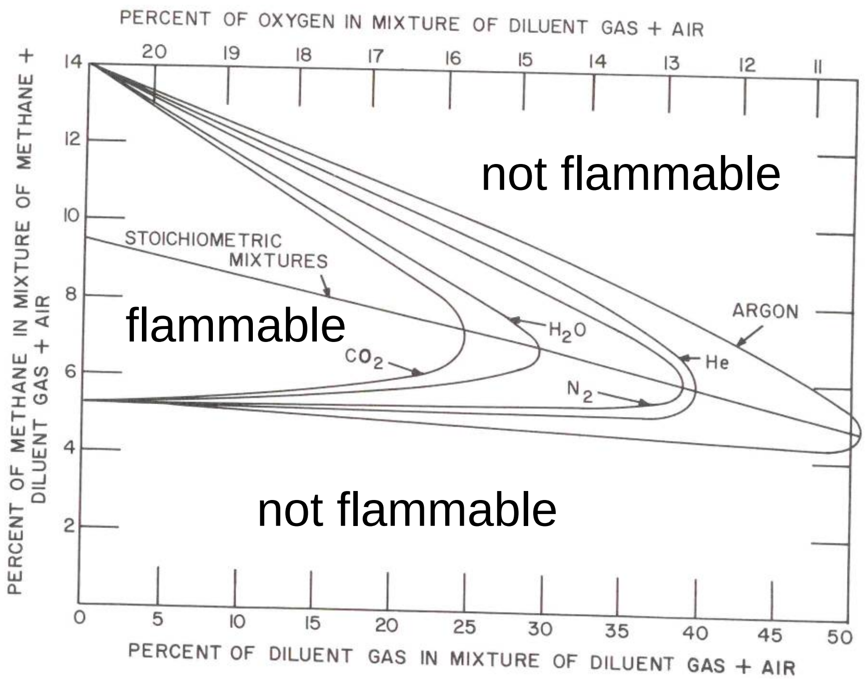
Final Exam

- **Wednesday, Dec. 17, 7 am to 10 am**
- Closed Book, Closed Notes
- Combustion Terms
  - From the sheet on the "pre-test"
- Short Answers
  - Describe this, how does this work, etc.
- Problems
  - Like the homework
  - Basis for solid fuels (daf?), oxygen demand, etc.
  - Bring a calculator!!
- I am aiming for 1-2 hours (not 3!)
  - Come at 7 am anyway

Outline

1. Flammability Limits
2. Flame Speeds
   - Flashback
   - Laminar vs. Turbulent
3. Explosions
   - Deflagration vs. Detonation
4. Pepcon video
5. Lab demos

1. Flammability Limits



(from Lewis and von Elbe, 1987)

- Measured in premixed gases
- Fuel Rich limit
- Fuel Lean limit
- Effects of diluents (see figure at left)
- Also functions of pressure
- Must be measured

Flammability Limits

(in air at 1 atm total pressure)

Species	Lean (ϕ)	Rich (ϕ)
Acetylene	0.19	∞
Carbon Monoxide	0.34	6.76
Methane	0.46	1.64
Methanol	0.48	4.08
Ethane	0.50	2.72
Ethylene	0.41	6.1
Hydrogen	0.14	2.54
Propane	0.51	2.83
n-Decane	0.36	3.92
n-Octane	0.51	4.25

(from Turns, p. 236)

(from The John Zink Combustion Handbook, 2001, p. 45)

