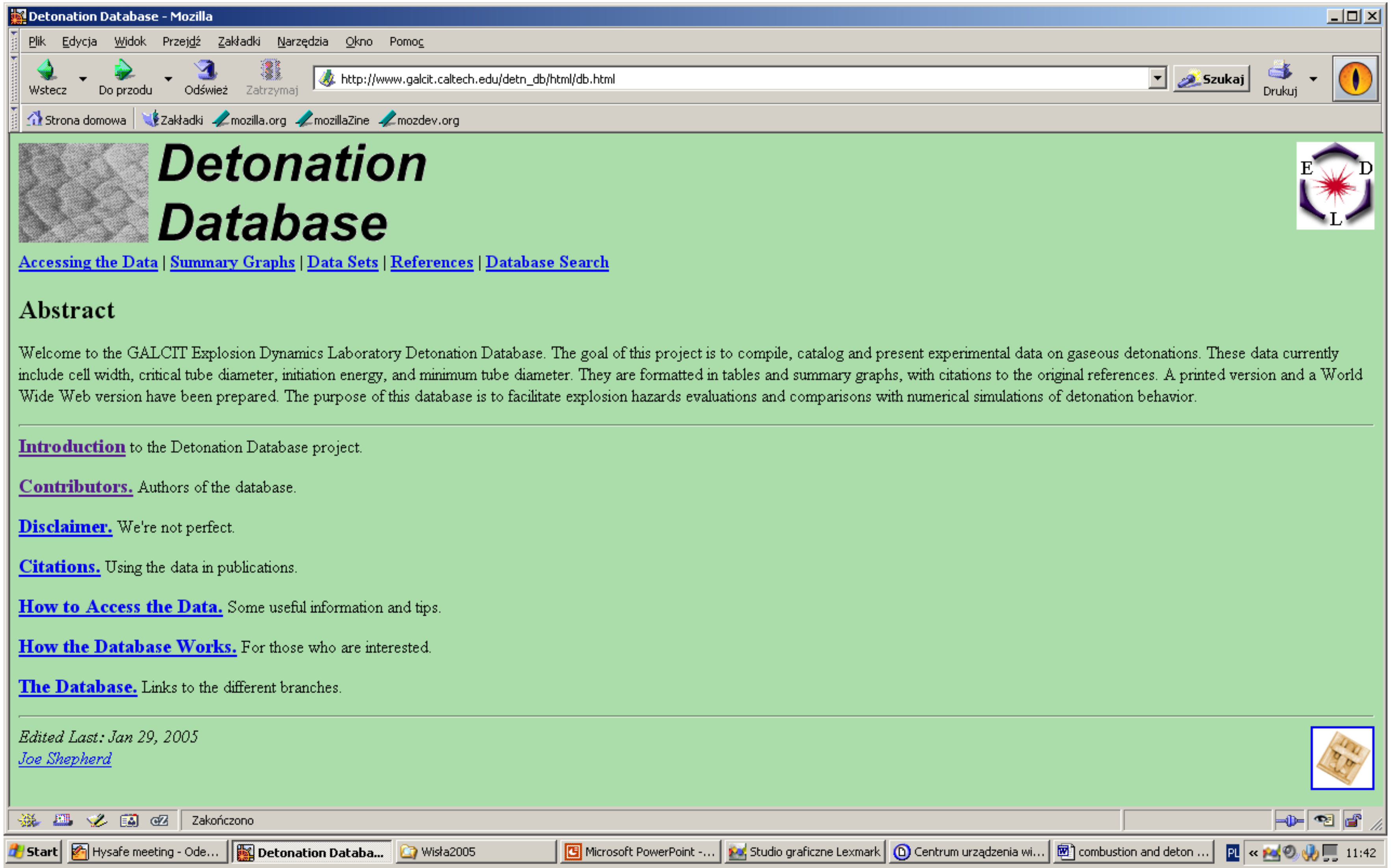


Critical energy for direct initiation

Fuel-Air Mixtures (T_o = 300 K, P_o = 1 atn



Detonation database



Detonation Database

Accessing the Data | Summary Graphs | Data Sets | References | Database Search

Abstract

Welcome to the GALCIT Explosion Dynamics Laboratory Detonation Database. The goal of this project is to compile, catalog and present experimental data on gaseous detonations. These data currently include cell width, critical tube diameter, initiation energy, and minimum tube diameter. They are