Explosion Hazards of Hydrogen-Air Mixtures

Professor John H.S. Lee
McGill University, Montreal, Canada

Hydrogen Safety Issues

- Wide spread use of hydrogen requires significant efforts to resolve safety issues
- Hydrogen is already used extensively in many industrial applications (but general public not exposed to the dangers)
- Extensive research efforts have already been devoted to hydrogen safety issues
- Post-Three Mile Island accident – information not widely disseminated

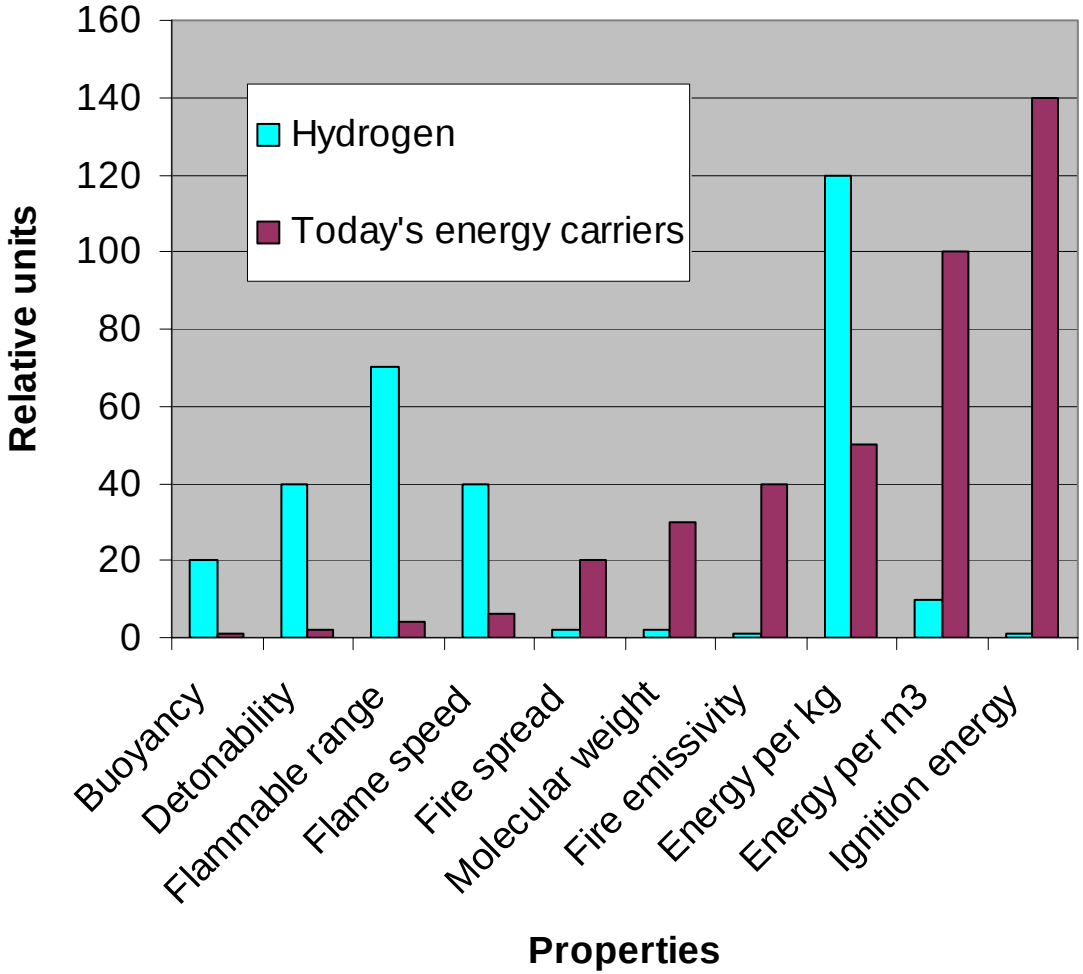
Hydrogen Safety Research

BEFORE HYDROGEN CAN BE USED AS A COMMON ENERGY CARRIER:

- Achieve public acceptance of hydrogen-technologies
- Provide at least the same level of safety, reliability, comfort as today's fossil fuels
- No solutions are available in terms of widely accepted standards, methodologies, mitigation techniques and regulations)

Hydrogen and today's fuels

- Qualitative comparison of "Safety profiles"
- Properties of hydrogen are different from today's fuels
  - H_2 is less dangerous in terms of thermal and fire hazards,
  - may be responsible for stronger pressure effects



Safety Issues

- To evaluate hydrogen safety the following set of issues should be addressed for each of the applications
  - Hydrogen release, mixing, and distribution
  - Thermal, pressure, and missile effects from H_2 fires and H_2-air cloud explosions
  - Mitigation techniques for detection, dilution, and removal of hydrogen
  - Risk evaluation, both specific and in comparison with today's fossil energy carriers
  - Standardization, and regulatory issues

Objectives

- To contribute to common understanding and approaches for addressing hydrogen safety issues
- To integrate experience and knowledge on hydrogen safety
- To integrate and harmonise the fragmented research base
- To provide contributions to safety requirements, standards and codes of practice
- To contribute to an improved technical culture on handling hydrogen as an energy carrier
- To promote public acceptance of hydrogen technologies

Accident scenarios

Unconfined Explosions

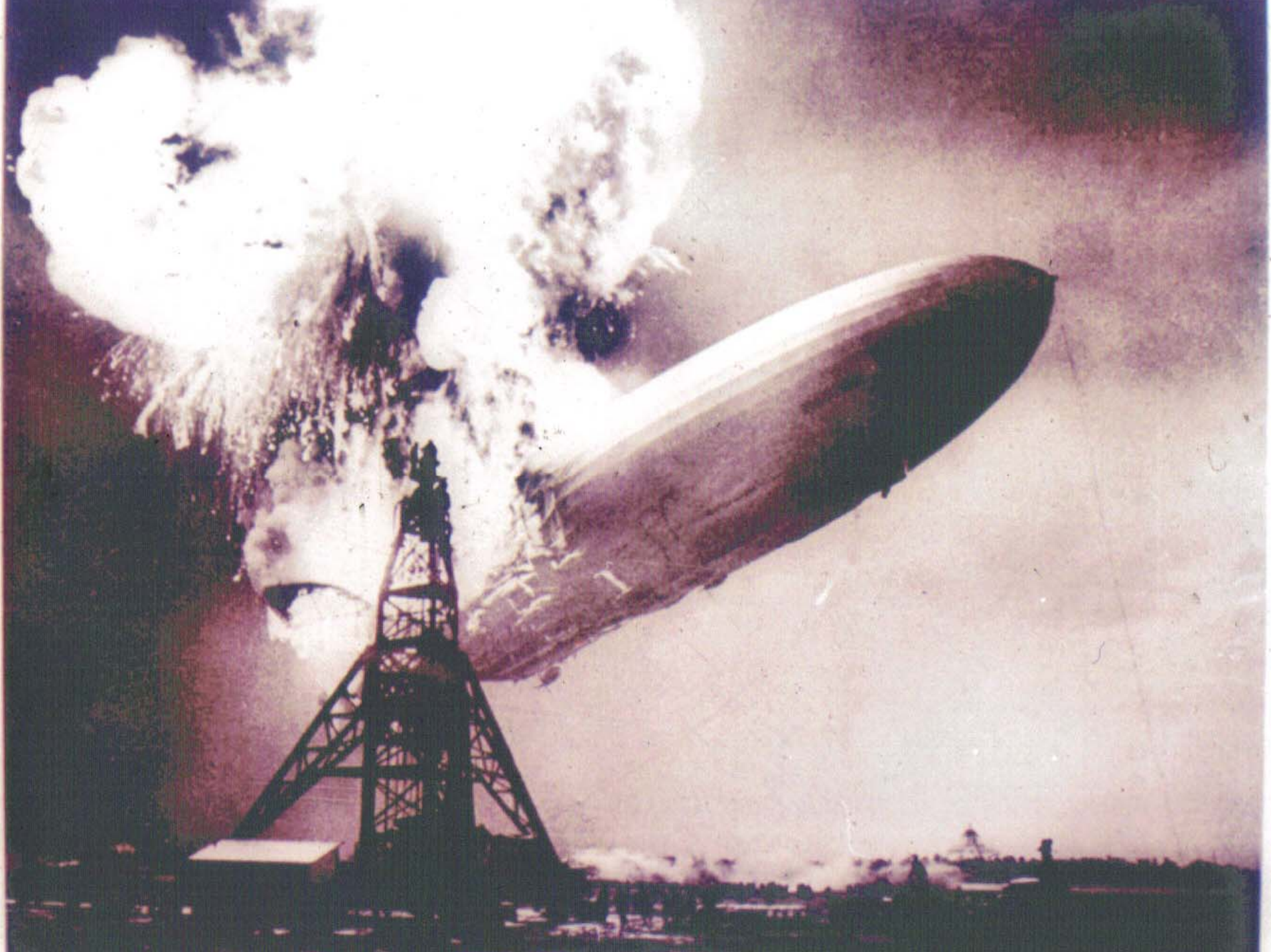
- major rapid release into the atmosphere

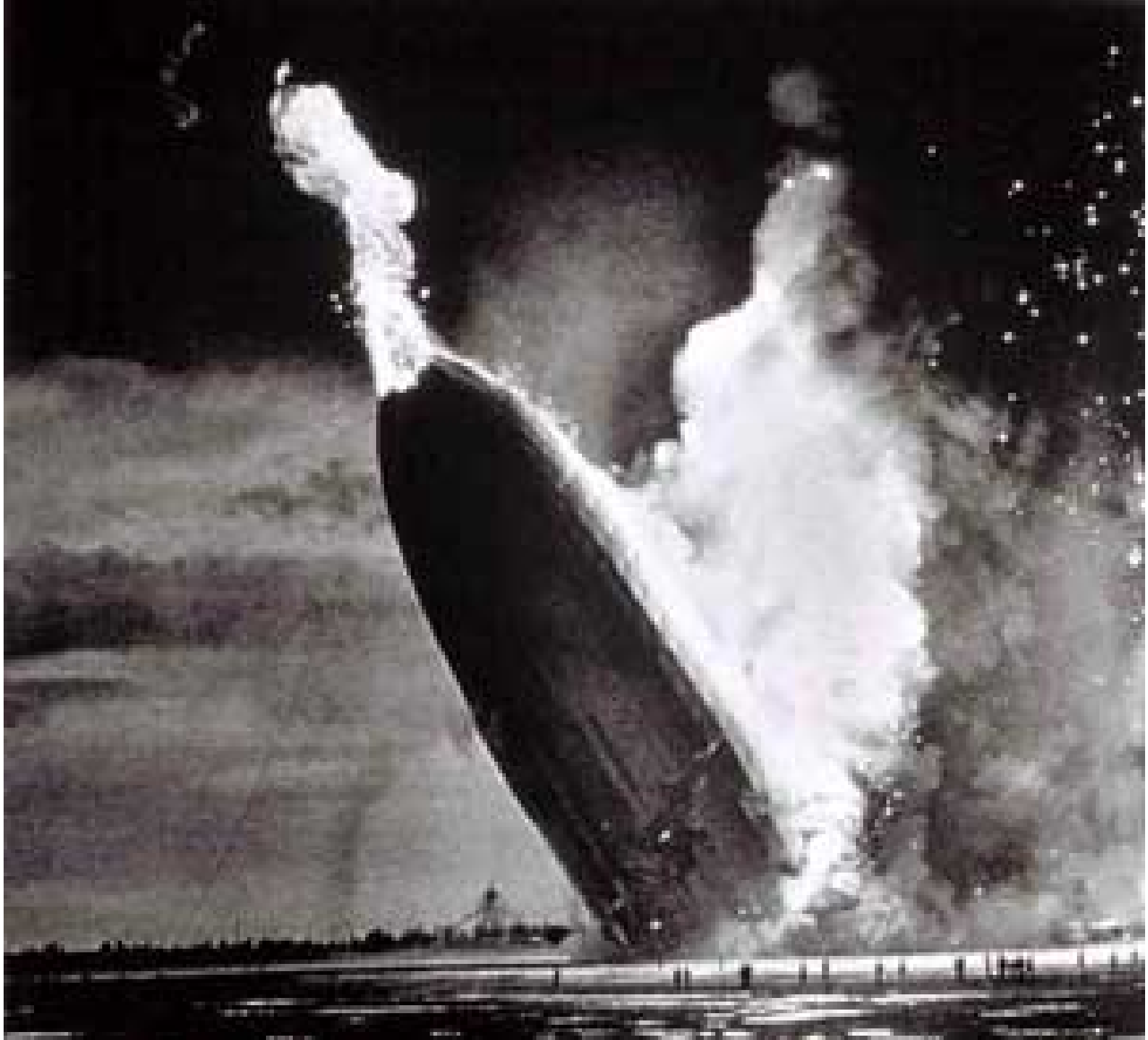
Confined Explosions

- leakage of H_2 into buildings
- contamination of high pressure H_2 storage facilities by air

Hindenburg (May 6, 1937)

- Lakehurst (New Jersey)
- Fired started near tail during landing
- Flame spread ~ 50 m/s
- Ship was 803 ft. ~ 245 m long
- Destruction completed in 32 seconds
- 36 lives lost





Crescent City, Illinois

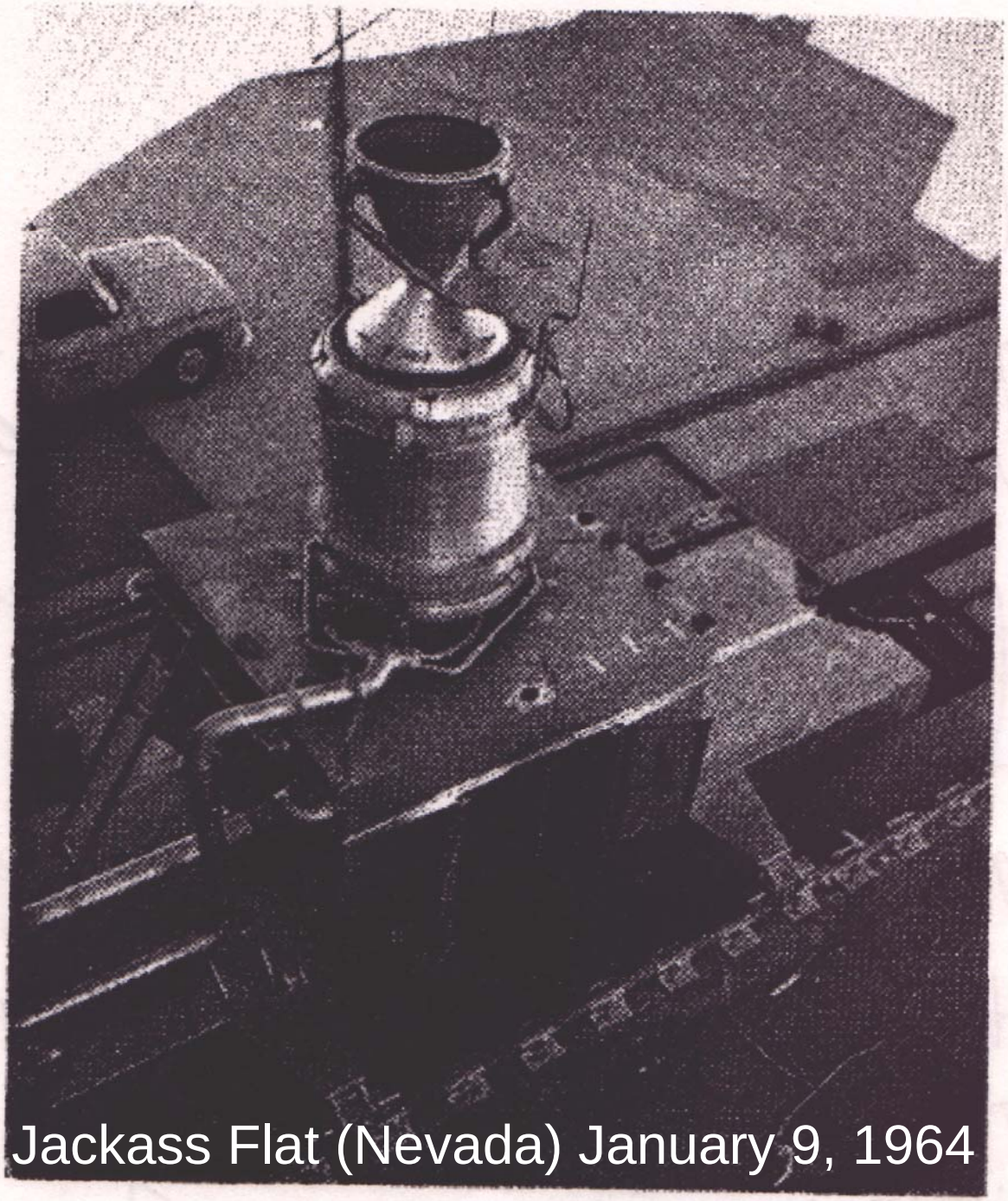
Crescent City, Illinois

Jackass Flat (Nevada)
January 9, 1964

- Unconfined H_2-air explosion
- Test to measure acoustic noise due to high flow rate hydrogen
- 1000 kg H_2 discharged from vertical rocket nozzle at 23 MPa in 30 seconds
- Discharge rate uniformly increased to 55 kg/s, maintained for 10 seconds then reduced to zero
- Ignition occurs 26 seconds after discharge begins