TABLE 2.4 Combustion Data for Hydrocarbons

Hydrocarbon	Formula	Higher Heating Value (vapor), Btu lb_m^{-1}	Theor. Air/fuel Ratio, by mass	Max Flame Speed, (ft s^{-1})	Adiabatic Flame Temp (in air) (°F)	Ignition Temp (in air) (°F)	Flash Point (°F)	Flammability Limits (in air) (% by volume)	
				Paraffins or Alkanes					
Methane	CH_4	23875	17.195	1.1	3484	1301	Gas	5.0	15.0
Ethane	C_2H_6	22323	15.899	1.3	3540	968–1166	Gas	3.0	12.5
Propane	C_3H_8	21669	15.246	1.3	3573	871	Gas	2.1	10.1
n-Butane	C_4H_{10}	21321	14.984	1.2	3583	761	–76	1.86	8.41
iso-Butane	C_4H_{10}	21271	14.984	1.2	3583	864	–117	1.80	8.44
n-Pentane	C_5H_{12}	21095	15.323	1.3	4050	588	< –40	1.40	7.80
iso-Pentane	C_5H_{12}	21047	15.323	1.2	4055	788	< –60	1.32	9.16
Neopentane	C_5H_{12}	20978	15.323	1.1	4060	842	Gas	1.38	7.22
n-Hexane	C_6H_{14}	20966	15.238	1.3	4030	478	–7	1.25	7.0
Neohexane	C_6H_{14}	20931	15.238	1.2	4055	797	–54	1.19	7.58
n-Heptane	C_7H_{16}	20854	15.141	1.3	3985	433	25	1.00	6.00
Triptane	C_7H_{16}	20824	15.151	1.2	4035	849	—	1.08	6.69
n-Octane	C_8H_{18}	20796	15.093	—	—	428	56	0.95	3.20
iso-Octane	C_8H_{18}	20770	15.093	1.1	—	837	10	0.79	5.94
				Olefins or Alkenes					
Ethylene	C_2H_4	21636	14.807	2.2	4250	914	Gas	2.75	28.6
Propylene	C_3H_6	21048	14.807	1.4	4090	856	Gas	2.00	11.1
Butylene	C_4H_8	20854	14.807	1.4	4030	829	Gas	1.98	9.65
iso-Butene	C_4H_8	20737	14.807	1.2	—	869	Gas	1.8	9.0
n-Pentene	C_5H_{10}	20720	14.807	1.4	4165	569	—	1.65	7.70
				Aromatics					
Benzene	C_6H_6	18184	13.297	1.3	4110	1044	12	1.35	6.65
Toluene	C_7H_8	18501	13.503	1.2	4050	997	40	1.27	6.75
p-Xylene	C_8H_{10}	18663	13.663	—	4010	867	63	1.00	6.00
				Other Hydrocarbons					
Acetylene	C_2H_2	21502	13.297	4.6	4770	763–824	Gas	2.50	81
Naphthalene	$C_{10}H_8$	17303	12.932	—	4100	959	174	0.90	5.9

Note: Based largely on: "Gas Engineers' Handbook", American Gas Association, Inc., Industrial Press, 1967. For heating value in J kg^{-1}, multiply the value in Btu lb_m^{-1} by 2324. For flame speed in m s^{-1}, multiply the value in ft s^{-1} by 0.3048.

Note: These adiabatic flame temperatures are a little bit off!

REFERENCES

American Institute of Physics Handbook, 2nd ed., D.E. Gray, Ed., McGraw-Hill Book Company, 1963.

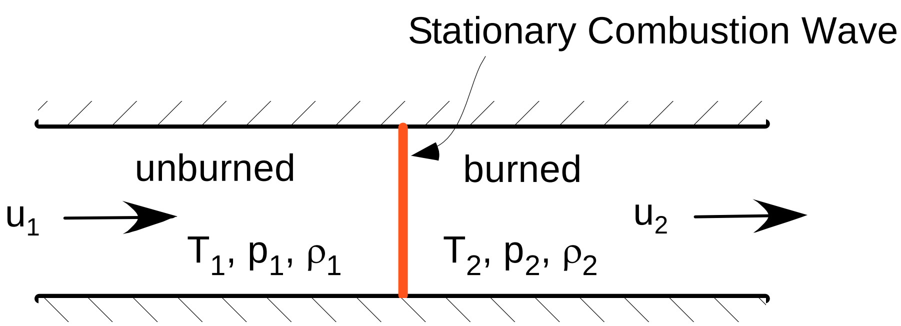
Chemical Engineers' Handbook, 4th ed., R.H. Perry, C.H. Chilton, and S.D. Kirkpatrick, Eds., McGraw-Hill Book Company, 1963.

Handbook of Chemistry and Physics, 53rd ed., R.C. Weast, Ed., The Chemical Rubber Company, 1972; gives the heat of combustion of 500 organic compounds.

Handbook of Laboratory Safety, 2nd ed., N.V. Steere, Ed., The Chemical Rubber Company, 1971.

Physical Measurements in Gas Dynamics and Combustion, Princeton University Press, 1954.