formatted in tables and summary graphs, with citations to the original references. A printed version and a World Wide Web version have been prepared. The purpose of this database is to facilitate explosion hazards evaluations and comparisons with numerical simulations of detonation behavior.

Introduction to the Detonation Database project.

Contributors. Authors of the database.

Disclaimer. We're not perfect.

Citations. Using the data in publications.

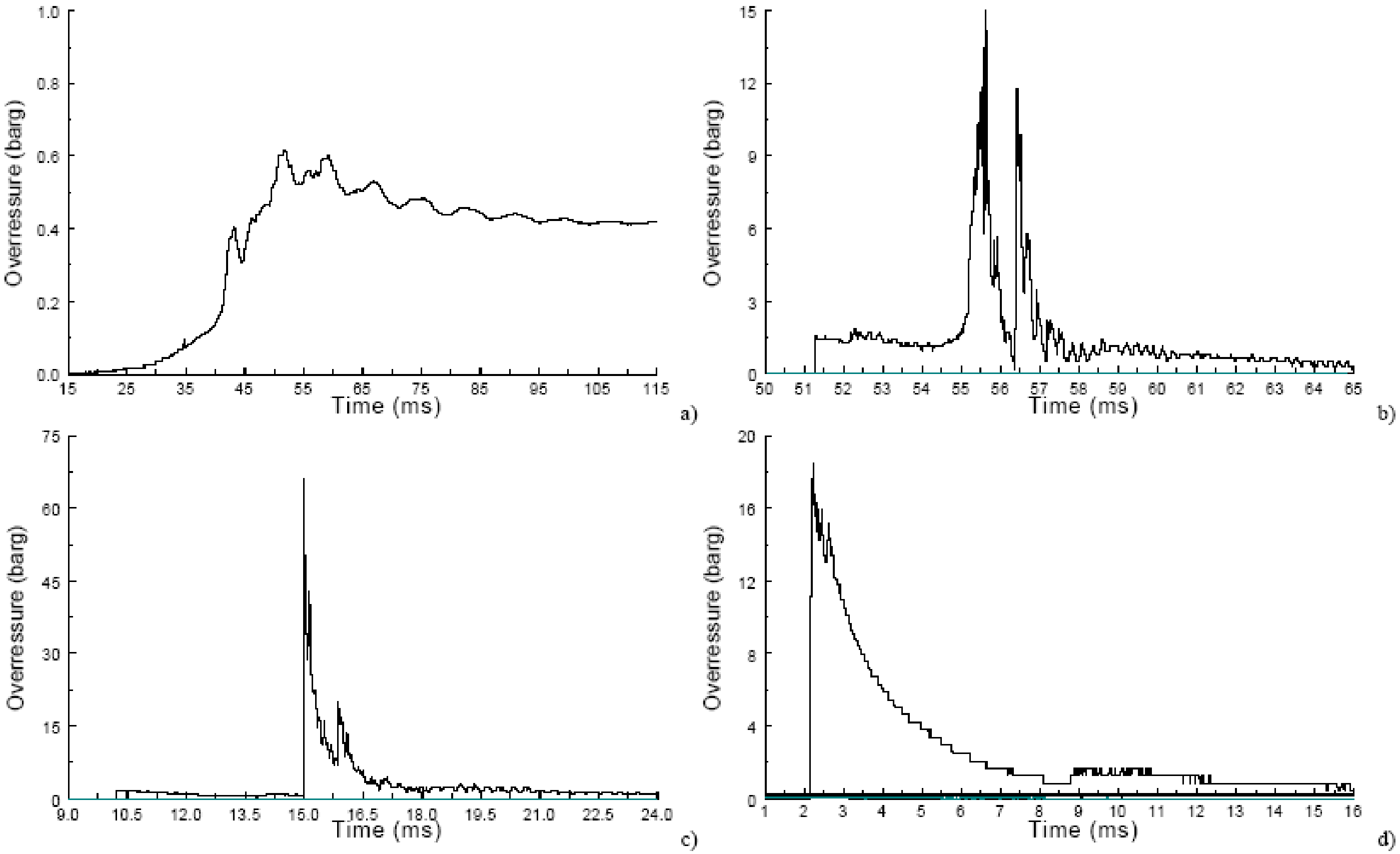
How to Access the Data. Some useful information and tips.