Jackass Flat (Nevada)
January 9, 1964

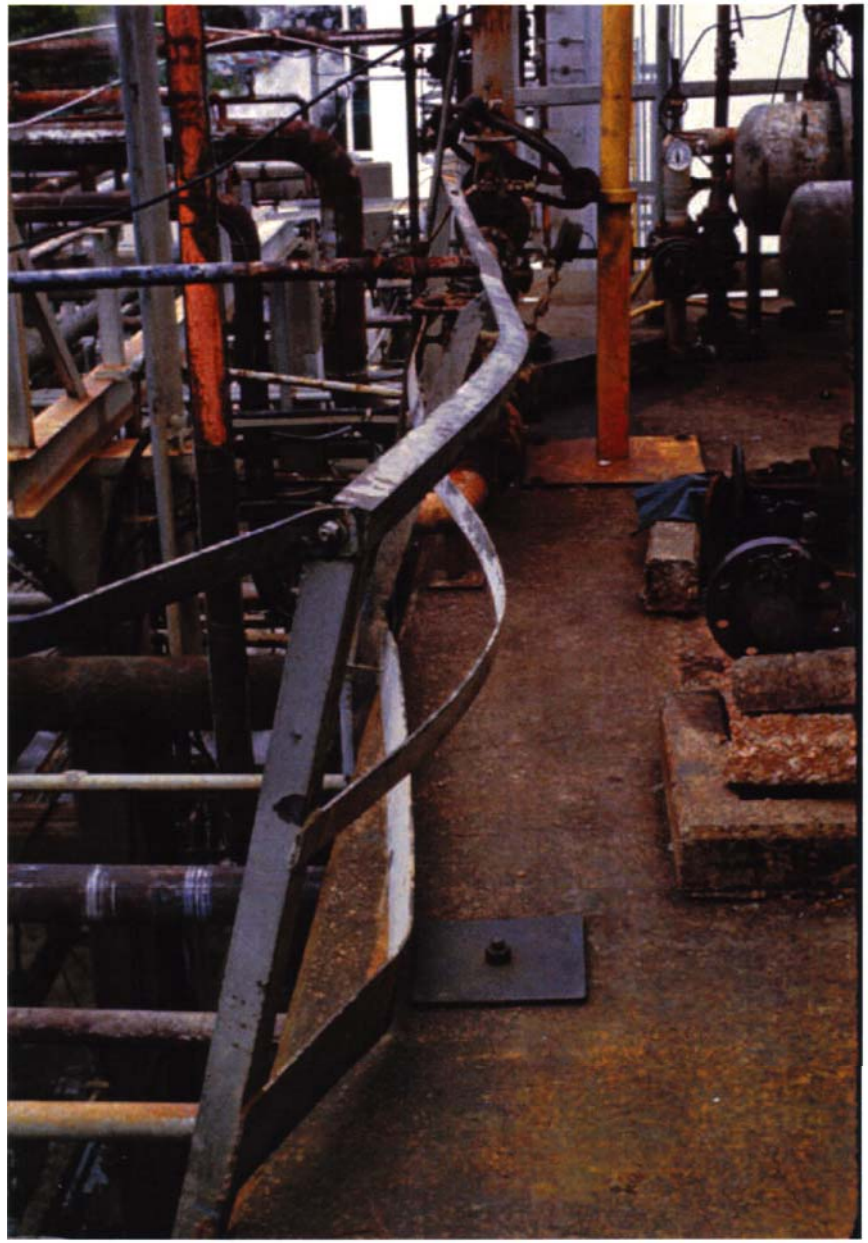
- No pressure wave detected in near field less than 0.8 km
- Explosion heard 3.2 km away
- Wide spread minor damage near hydrogen discharge, but superficial
- Estimate 10 kg of H_2 involved in the explosion
- TNT equivalent of 8%



Jackass Flat (Nevada) January 9, 1964

Polysar (April 19, 1984)

- Unconfined H_2-air explosion
- Rapid release of H_2 from a ruptured gasket of a Worthington Compressor at 600psi
- 10-20 seconds delay before ignition
- Three fatalities
- Extensive major structural damage in the near field
- Glass and minor structural damage up to 1 km
- Detonation occurred in near field
- Damage compatible to detonation of about 0.1 kg H_2-air cloud




Cold Box

China Light and Power Cast Peak Generating Station (August 28, 1992)

- Confined explosion
- Explosion in hydrogen receiver
- Production of hydrogen by electrolysis
- Low pressure compressor: 500 kPa
- High pressure compressor: 13.6 MPa
- Two hydrogen receivers: 8.68 m long x 1.12 m diameter
- Hydrogen plant shut down August 24 to 26
- Hydrogen plant resume to supply H_2 to receivers @ 06:30 on August 27

China Light and Power Cast Peak Generating Station (August 28, 1992)

- Pressure at receiver: 6.9 MPa
- August 28 from 00:30 to 02:00 gas from receiver supplied to generator
- Hydrogen purity in generator dropped to 85%
- Receiver disconnected from generator at 02:30; H_2 supplied from bottles
- Sampling indicated hydrogen purity in receivers about 95%
- Receiver #1 reconnected to generator to supply H_2 to generator at 09:45 on August 28

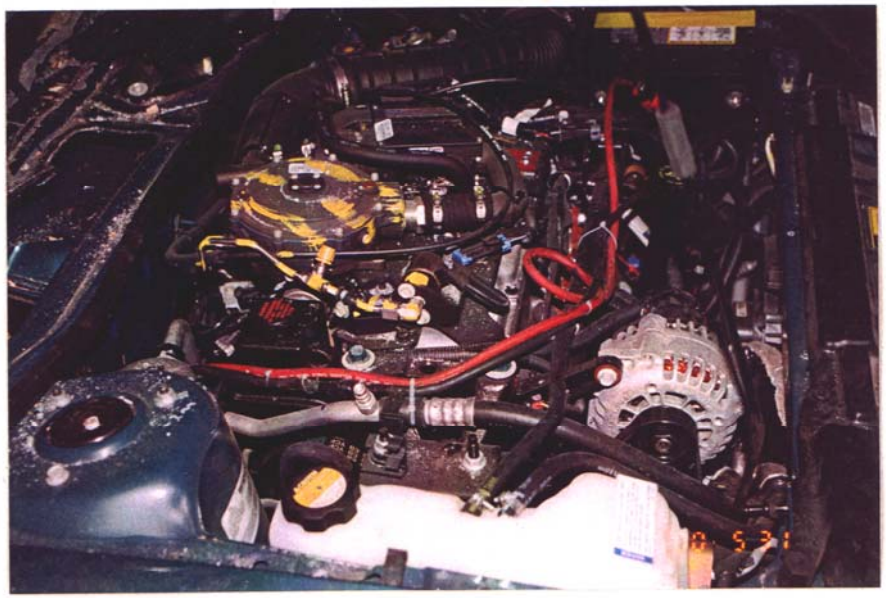
China Light and Power Cast Peak Generating Station (August 28, 1992)

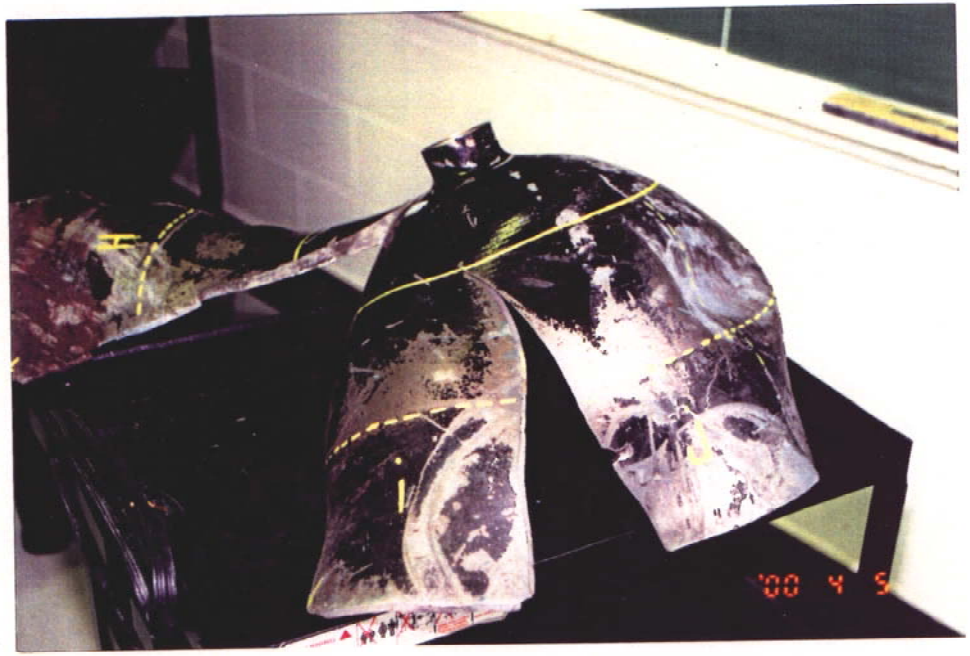
- A drop in H_2 purity in generators noted immediately
- Both receivers exploded at 10:05
- Two fatalities; 18 injured by fragments
- Extensive blast damage ~ 100 m radius
- TNT equivalent 275 kg
- Conclusion: all the gas supplied to the receiver over a 20 hour period (from 06:30 on August 27 to 02:30 on August 28) was air!

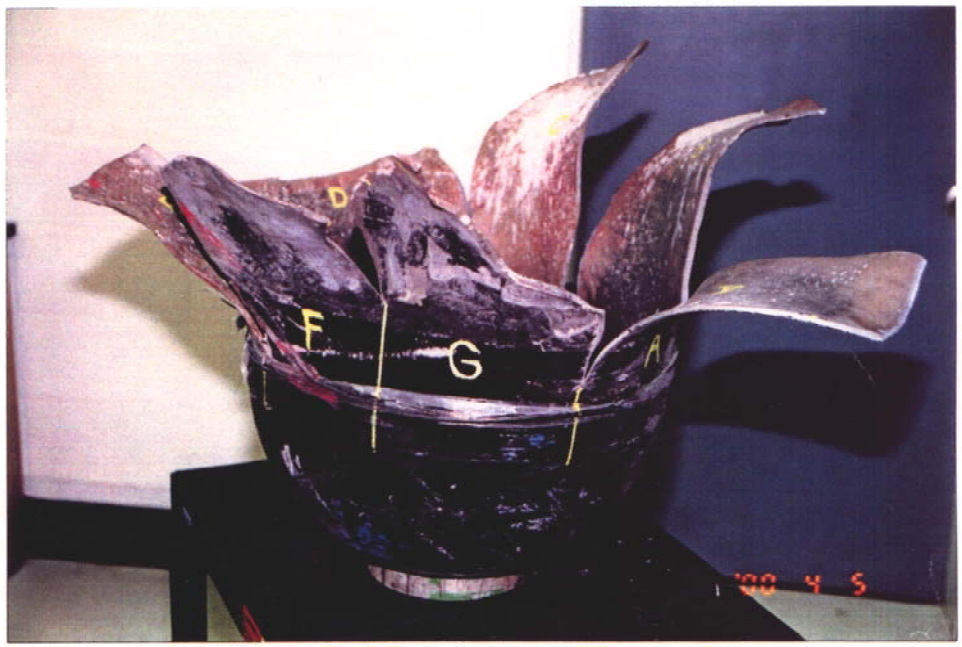
Blainville, Quebec (March, 2000)

- Confined explosion
- Motor vehicle test center
- Tank with 350 psi natural gas filled with air to 3500 psi instead of nitrogen
- Explosion occur during pressure adjustment before crash test
- Extensive damage to car and building
- 3 workers killed