2. Flame Speeds



- Usually measured at stoichiometric conditions (ϕ = 1.0)
- Premixed gases
- Refers to velocity of unburned gas (u_1)
- Must be measured

(from In Air Zink Combustion Handbook, 2001, p. 45)

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Note: Based largely on: "Gas Engineers' Handbook", American Gas Association, Inc., Industrial Pres[illegible] 1967. For heating value in J kg^{-1}, multiply the value in Btu lb_m^{-1} by 2324. For flame speed in m s^{-1}, multiply the value in ft s^{-1} by 0.3048.

All the same!

Note: These adiabatic flame temperatures are a little bit off!

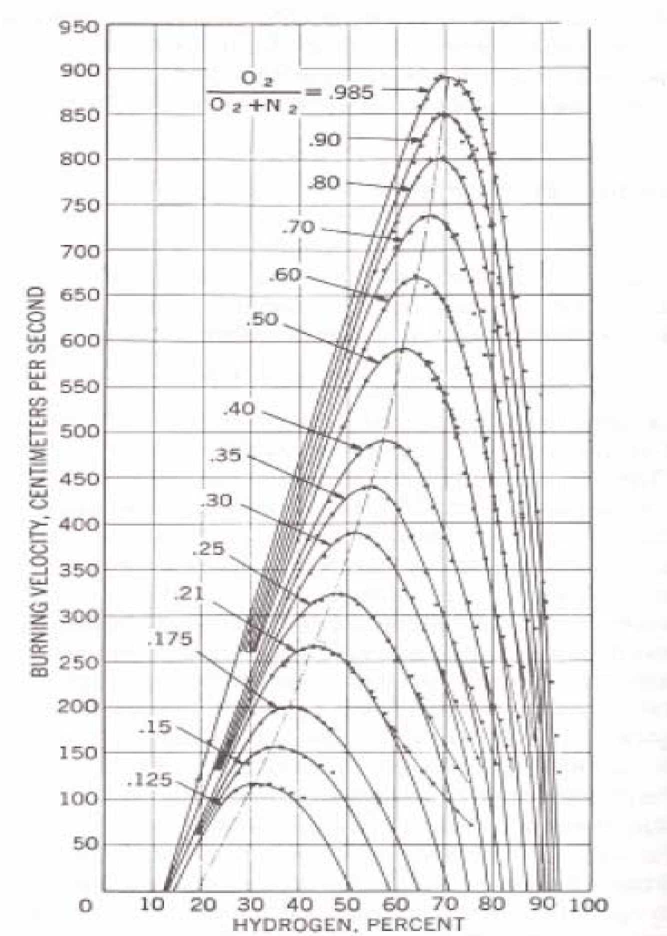
1.1 ft/s = 33 cm/s = 0.3 m/s

REFERENCES

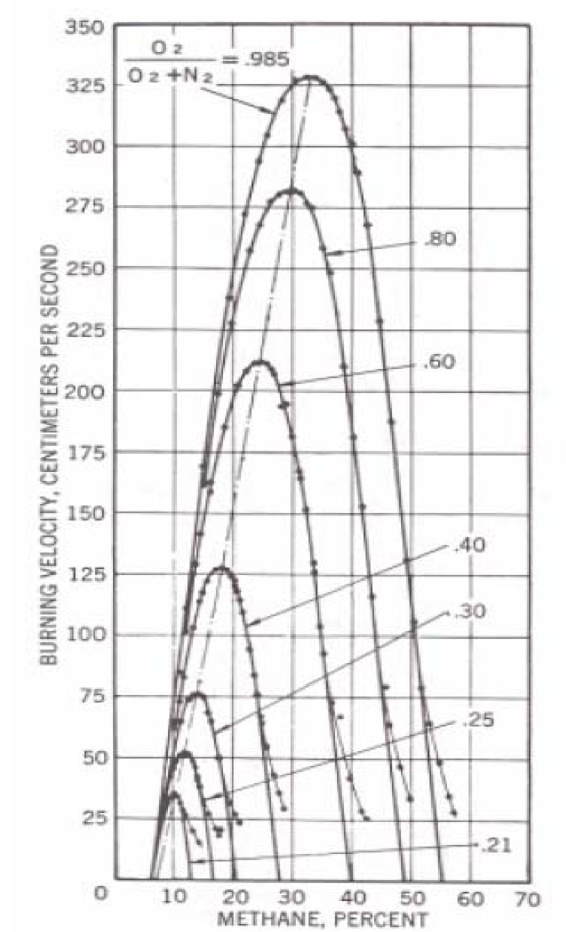
American Institute of Physics Ha[illegible] ompany, 19[illegible]
Chemical Engineers' Handbook, [illegible], Eds., McG[illegible] Hill Book Company, 1963.
Handbook of Chemistry and Phys[illegible] mpany, 197[illegible] s the heat of combustion of 500 organic compounds.
Handbook of Laboratory Safety, 2nd ed., N.V. Steere, Ed., The Chemical Rubber Company, 1971.
Physical Measurements in Gas Dynamics and Combustion, Princeton University Press, 1954.