How the Database Works. For those who are interested.

The Database. Links to the different branches.

Edited Last: Jan 29, 2005
Joe Shepherd

Deflagration and detonation pressure



a) Slow deflagration; b) fast deflagration; c) overdriven detonation DDT; d) CJ detonation

Transition distance to DDT

Depends on:

- Combustible mixture (chemistry and thermodynamics)
- Tube diameter – for hydrogen-air in smooth tube:
  - 8 m in 50 mm tube
  - 30 m in 400 mm tube
- Ignition source
- Obstacles, wall roughness
- Initial conditions
- ???

DDT in tube with obstacles

Flame velocity versus fuel concentration for H2-air mixtures

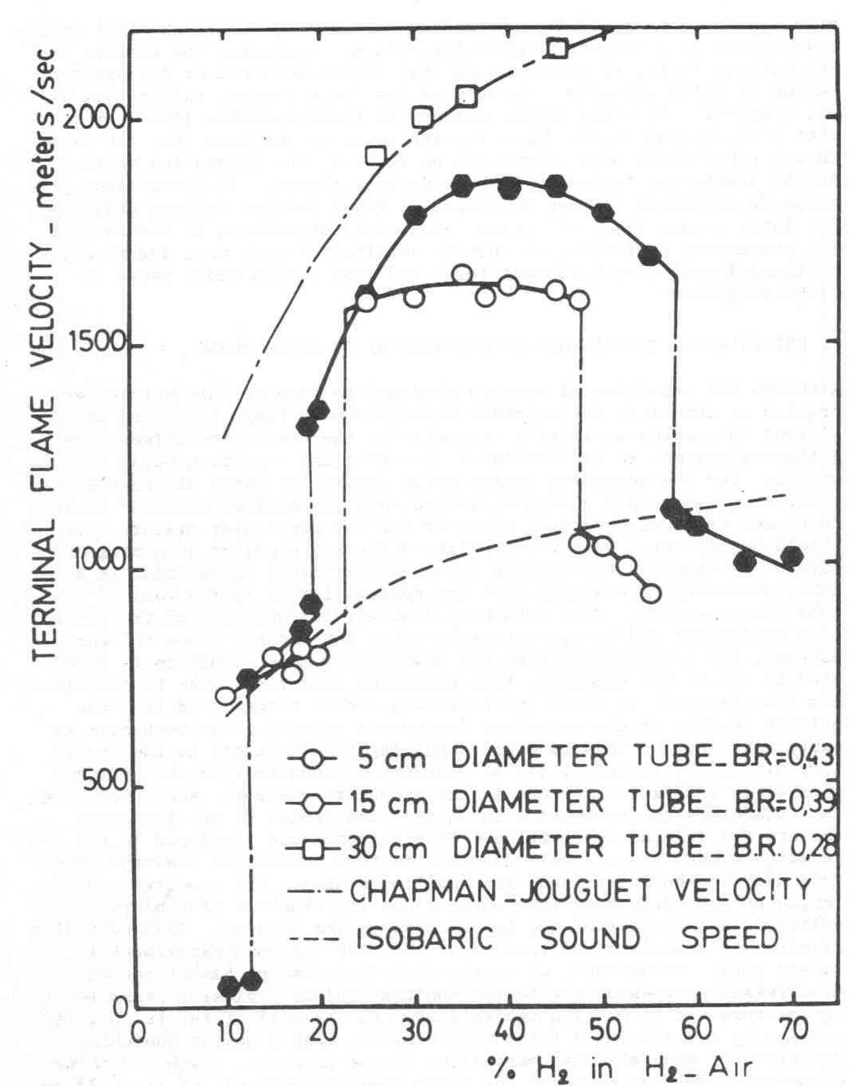
10 m long tubes of 5 cm, 15 cm and 30 cm in internal diameter with obstacles (orifice plates).