SPORTS
ONLY DO NOT
AFTER 01/201
1V2D UNAB
CNG
'00 5 31




'00 4 5


D
F
G
A
'00 4 5

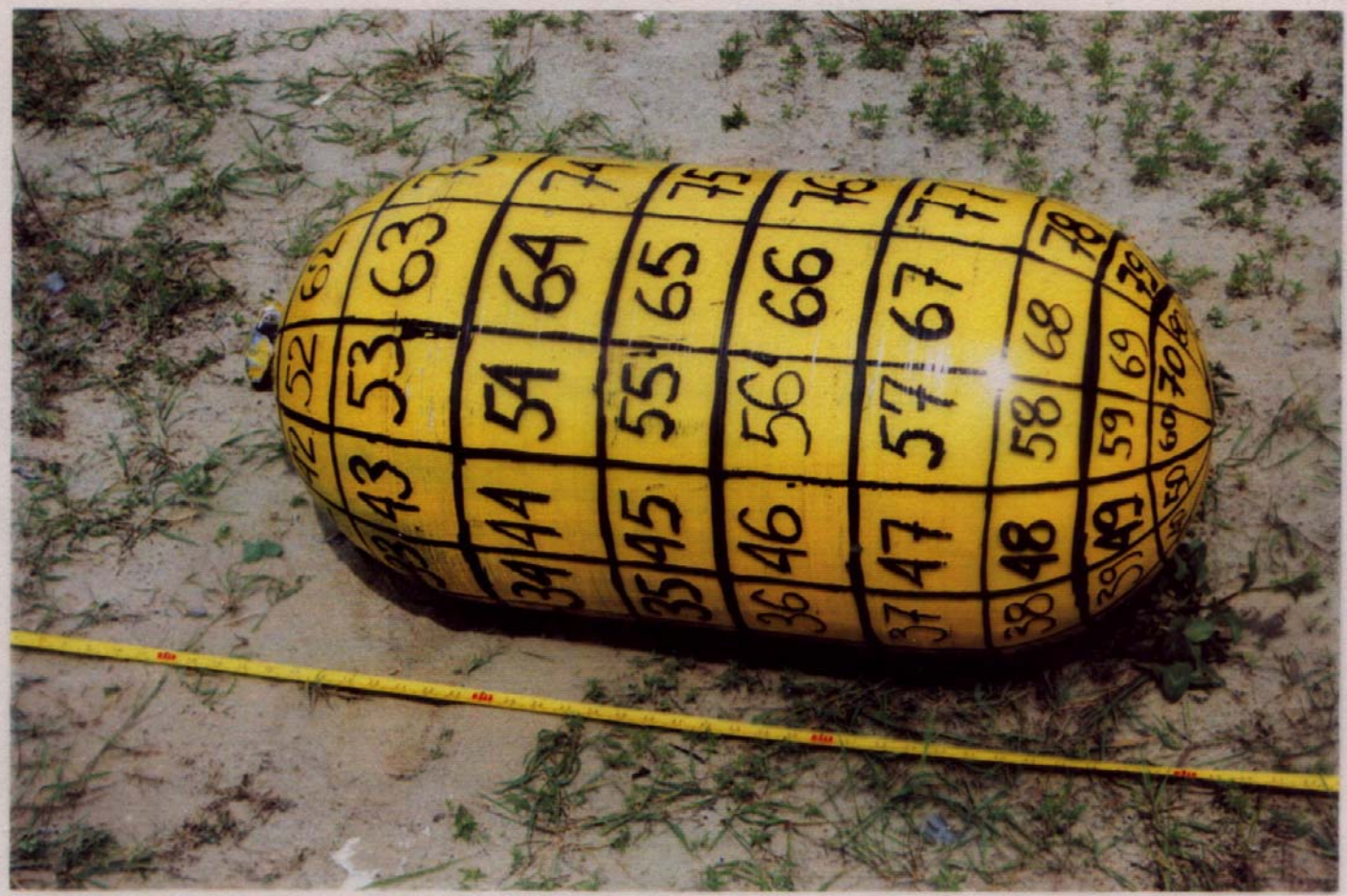


Fig. 4 The painted tank with a numbered grid for recovery of fragments

Top Views of the Inside of the Bottom Fragment (continued)

c)

d)

Conclusion from Accidents

- Rapid release in open atmosphere (Jackass Flat)
  - minor blast damages
- Rapid release in a congested area with equipment, structure etc. (Polysar)
  - severe blast damages, DDT
- Contamination of high pressure storage facility by air (China Light)
  - severe blast damages

Accident scenarios to avoid

- Rapid release in congested area (high density of equipment)
- Air contamination of high pressure hydrogen storage facilities
- Leakage of hydrogen into poorly vented enclosures

Explosion properties of hydrogen

- Equilibrium thermodynamics properties for hydrogen explosion well established
- Chemical kinetics of hydrogen oxidation sufficiently understood quantitatively (explosion limits, laminar flame propagation)
- Explosion parameters are also well established (flammability limit, ignition energy, quenching distance, etc.)

Explosion properties of hydrogen

- Detonation states are well known (Chapman-Jouguet detonation velocity, overpressure, etc.)
- Dynamic detonation parameters adequately known (initiation energy, detonability limit, critical diameter)
- Detonation sensitivity of high pressure H_2-air mixtures does not increase as other hydrocarbon fuels do
- Transition and onset of detonation (i.e. quantitative description of turbulent flame acceleration, condition for the onset of detonation) still not understood

Major unresolved problem

- Development of turbulent combustion models to describe high speed deflagrations with consideration of compressibility effects
- Quantitative theory for the onset of detonation

The Problem of the Transition from Deflagration to Detonation

Current Understanding
and Outstanding Problems

Two Modes of Combustion

Deflagration

- propagation via diffusion mechanism

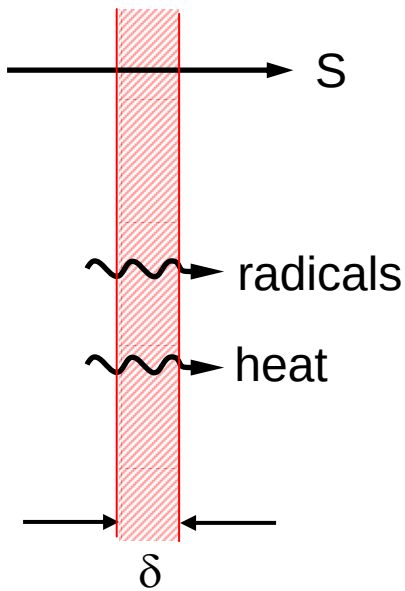
Detonation

- Propagation via shock ignition

Slowest Burning Rate

Laminar Flame

- molecular diffusion of heat and species



$$S \sim \sqrt{\frac{\alpha}{t_c}} \sim \sqrt{\frac{10^{-5}}{10^{-3}}} \approx 10^{-1}\,\mathrm{m/s}$$

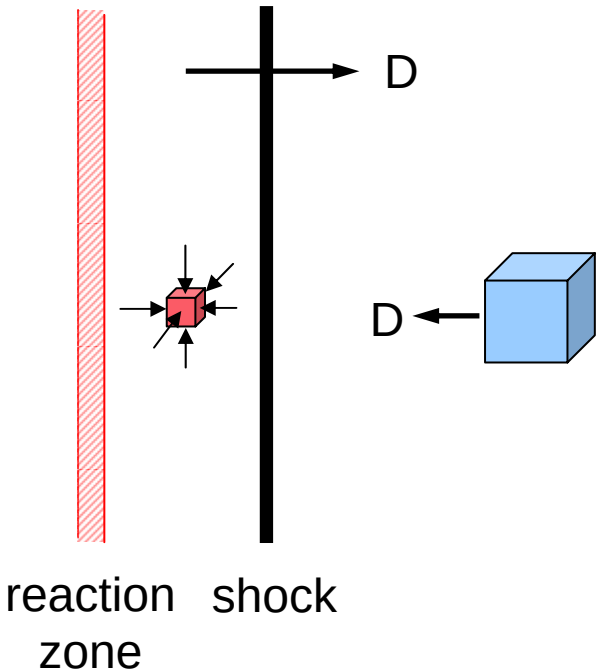
Flame Thickness:

$$\delta \sim \sqrt{\alpha t_c} \sim \sqrt{10^{-5} \cdot 10^{-3}} \approx 10^{-1}\,\mathrm{mm}$$