Laminar Premixed Flame Speeds

(from Lewis and von Elbe, 1987, pp. 396, 401)

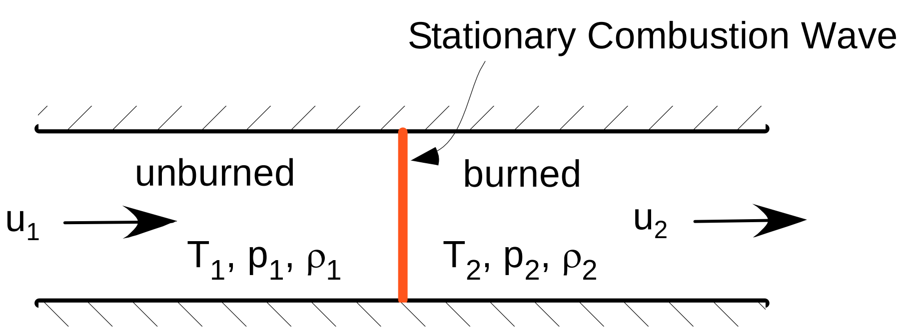


H_2, O_2, and N_2 at room T and atmospheric pressure



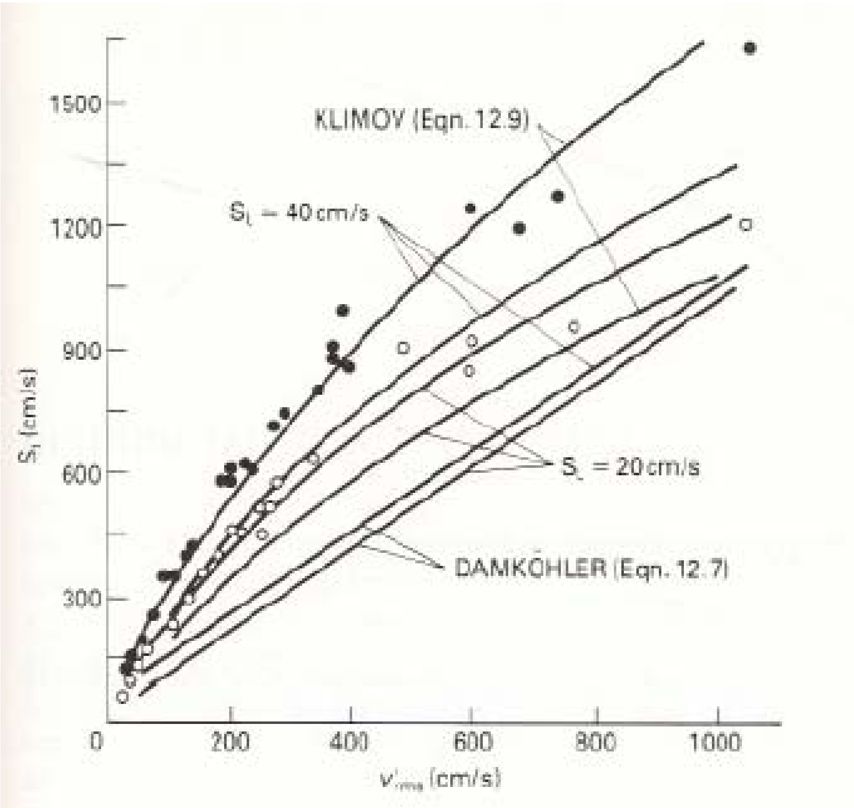
CH_4, O_2, and N_2 at room T and atmospheric pressure

Flame Speeds (cont.)