BR = 1 - d2/D2 – blockage ratio

d - orifice diameter

D - tube diameter

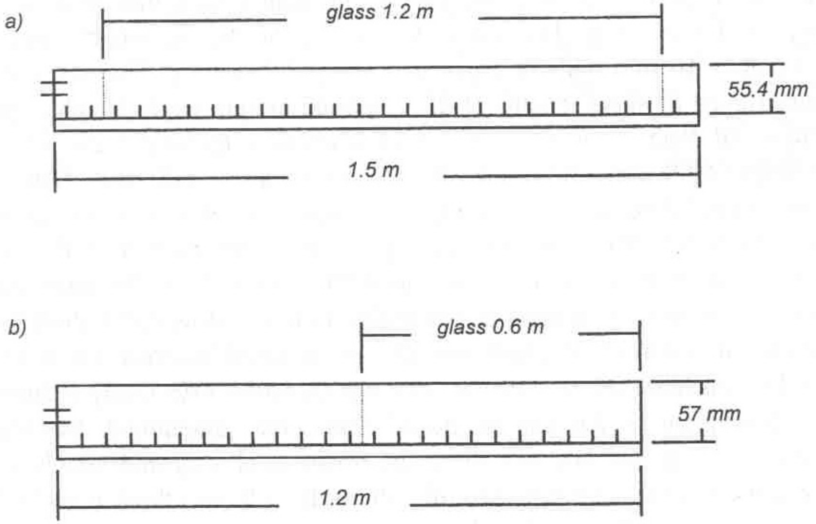
(Lee, 1986)



Regimes of flame propagation in tubes with obstacles

- **quenching regime** - flame fails to propagate,
- **subsonic regime** - flame is traveling at a speed that is slower than the sound speed of the combustion products,
- **choked regime (CJ Deflagration)** - flame speed is comparable with the sound speed of the combustion products,
- **quasi-detonation regime** - velocity between the sonic and Chapman-Jouguet (CJ) velocity,
- **CJ detonation regime** - velocity is equal to the CJ detonation velocity