Fastest Burning Rate

CJ Detonation

- Ignition by adiabatic shock compression



$$D \sim c$$

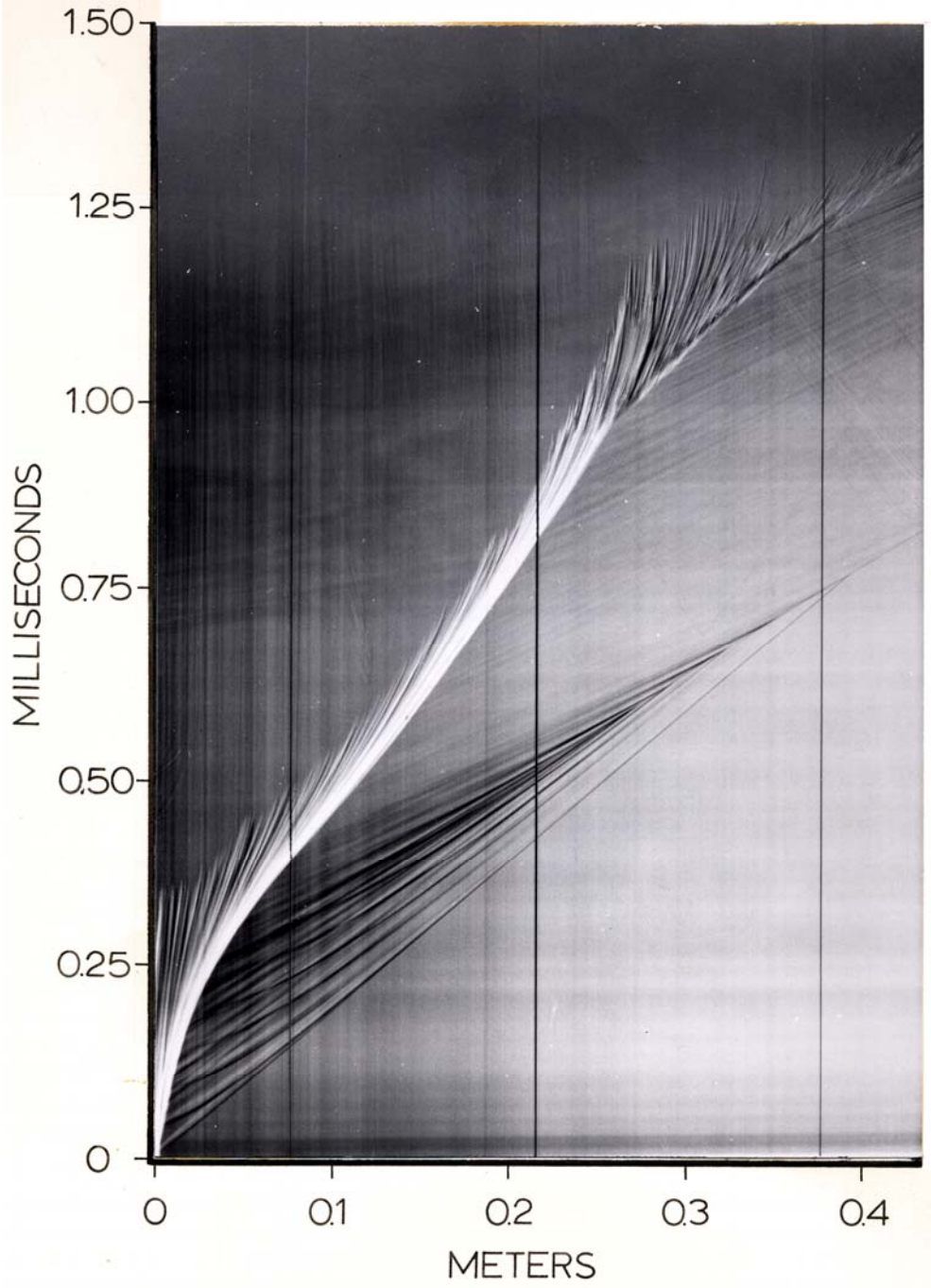
$$c \sim \sqrt{e} \approx \sqrt{Q}$$

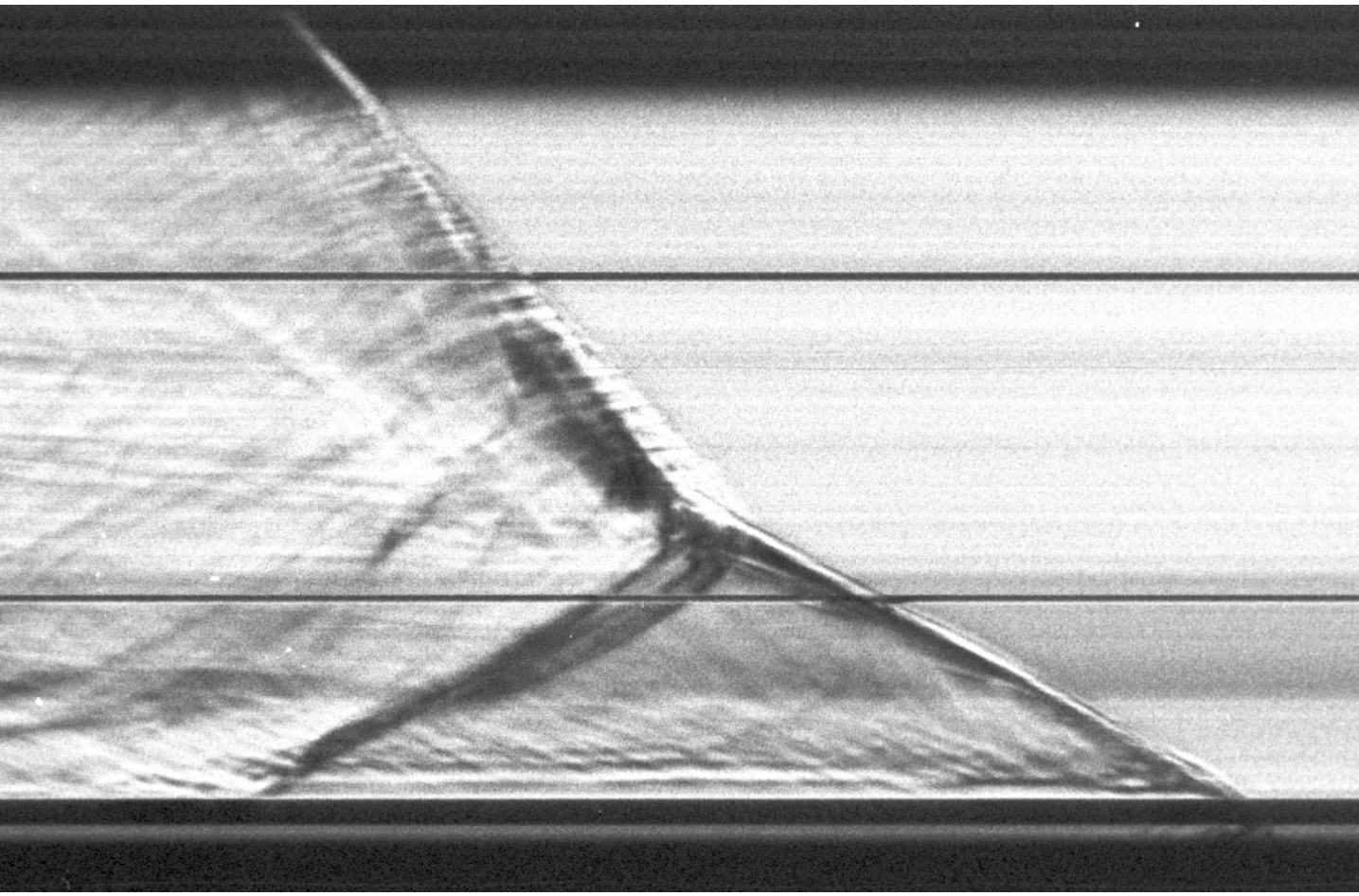
$$Q \approx 30 e_o \sim 30 c_o^2$$

$$D \approx 5.5 c_o \approx 1800 \text{m/s}$$

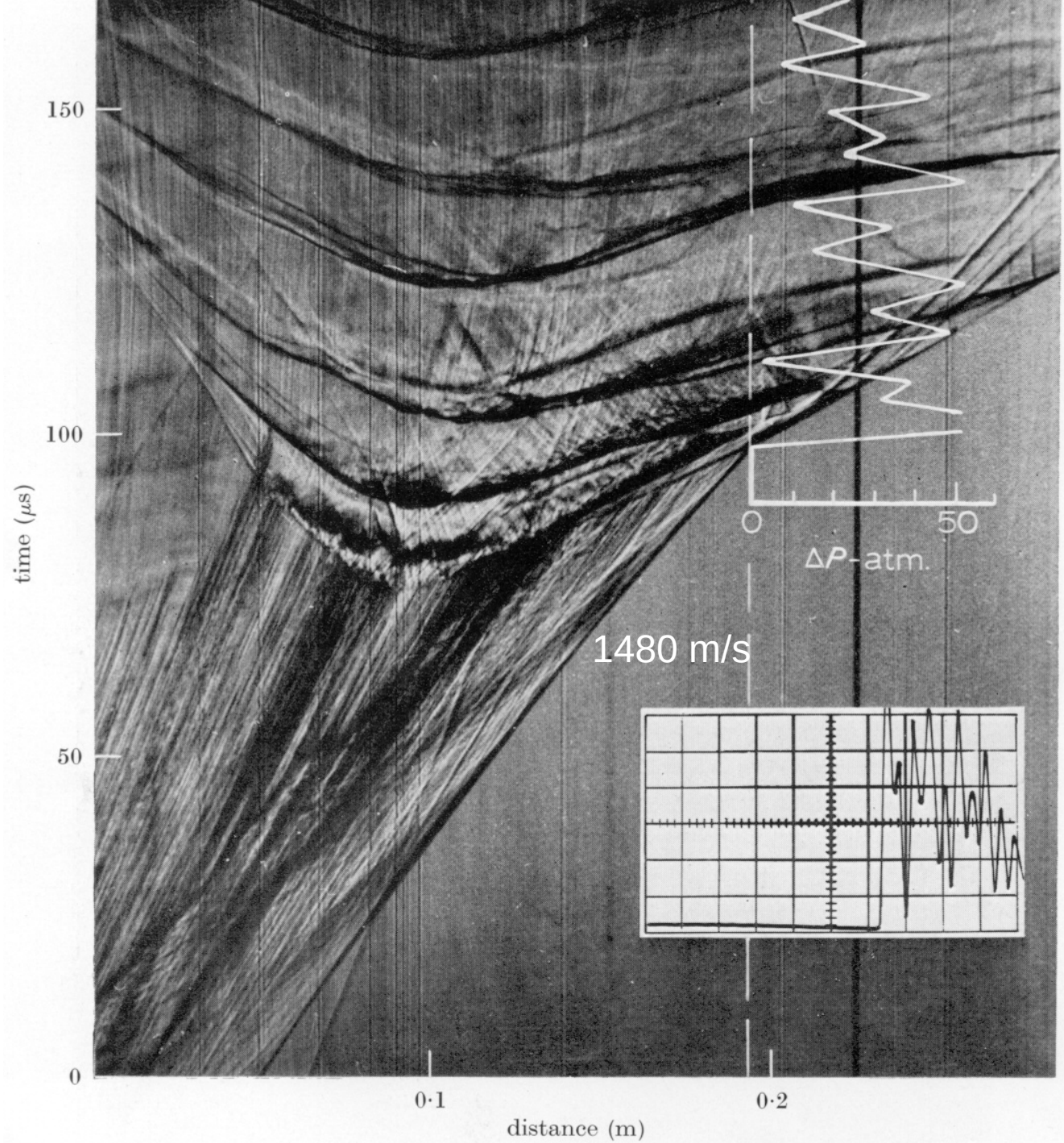
Self-Propagating Deflagration Waves

- are unstable
- accelerate to some critical state and undergo transition to detonation waves


1.50
1.25
1.00
0.75
0.50
0.25
0
MILLISECONDS
0
0.1
0.2
0.3
0.4
METERS

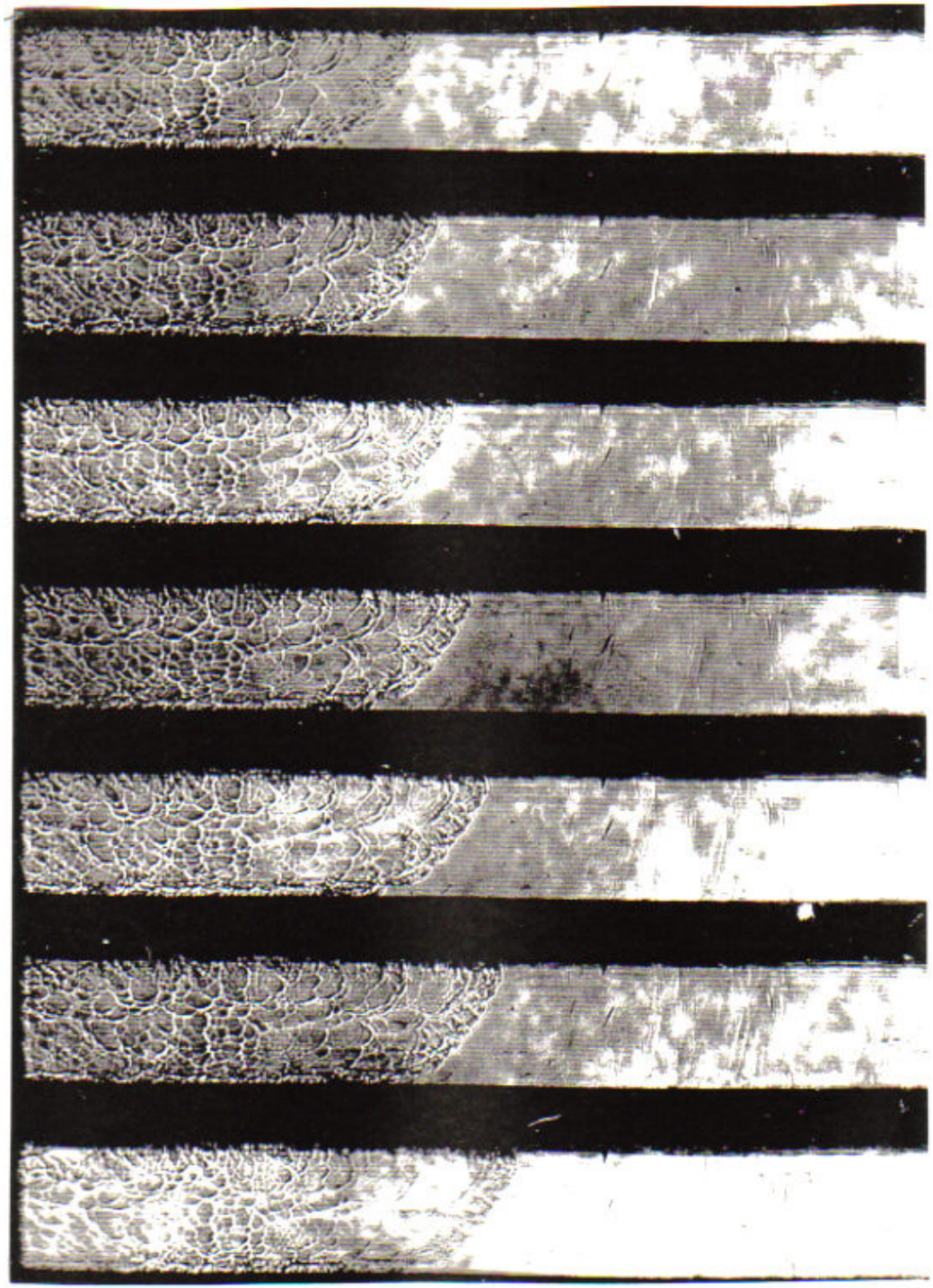


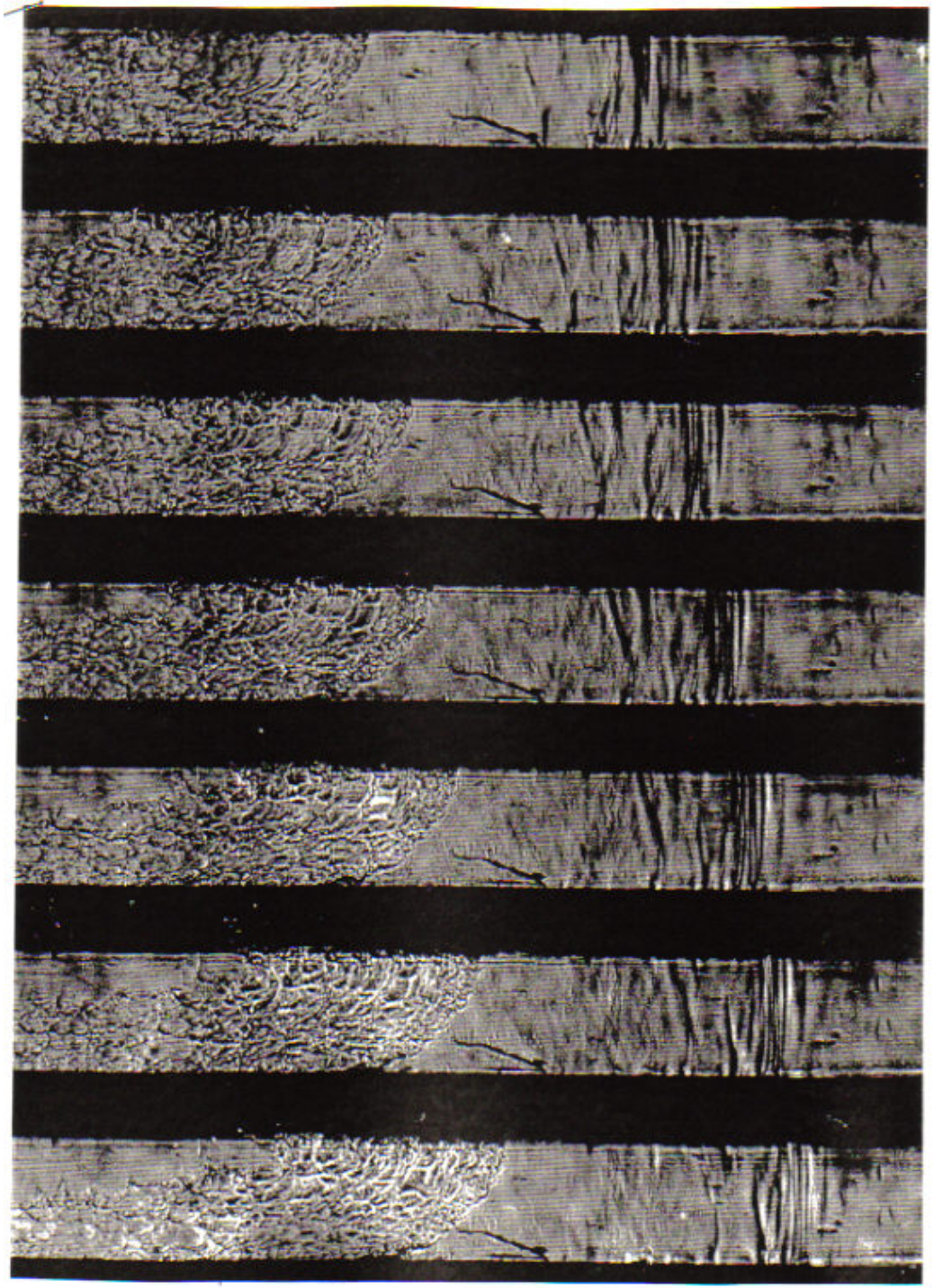
Urtiew & Oppenheim (1966)