- Flashback:
  when $u_1 < S_L$
  (flame travels upstream)
- If $u_1 > S_L$, flashback is not possible!
- Refers to unburned gas velocity (u_1)
- Must get correct S_L
  (correct concentrations, pressure, temperature, etc.)
- Most fuels similar, except C_2H_2, C_2H_4, and H_2

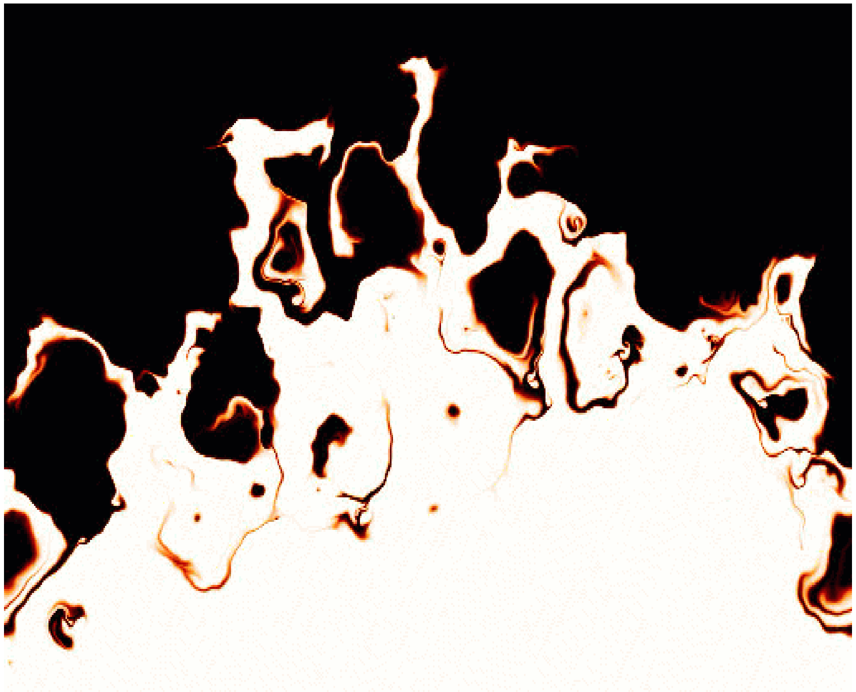
Turbulent Flame Speeds (S_t)



- Dependent on the turbulent fluctuation velocity (v'_{rms})
- Depends on strength of recirculation, geometry, etc.
- Can be much higher than laminar flame speed (S_L)

So for S_L = 0.4 m/s, S_t can be 15 m/s!!

Why is $S_t > S_L$?