DDT in tube with obstacles

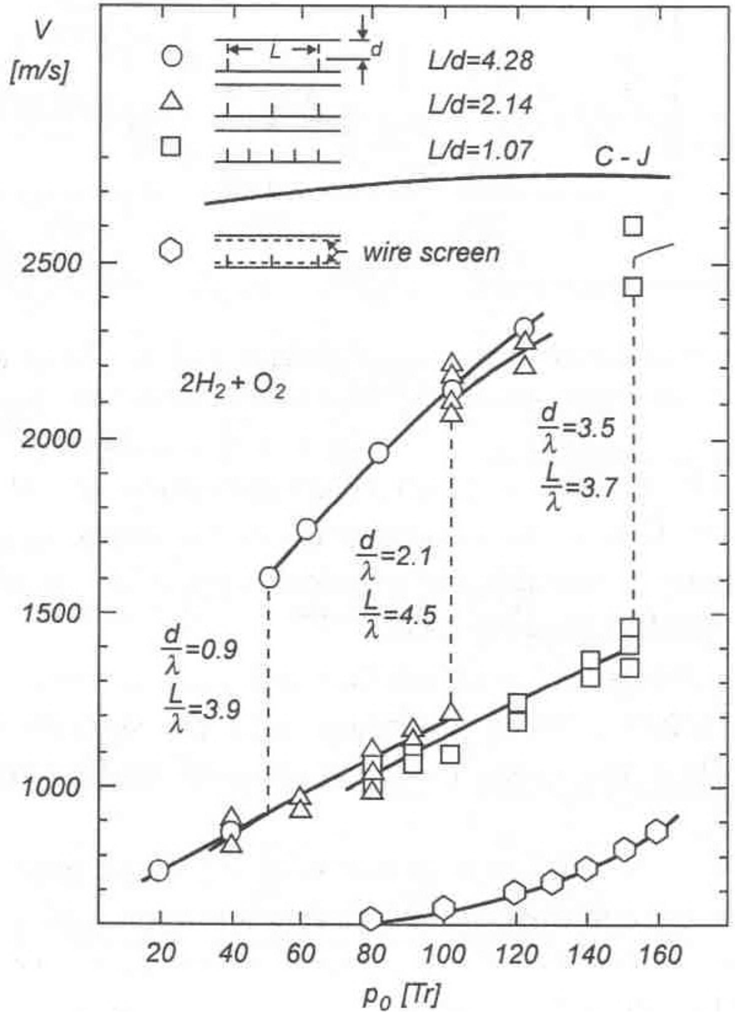


Stoichiometric hydrogen-oxygen

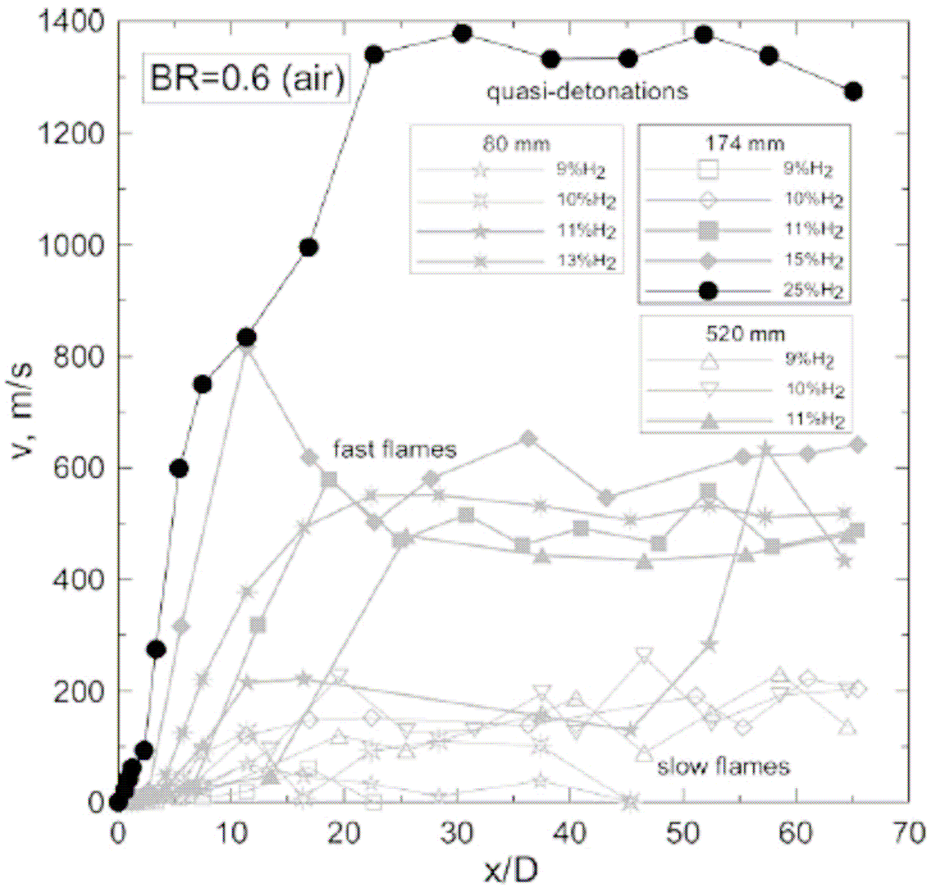
Pressure 20-150 torr

Ignition by exploding wire

(Teodorczyk, et al..1988)