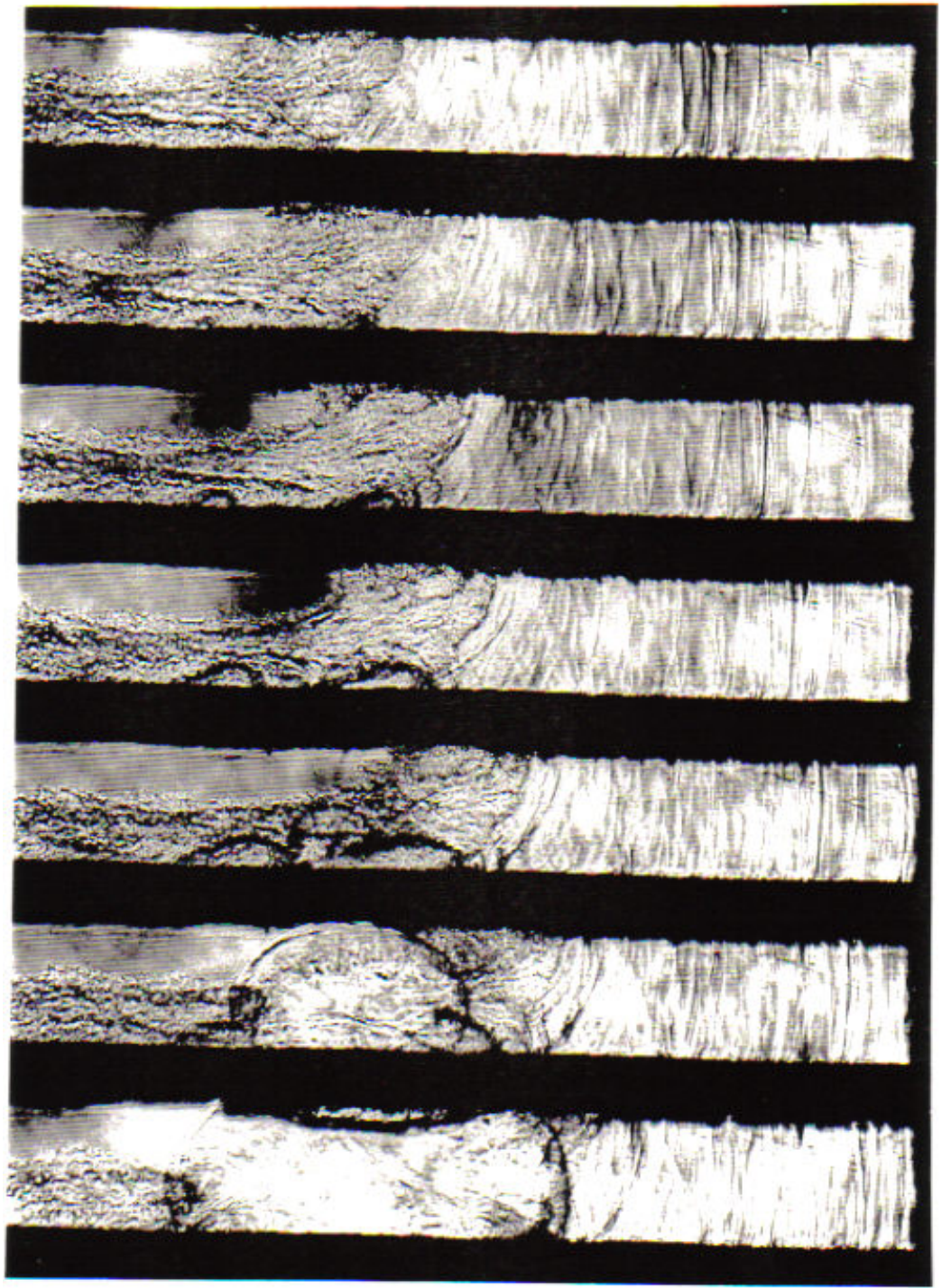


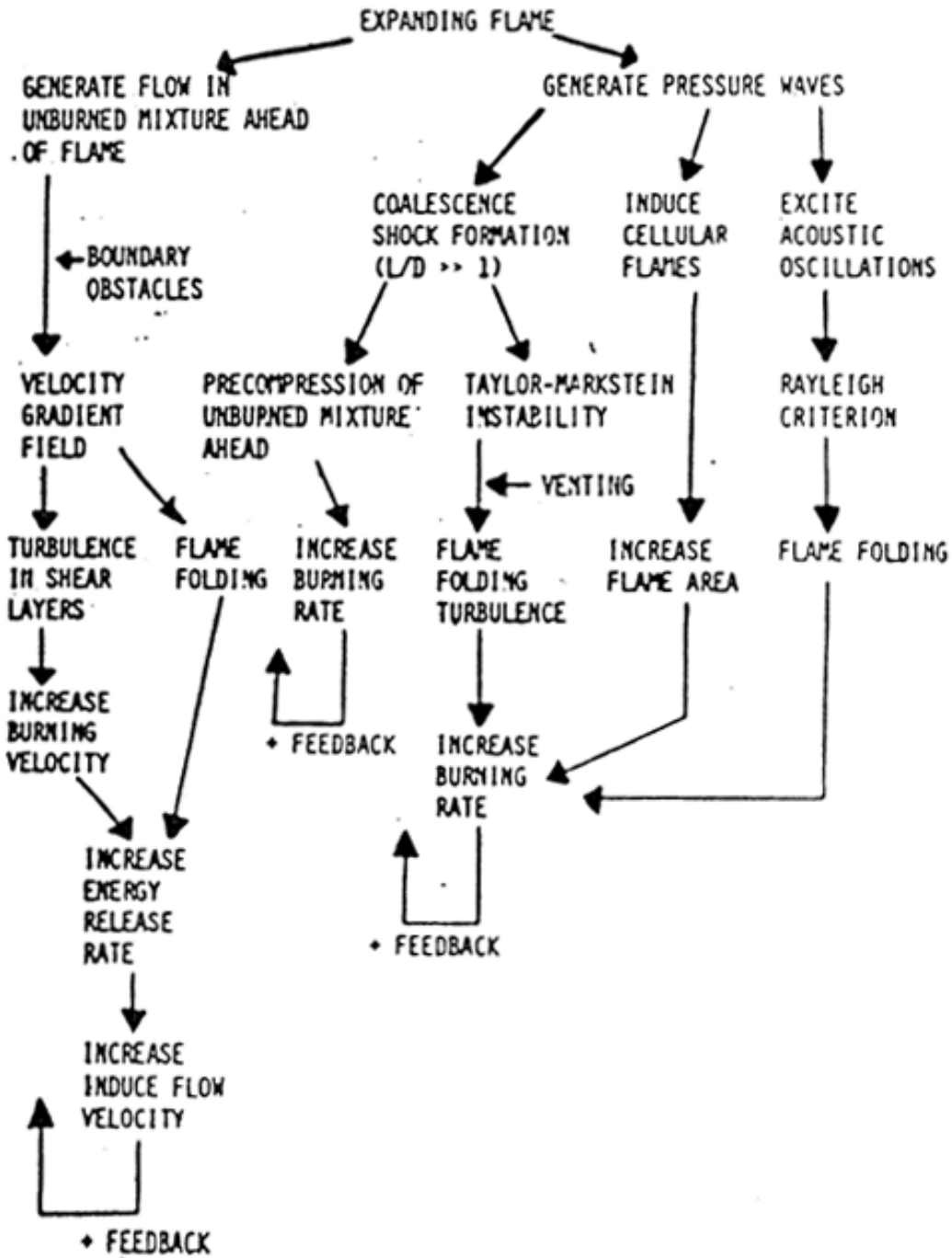
$H_2 + 0.5\ O_2$
@ $P_o = 1$ atm

$V_{CJ} = 2837$ m/s







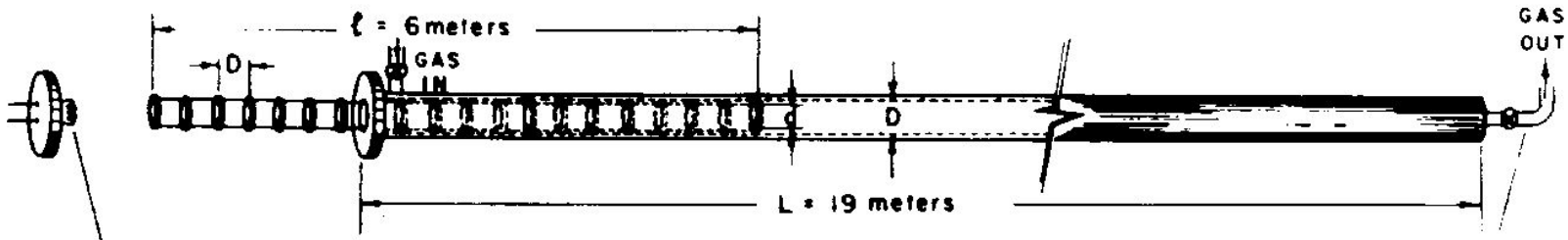

EXPANDING FLAME
GENERATE FLOW IN UNBURNED MIXTURE AHEAD OF FLAME
GENERATE PRESSURE WAVES
BOUNDARY OBSTACLES
COALESCENCE SHOCK FORMATION (L/D >> 1)
INDUCE CELLULAR FLAMES
EXCITE ACOUSTIC OSCILLATIONS
VELOCITY GRADIENT FIELD
PRECOMPRESSION OF UNBURNED MIXTURE AHEAD
TAYLOR-MARKSTEIN INSTABILITY
RAYLEIGH CRITERION
VENTING
TURBULENCE IN SHEAR LAYERS
FLAME FOLDING
INCREASE BURNING RATE
FLAME FOLDING TURBULENCE
INCREASE FLAME AREA
FLAME FOLDING
INCREASE BURNING VELOCITY
+ FEEDBACK
INCREASE BURNING RATE
INCREASE ENERGY RELEASE RATE
+ FEEDBACK
INCREASE INDUCE FLOW VELOCITY
+ FEEDBACK

- initial phase of flame acceleration involves numerous instability mechanisms

- not possible to characterize the flame acceleration phase by a single reproducible parameter like the <u>run-up distance</u>

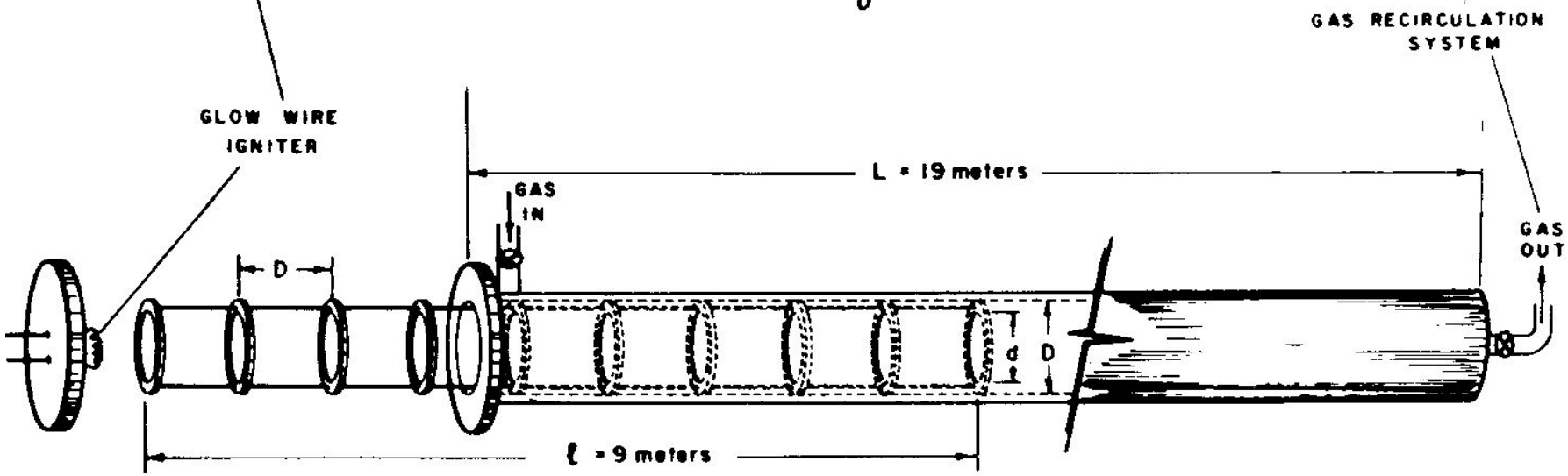
- bypass the initial phase and look at the final phase of the onset of detonation
- determine the critical deflagration speed prior to onset of detonation
- use obstacles to get to critical speed rapidly

- systematic studies of DDT in rough tubes began at McGill in the late 1970’s
- tubes from 5 cm to 2.5 m were used
- obstacles were in the form of orifice plates, cylindrical rods, Shchelkin spirals, etc.



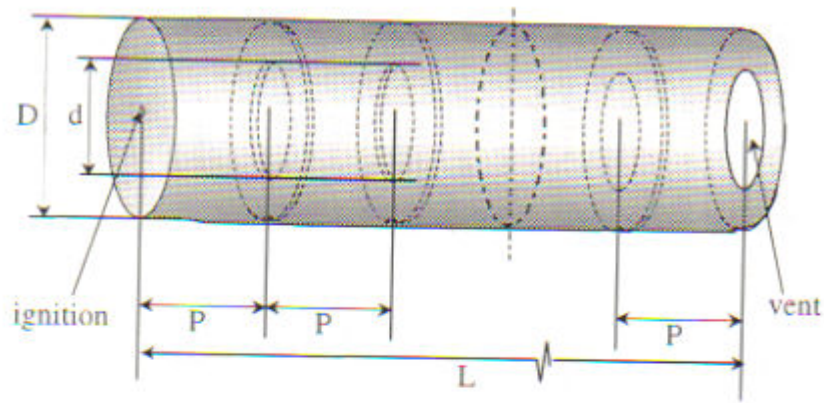
TUBE DIAMETER D = 5cm, OBSTACLE PITCH P = 5cm

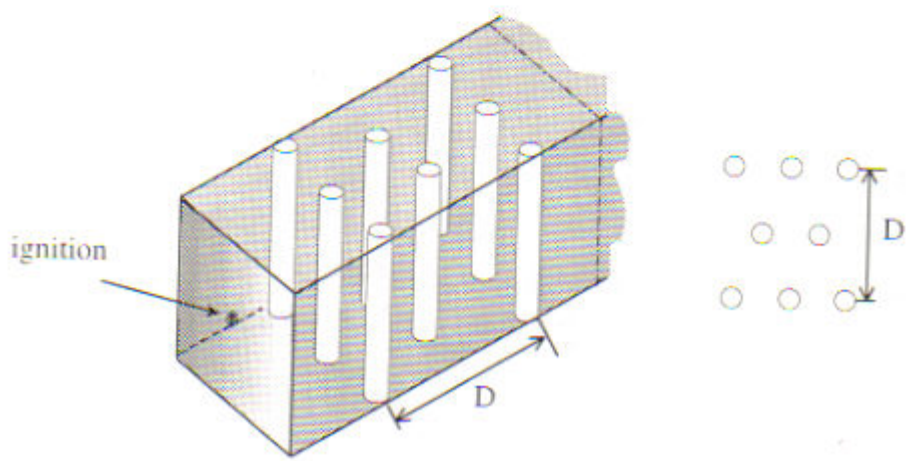
BLOCKAGE RATIO $BR = 1 - \left(\frac{d}{D}\right)^2 = 0.43$