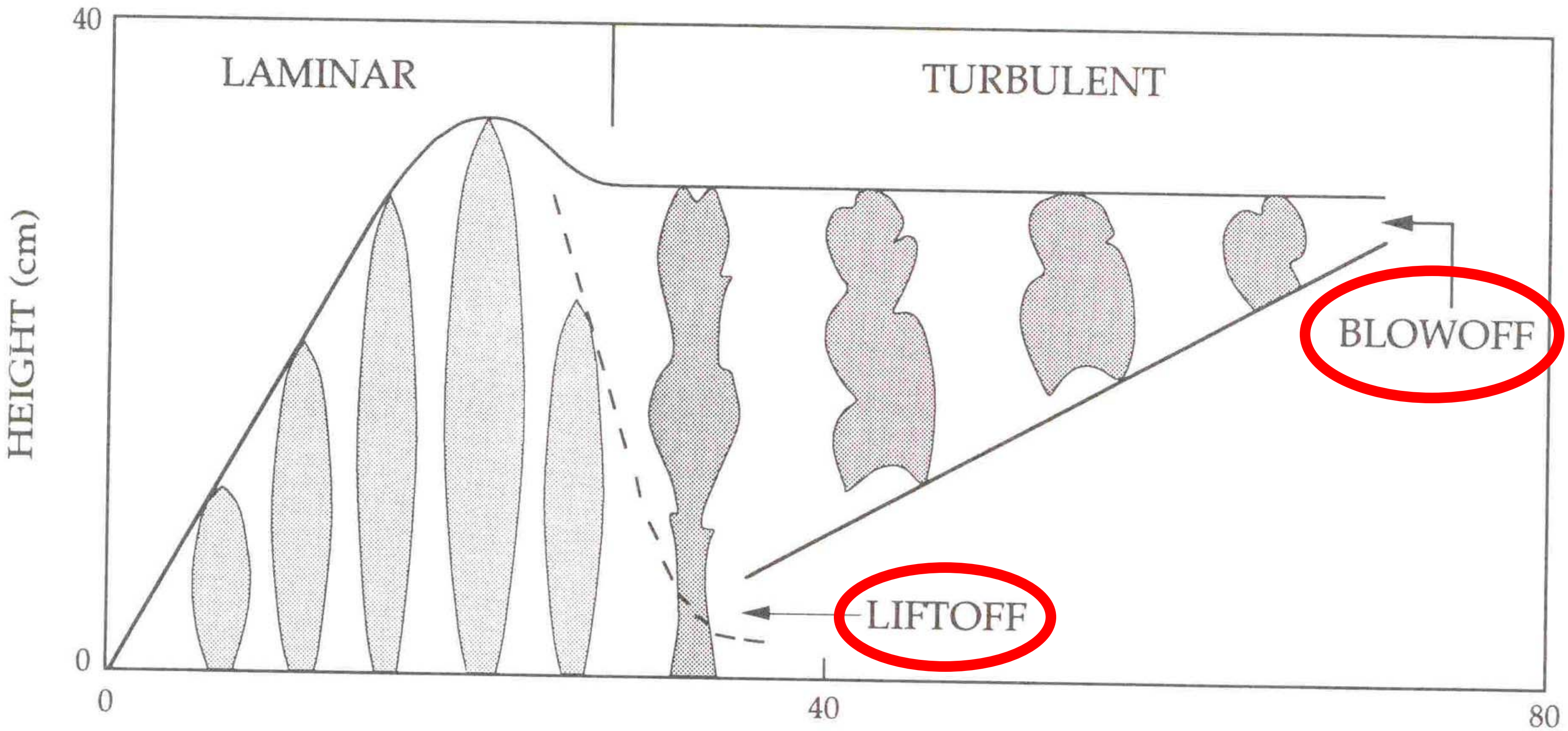


Movies:

http://flash.uchicago.edu/~nata/combustion/

- S_L depends on molecular diffusion of heat and radicals
  - relatively slow
- S_t depends on turbulent mixing of heat and radicals
  - can be much faster than molecular diffusion
- Greater surface area between burned and unburned in turbulent eddies

Effects of Turbulence on a Gaseous <u>Diffusion</u> Flame



Fuel Jet Exit Velocity (m/s)

(from Glassman, Combustion, 1977, p. 285)

Effects of Turbulence on Flames

A. Turbulent diffusion flames

- Enhanced mixing rate of oxidizer and fuel
- Enhanced surface area of flame (wrinkled)
- Higher heat release per unit volume

B. Premixed flames

- Enhanced mixing rate of combustion products with reactants
  - Heat
  - Radical species

3. Explosions

Explosion	Rapid expansion due to reaction (something blew up). Not really a technical term
Deflagration	Combustion at subsonic speeds
Conflagration	Large disastrous fire (may also mean a conflict or war)
Detonation	Combustion at supersonic speeds (includes shock wave)

Examples:

- Combustion of mixture in a tube with one or both ends open leads to deflagration.

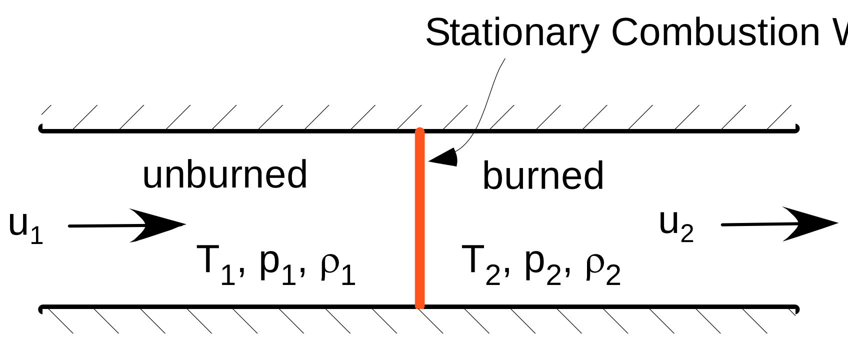
- Combustion of mixture in closed vessel may lead to a detonation if the flame speed is high enough. The combustion wave follows the shock (pressure) wave.

How Do You Get A Detonation?