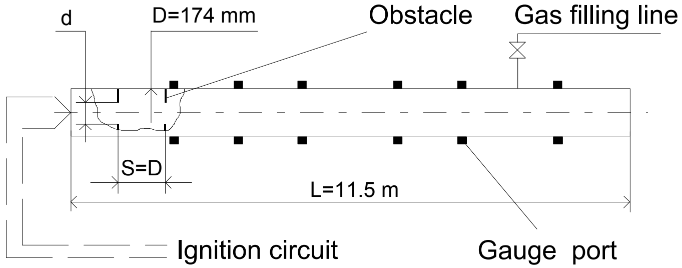
Regimes of flame propagation leading to DDT

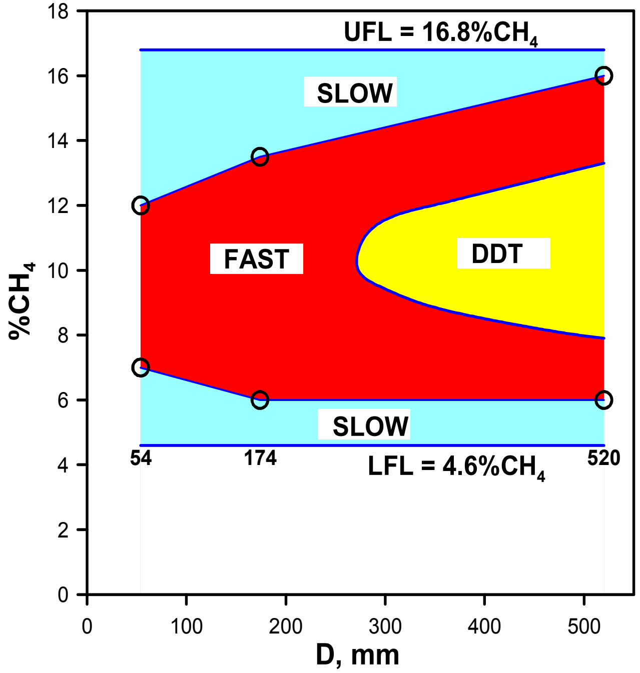


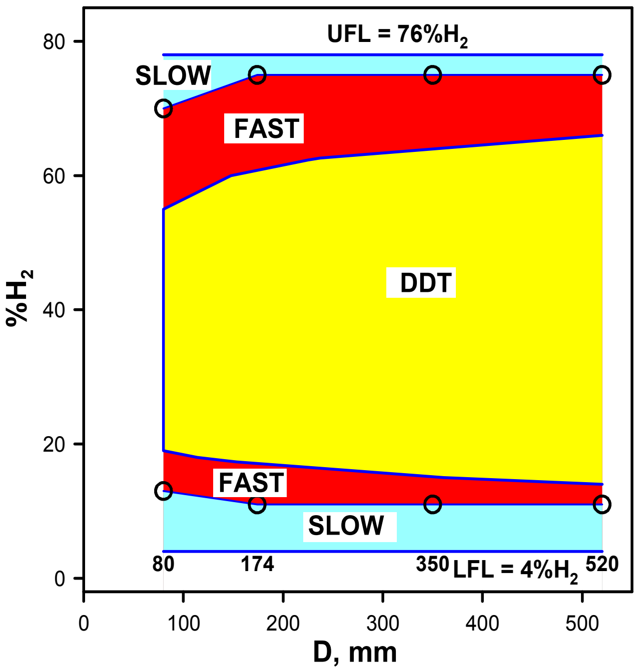
Propagation speeds of flames and detonations along the tube versus ratio of distance, *x*, to tube diameter, *D* (hydrogen–air mixtures).