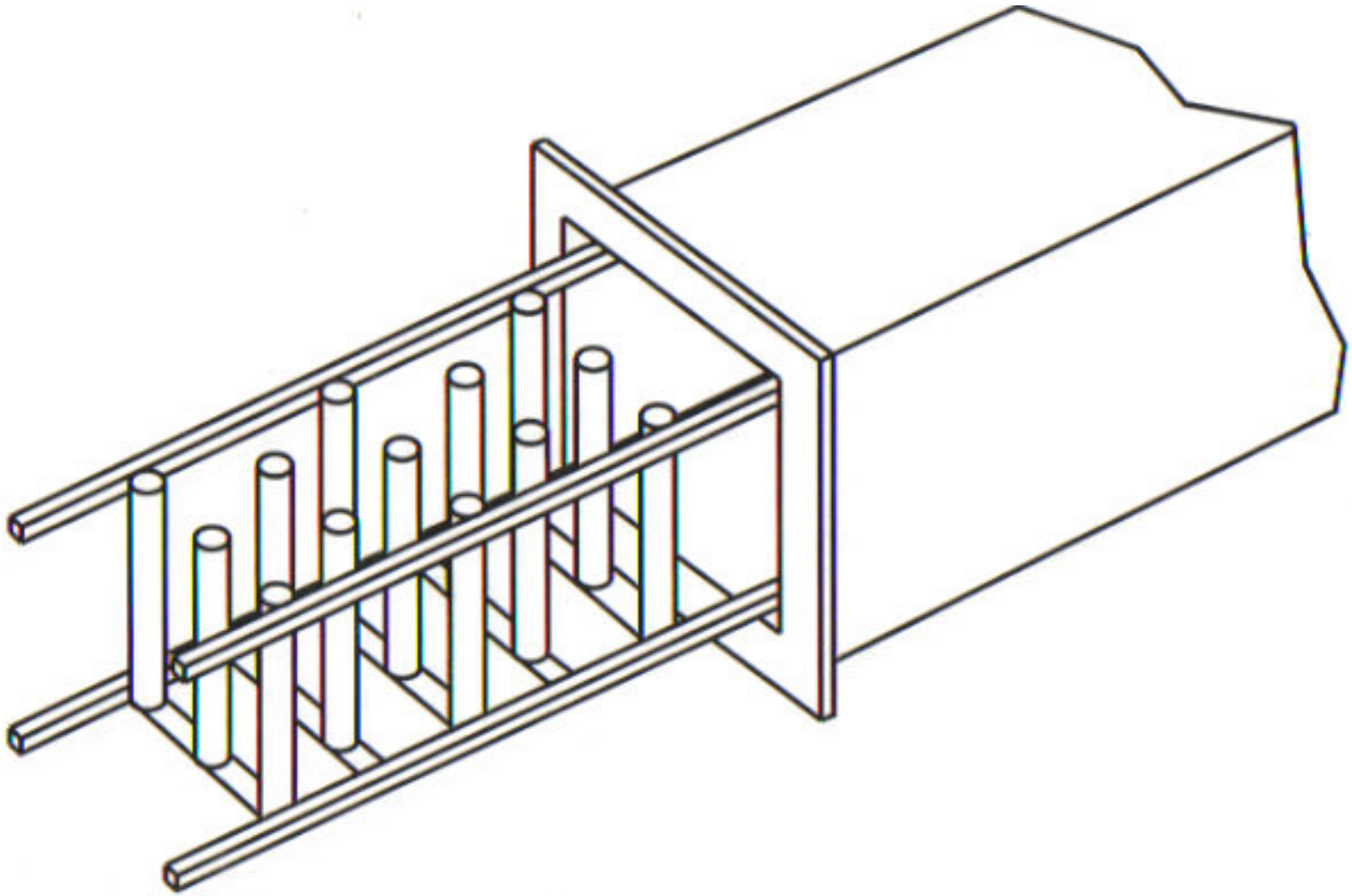


TUBE DIAMETER D = 15cm, OBSTACLE PITCH P = 15cm

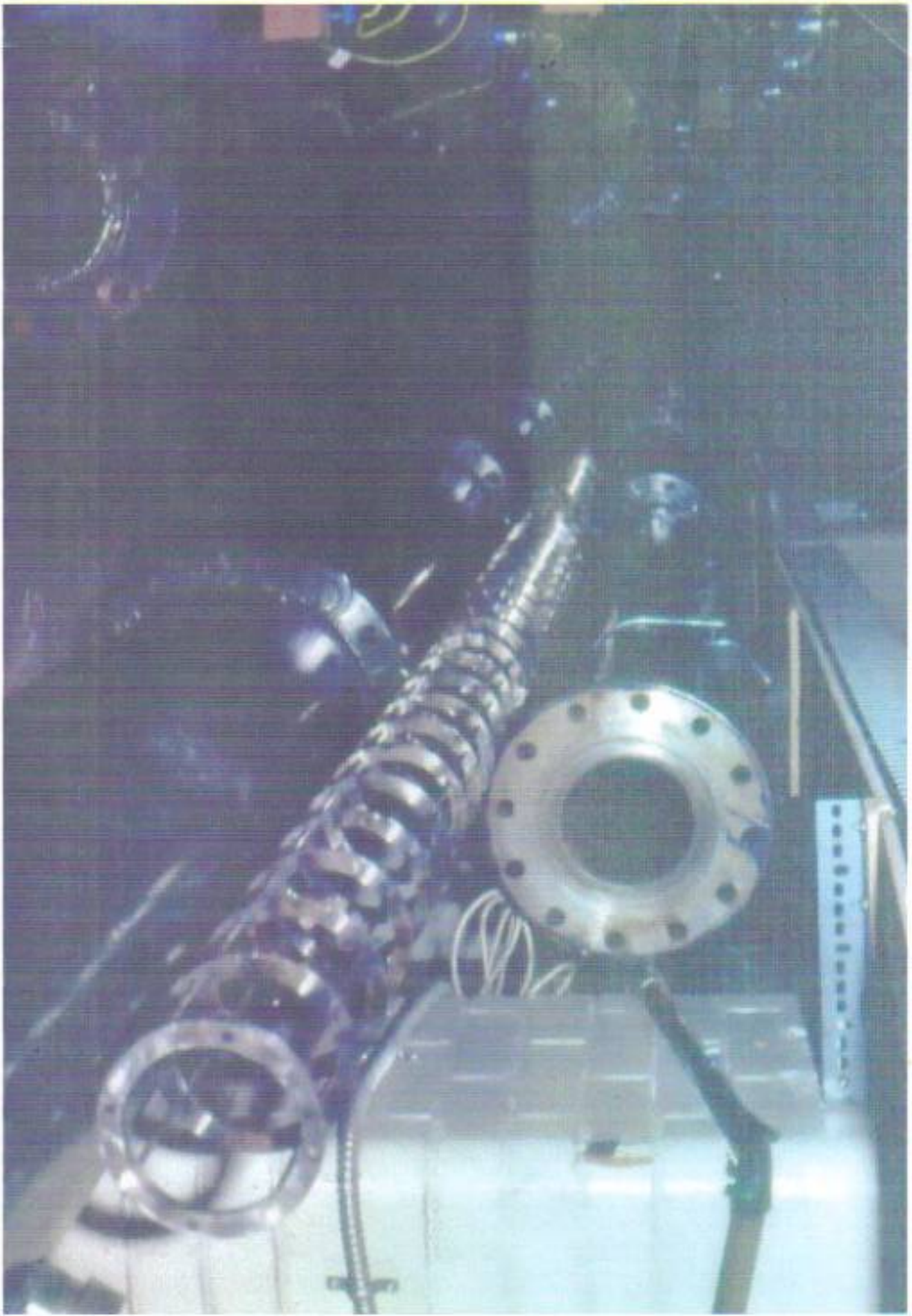
BLOCKAGE RATIO $BR = 1 - \left(\frac{d}{D}\right)^2 = 0.39$