- <u>Enormous</u> energy release per unit volume
  - Short time
  - Small space

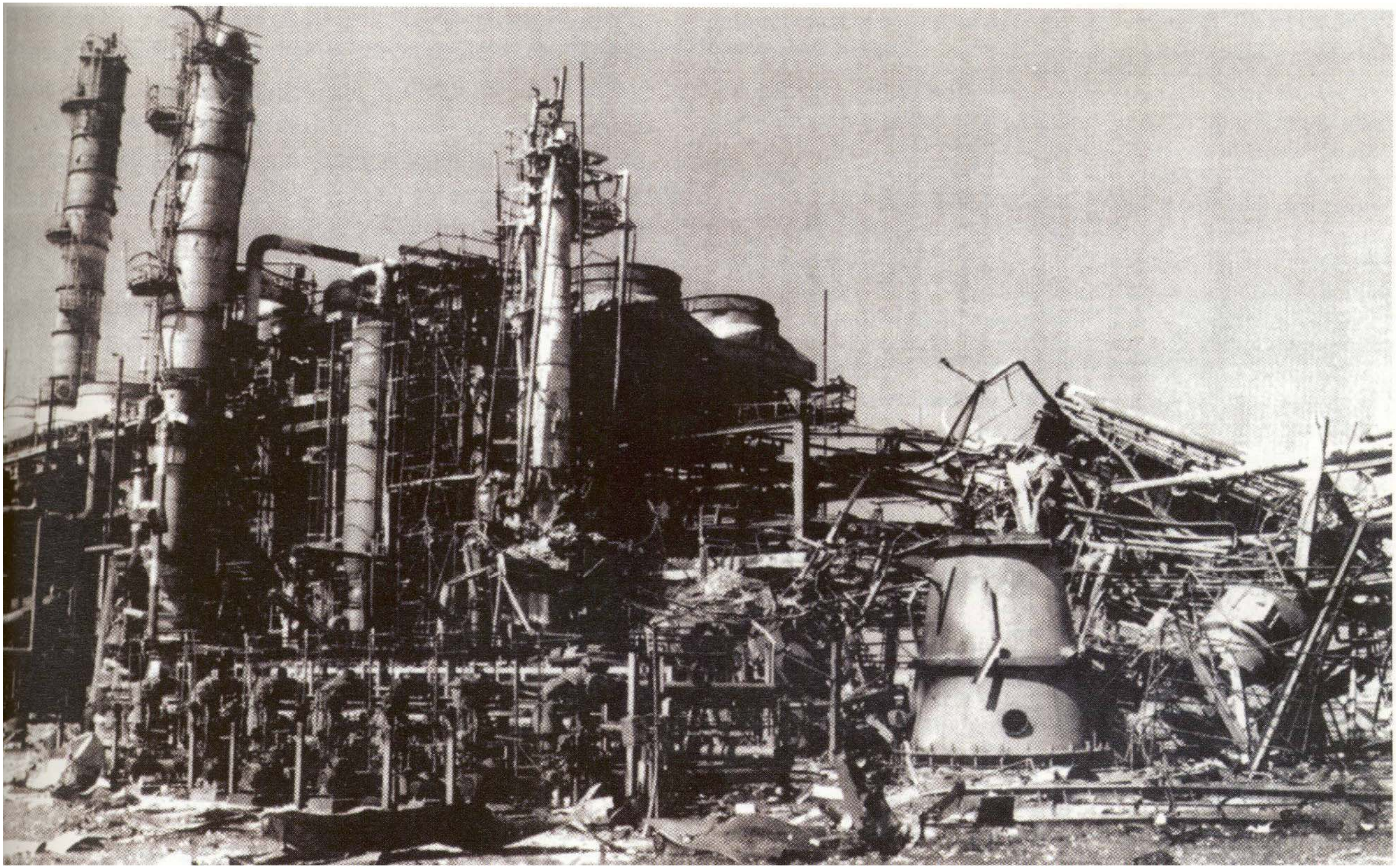
  - A firecracker does not detonate
  - Most bombs do not cause detonations