Source: S.Dorofeev et al., *Journal of Loss Prevention in the Process Industries 14 (2001) 583–589*

Flame acceleration and DDT in obstructed channels

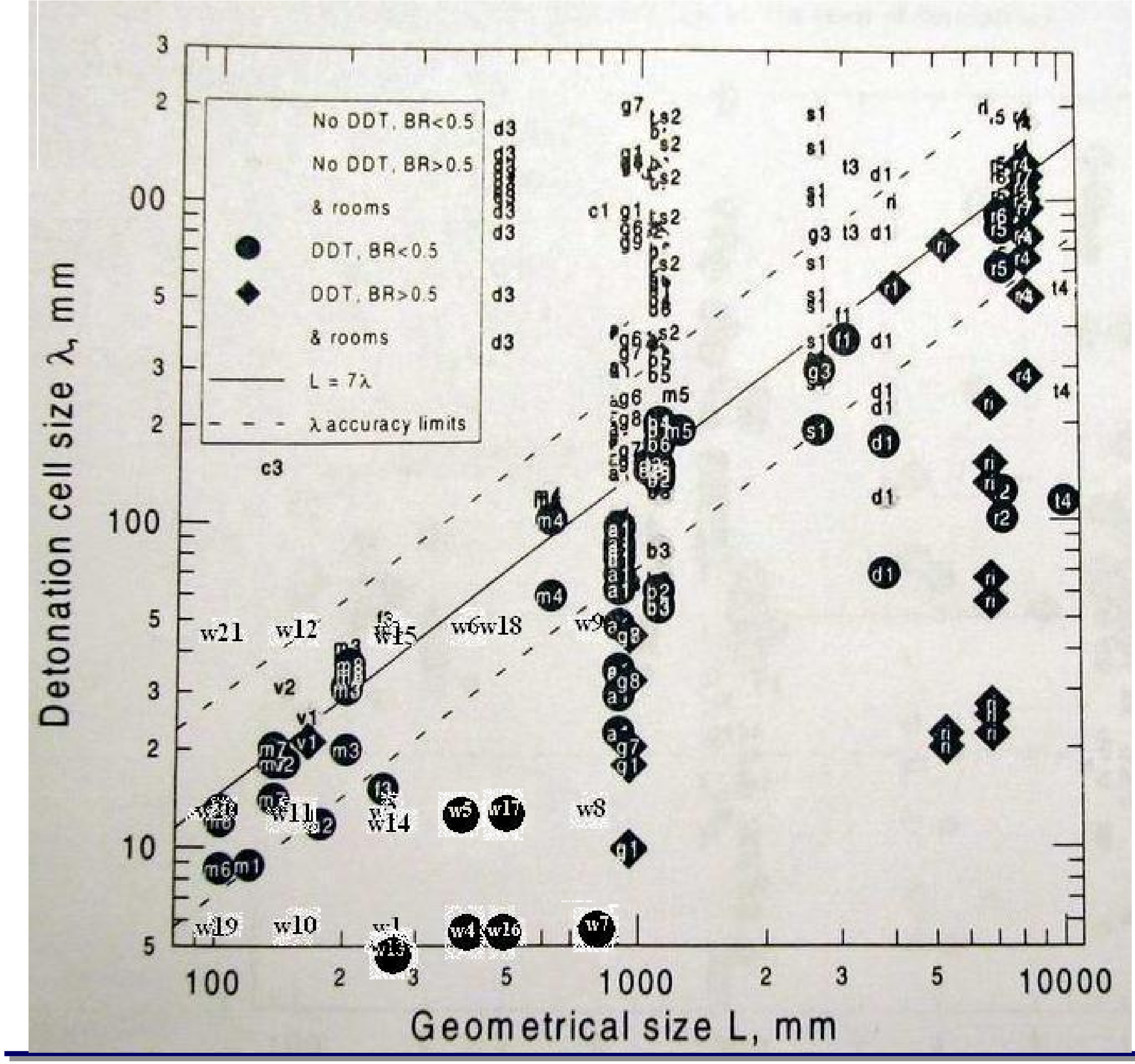






(Courtesy of M.Kuznetzov)