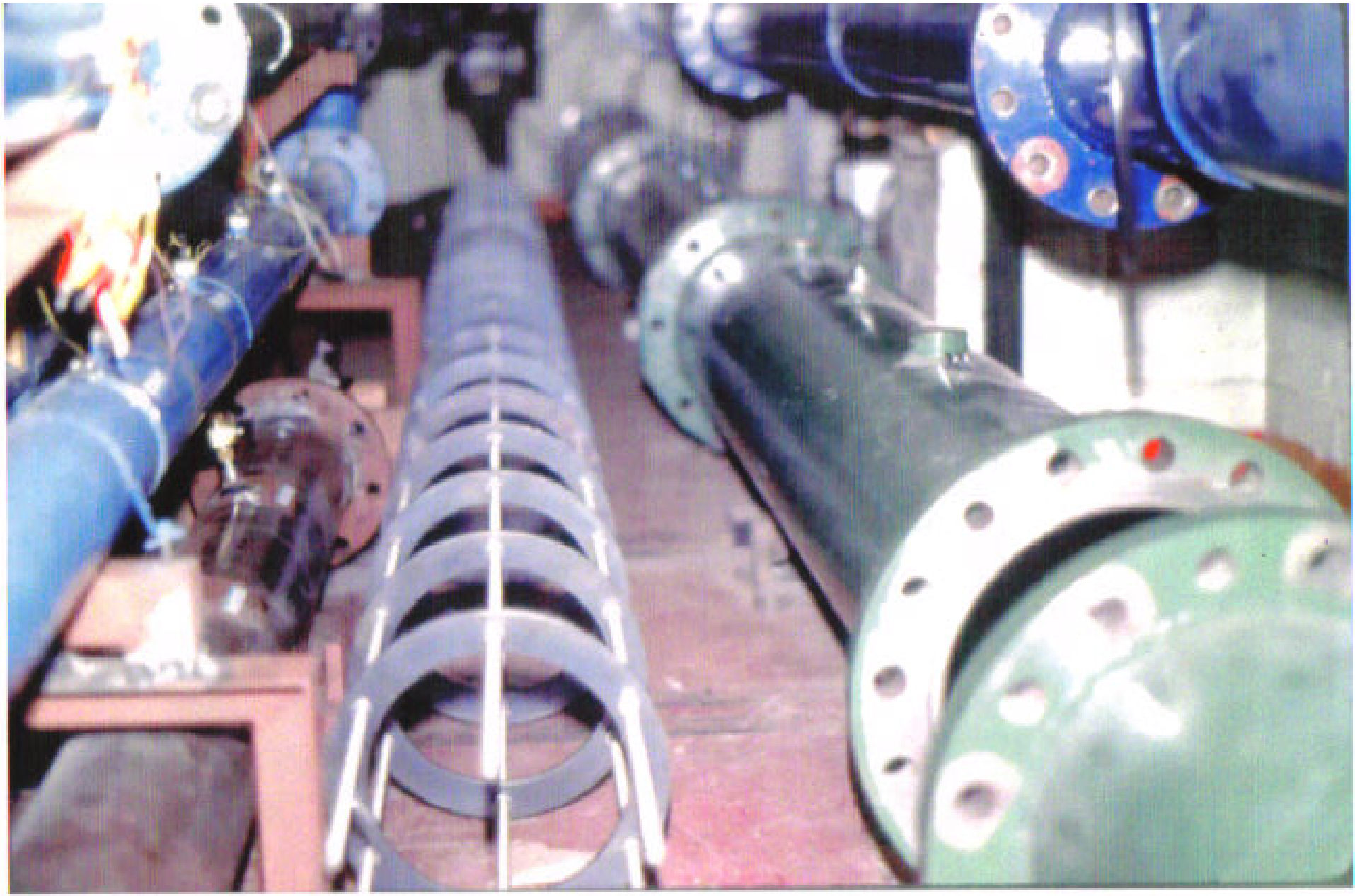

D
d
ignition
P
P
P
vent
L

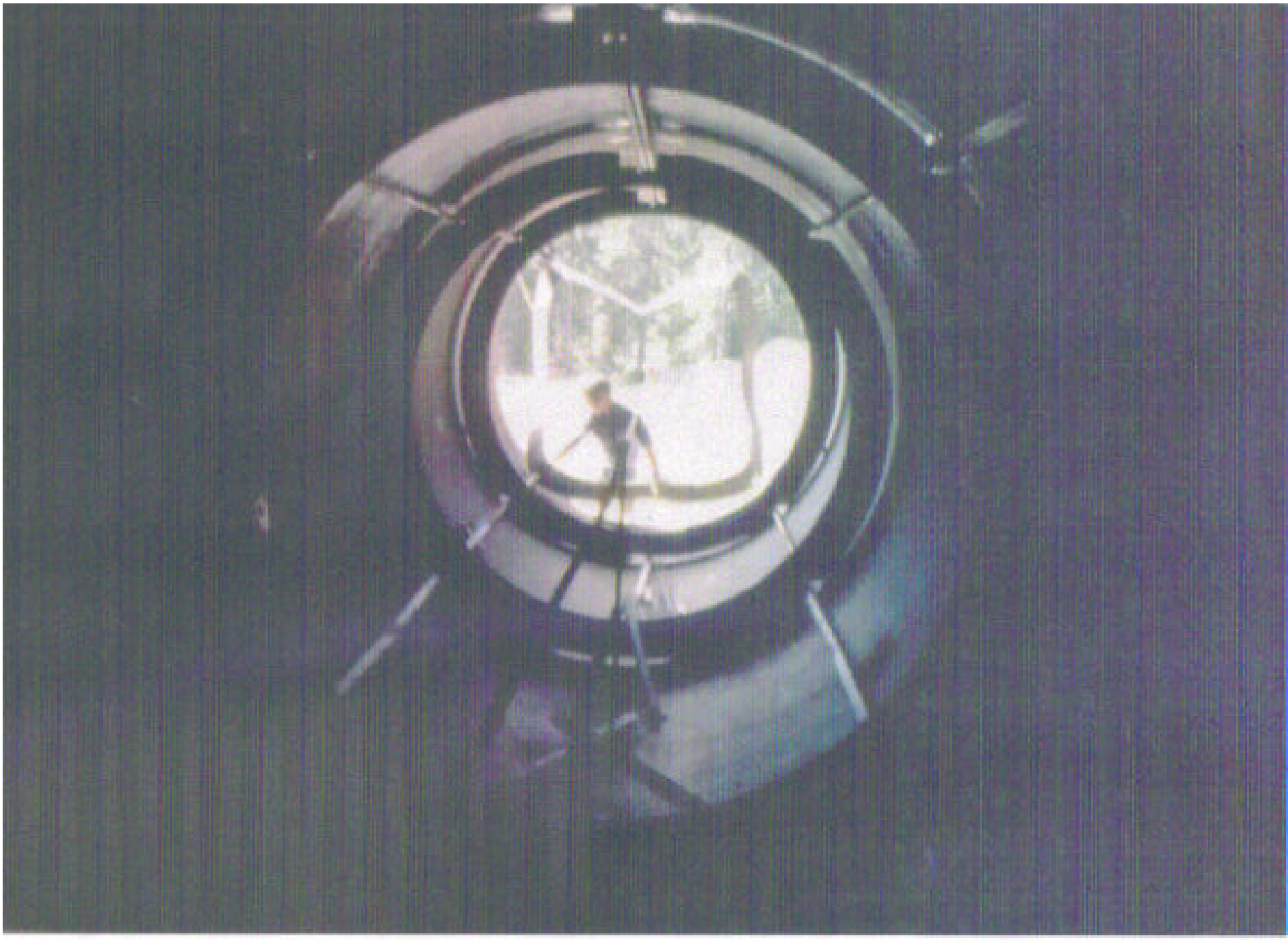

ignition
D
D

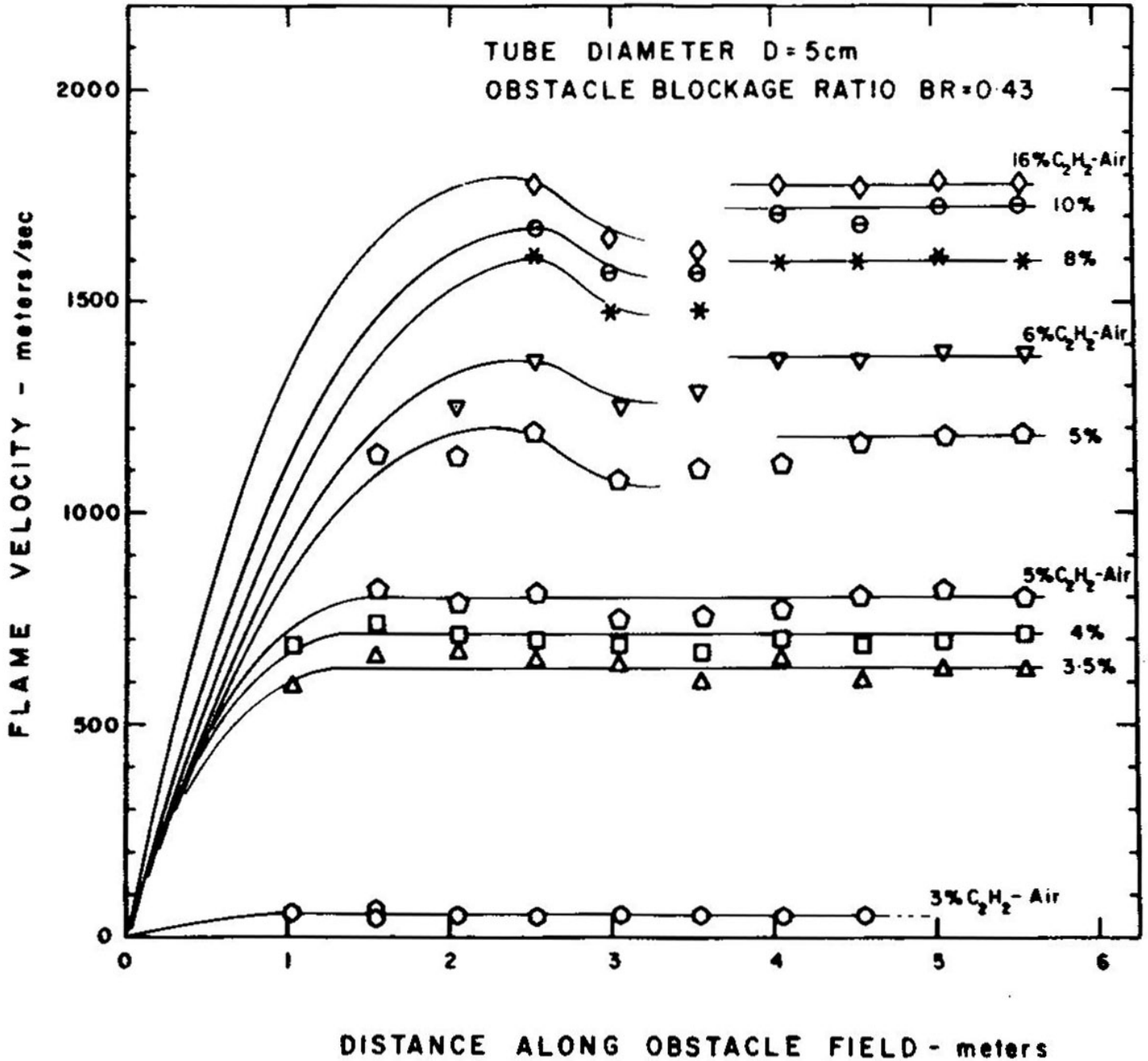


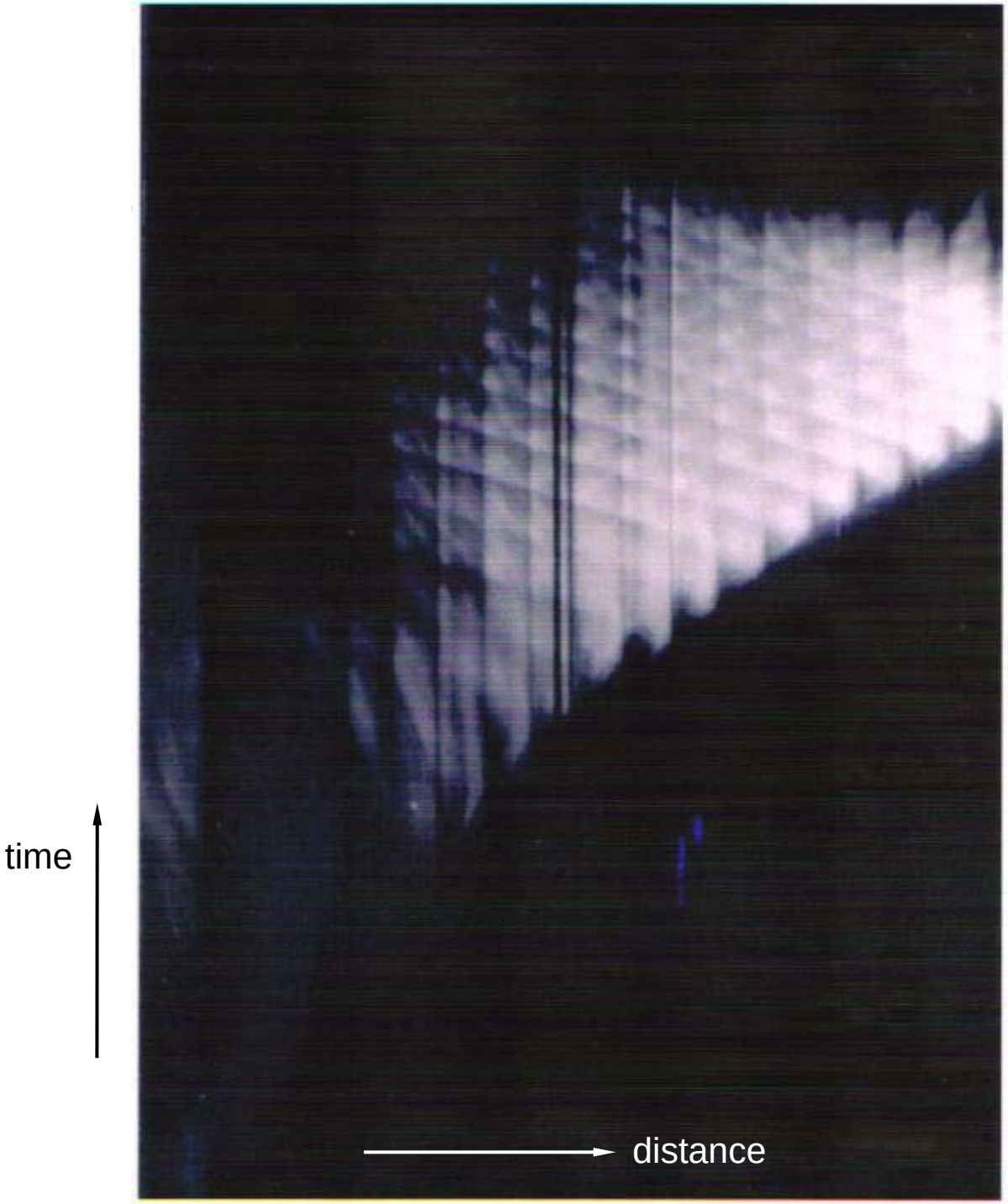
Three-dimensional view of the Tube-Obstacle Assembly





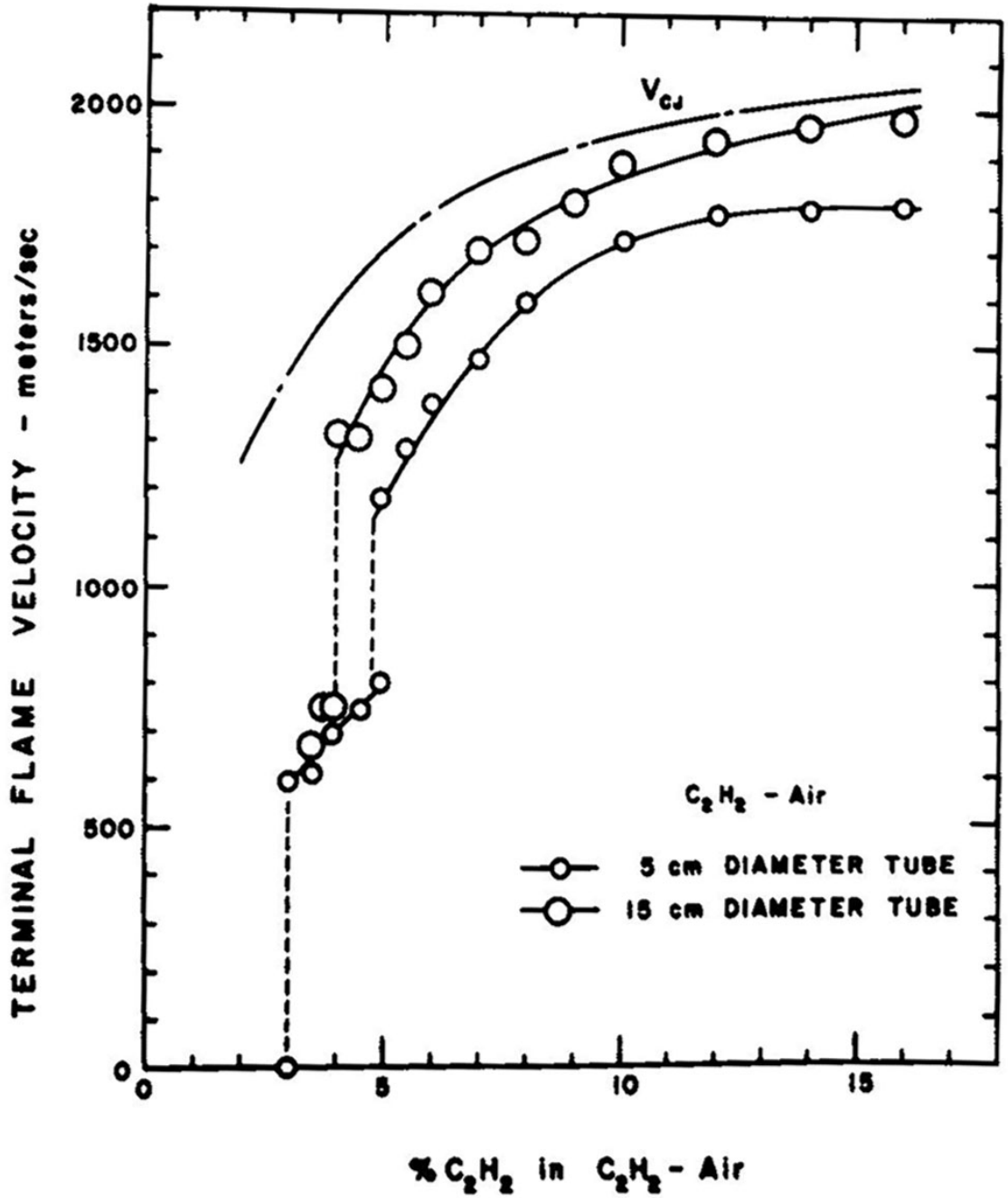


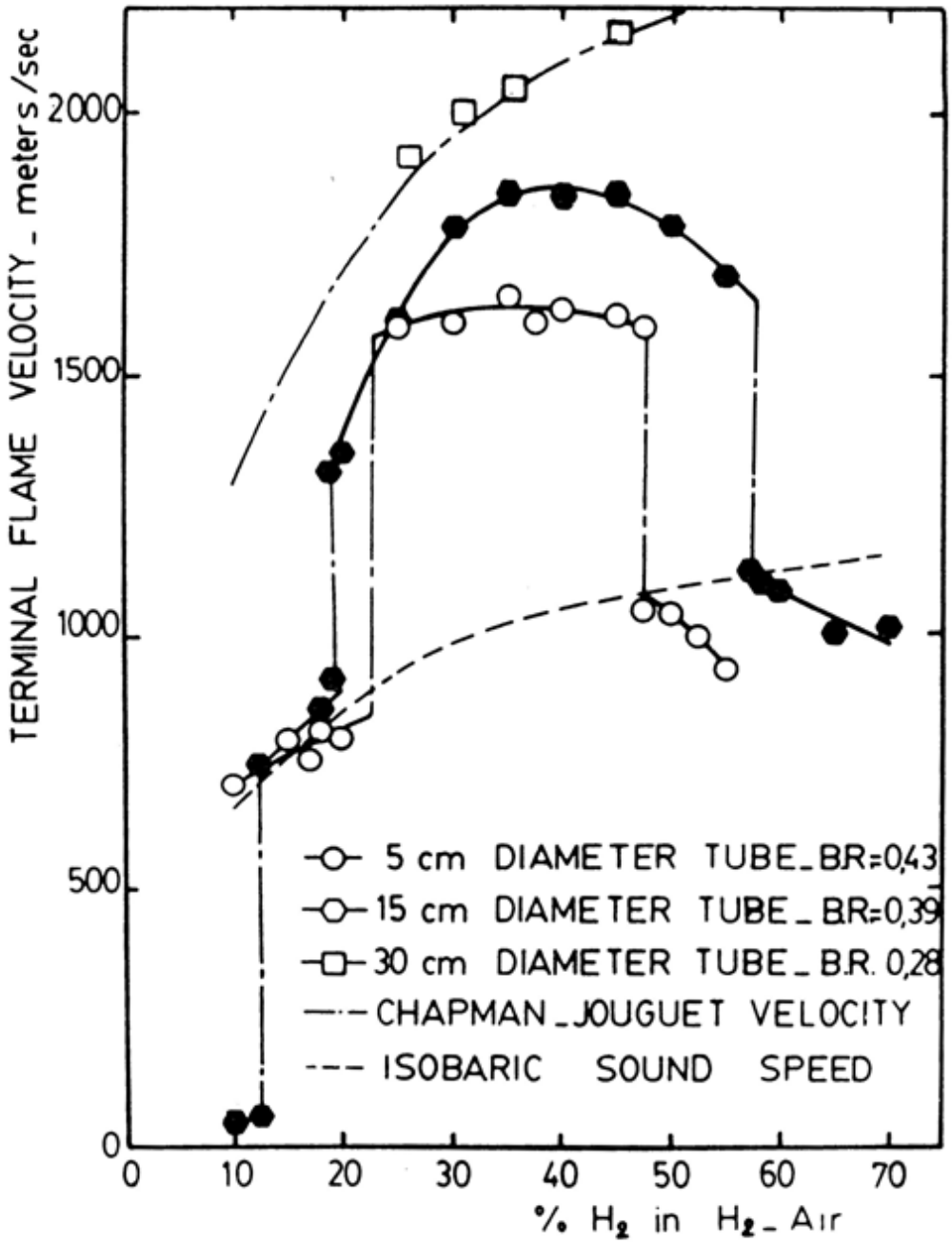

TUBE DIAMETER D = 5cm
OBSTACLE BLOCKAGE RATIO BR = 0·43
16% C_2H_2-Air
10%
8%
6% C_2H_2-Air
5%
5% C_2H_2-Air
4%
3·5%
3% C_2H_2 - Air
FLAME VELOCITY - meters/sec
2000
1500
1000
500
0
0
1
2
3
4
5
6
DISTANCE ALONG OBSTACLE FIELD - meters

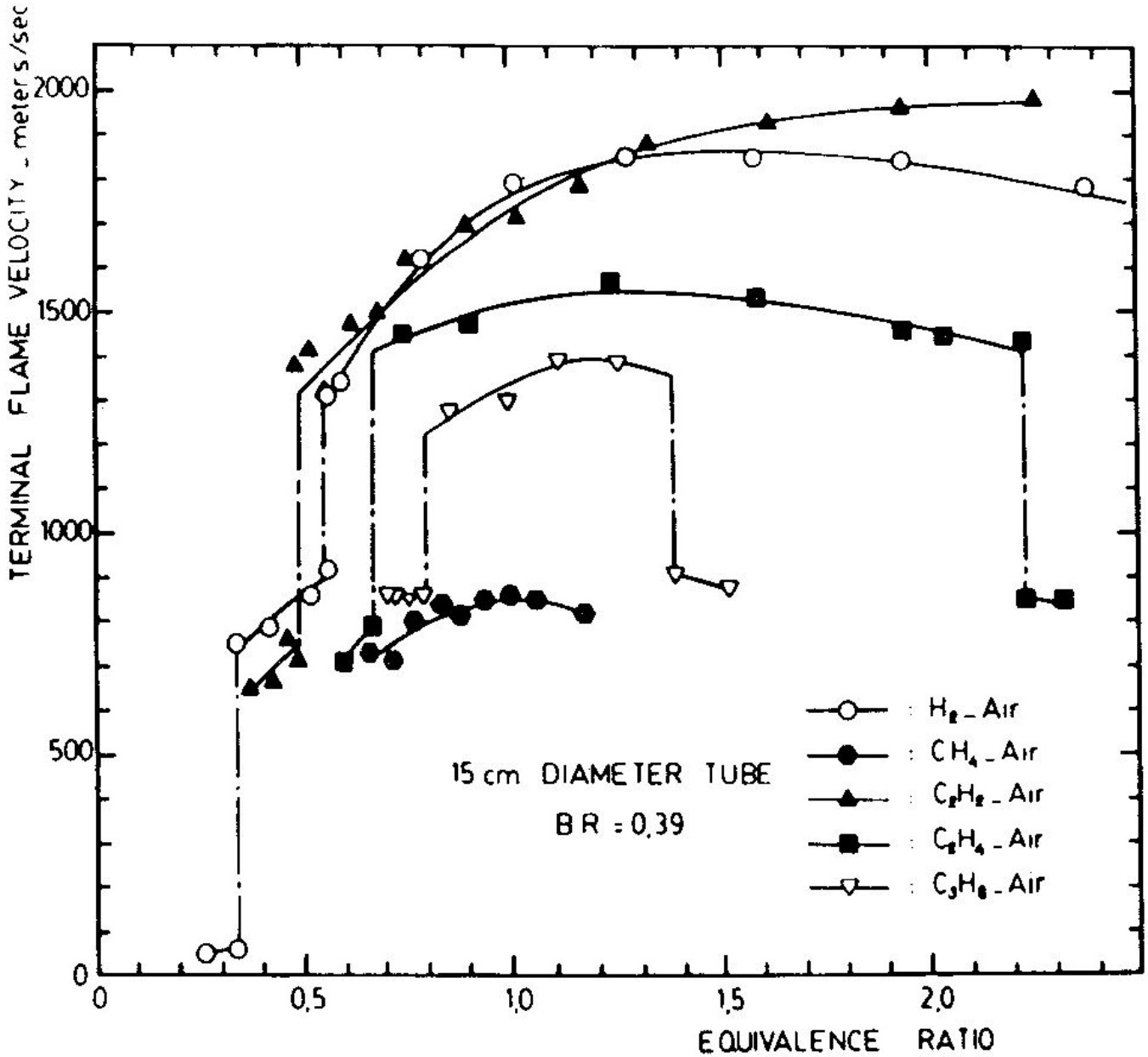

time
distance

Findings from Rough Tube Experiments

- rapid acceleration to a quasi-steady velocity
- steady velocity is not too sensitive to tube diameter or obstacle configuration
- distinct transition from steady velocity to a higher value when mixture sensitivity varies