Detonation vs. Deflagration in Gases



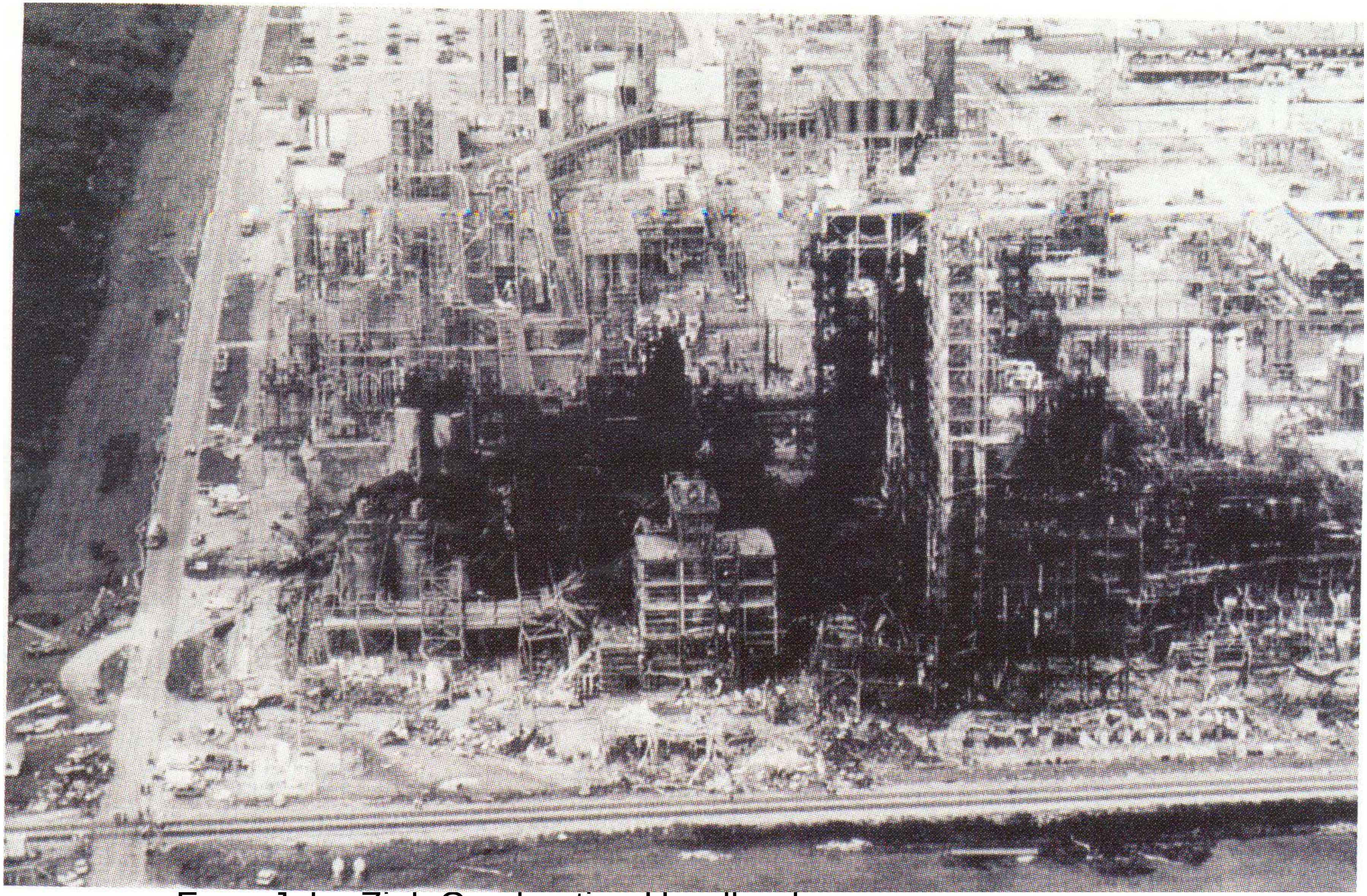
	Detonation	Deflagration
u_1/c_1	5 to 10	0.0001 to 0.03
u_2/u_1	0.4 to 0.7 (deceleration)	4 to 6 (acceleration)
p_2/p_1	13 to 55 (compression)	~0.98 (slight expansion)
T_2/T_1	8 to 21 (heat addition)	4 to 16 (heat addition)
ρ_2/ρ_1	1.7 to 2.6	0.06 to 0.25

Ethylene oxide plant explosion caused by autoignition



From John Zink Combustion Handbook

Refinery damage due to improper maintenance procedures



From John Zink Combustion Handbook