DDT limits in obstructed channels (H_2-air)



Geometrical size

$$L = \frac{L_1}{1-\alpha}$$

where

$$L_1 = \frac{L+H}{2}$$

$$\alpha = \frac{1-h}{H}$$

L – distance between obstacles

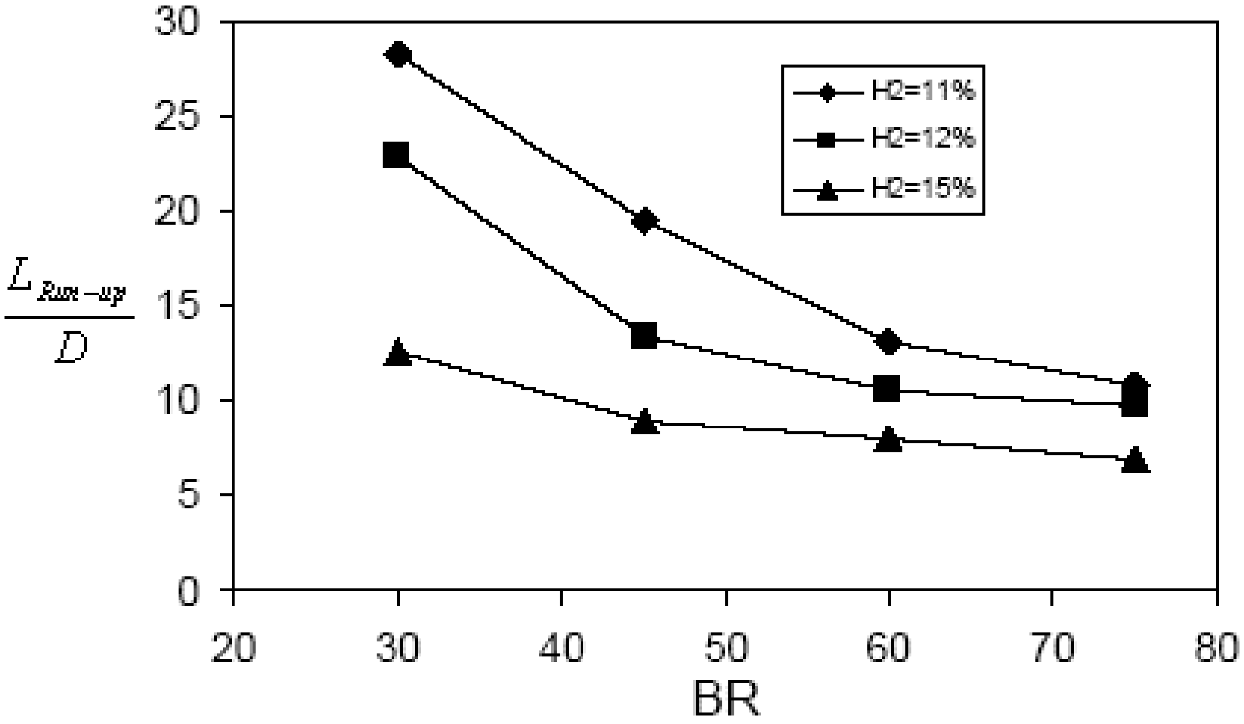
H – channel height

h – obstacle height

(Courtesy of S.Dorofeev)

Run-up distance for DDT in obstructed channels

In tubes at 0.1 MPa, H_2-air



(Courtesy of S.Dorofeev)

DDT simulations

V.Gamezo et al., 31st Symposium International on Combustion, Heidelberg 2006

- stoichiometric hydrogen-air mixture at 0.1 MPa
- Reactive Navier-Stokes equations with one-step Arrhenius kinetics
- 2D channel with obstacles
- Grid: 0.02 mm (min)