TERMINAL FLAME VELOCITY - meters/sec
2000
1500
1000
500
0
0
5
10
15
% C_2H_2 in C_2H_2 - Air
V_{CJ}
C_2H_2 - Air
5 cm DIAMETER TUBE
15 cm DIAMETER TUBE


TERMINAL FLAME VELOCITY - meters/sec
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
% H₂ in H₂ - Air
5 cm DIAMETER TUBE - B.R=0,43
15 cm DIAMETER TUBE - B.R=0,39
30 cm DIAMETER TUBE - B.R. 0,28
CHAPMAN - JOUGUET VELOCITY
ISOBARIC SOUND SPEED


TERMINAL FLAME VELOCITY _ meters/sec
2000
1500
1000
500
0
0
0,5
1,0
1,5
2,0
EQUIVALENCE RATIO
15 cm DIAMETER TUBE
B R = 0,39
: H₂ _ Air
: CH₄ _ Air
: C₂H₂ _ Air
: C₂H₄ _ Air
: C₃H₈ _ Air

Three Distinct Regimes

- turbulent deflagration < 100 m/s
- sonic regime

  deflagration speed ~ sound speed of products

  ~ 1000 m/s (~½ V_{CJ})
- quasi-detonation or detonation

  ~ V_{CJ} with large velocity deficit

Three parameters that can characterize the condition for onset of detonation:

1. critical deflagration speed
2. tube diameter
3. sensitivity of mixture

Table 1 Transition within obstacle field

Mixture	D, cm	d, mm	λ, mm	λ/d
4.75% C_2H_2-air	5	37.4	19.8	0.51
22% H_2-air	5	37.4	30.7	0.82
47.5% H_2-air	5	37.4	41.2	1.10
6% C_2H_4-air	5	37.4	37.8	1.01
9% C_2H_4-air	5	37.4	30.1	0.81
4% C_2H_2-air	15	114.0	58.3	0.51
3.25% C_3H_8-air	15	114.0	112.0	0.98
5.5% C_3H_8-air	15	114.0	116.0	1.02

No Transition

Mixture	D, cm	d, mm	λmin, mm	λ/d
C_3H_8-air	5	37.4	52.5	1.40
CH_4-air	5	37.4	300.0	8.02
CH_4-air	15	114.0	300.0	2.63

Table 2 Transition in smooth-walled tube

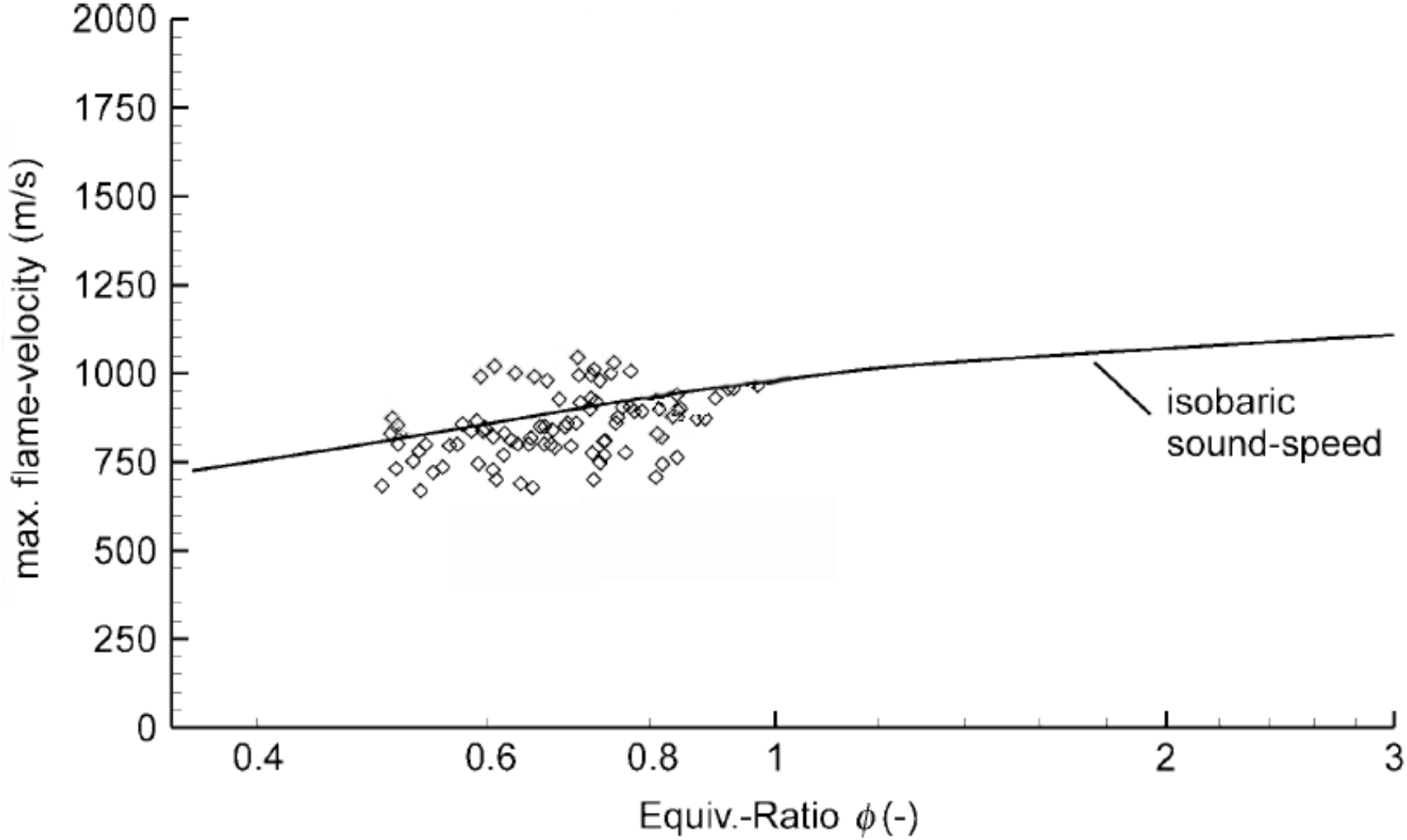
Mixture	D, cm	λ, mm	λ/D
4% C_2H_2-air	5	58.3	1.18
5% C_2H_4-air	5	65.1	1.32
10% C_2H_4-air	5	39.7	0.80
4% C_3H_8-air	5	52.2	1.06
5% C_3H_8-air	5	59.0	1.19
20% H_2-air	5	55.4	1.12
51% H_2-air	5	52.5	1.06

Critical Deflagration Speed for Onset of Detonation

$\sim \frac{1}{2} V_{CJ}$

~ sound speed of products

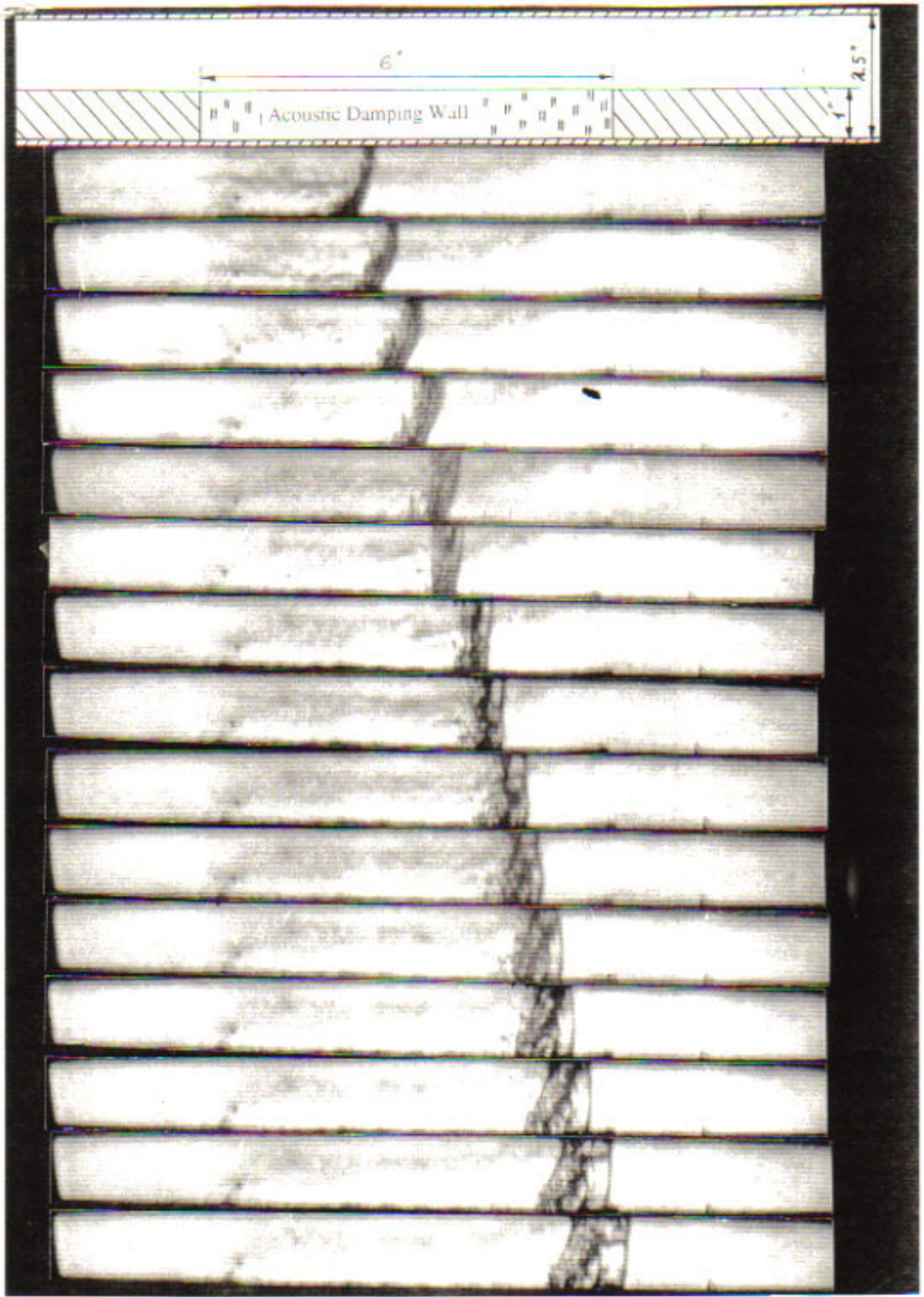
Eder & Brehm (2001)



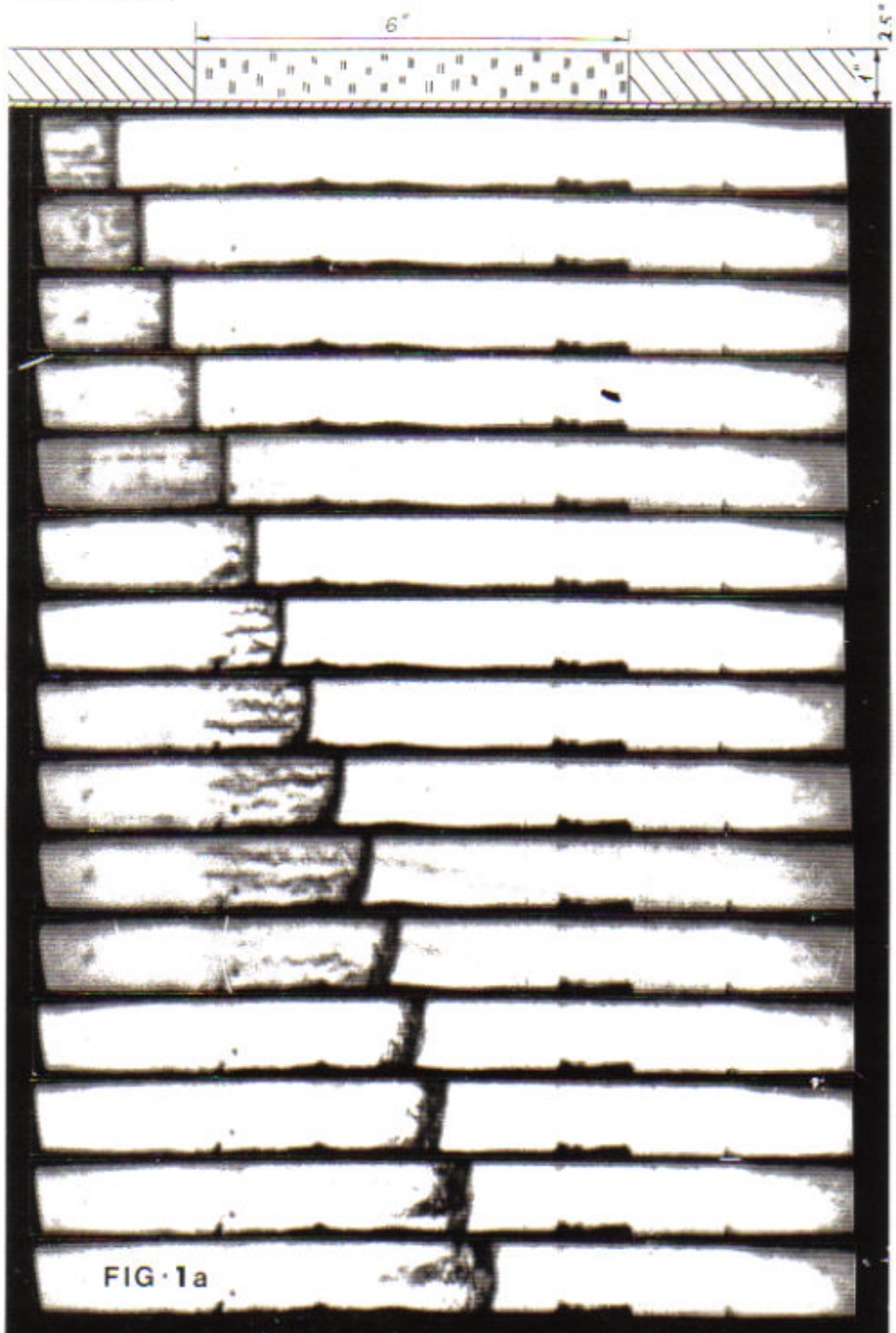
Vasil'ev (2006)

Mixture	c_0, m/sec	P_{CJ}	σ_{CJ}	P_V	σ_P	P_{def}	σ_{def}	π^*	M_{inc}	M_{ref}	M_0
$C_2H_2 + 2.5O_2$	330	33.83	1.84	17.07	0.07	0.48	0.036	18.2	3.95	2.1	7.34
C_2H_2 + air (stoichiometric ratio)	347	19.11	1.82	9.77	0.12	0.48	0.062	10.6	3.05	1.8	5.38
$C_2H_4 + 3O_2$	328	33.43	1.85	16.87	0.07	0.48	0.036	17.8	—	—	7.24
C_2H_4 + air (stoichiometric ratio)	347	18.35	1.81	9.38	0.12	0.48	0.064	10.1	2.95	1.8	5.26
$2H_2 + O_2$	537	18.79	1.84	9.59	0.12	0.49	0.062	10.4	3	1.8	5.28
H_2 + air (stoichiometric ratio)	409	15.58	1.8	8	0.15	0.48	0.076	9	2.8	1.75	4.82
$CH_4 + 2O_2$	355	29.32	1.85	14.84	0.08	0.49	0.04	15.8	3.65	2.05	6.73
CH_4 + air (stoichiometric ratio)	354	17.17	1.81	8.79	0.13	0.47	0.069	9.6	2.9	1.75	5.09

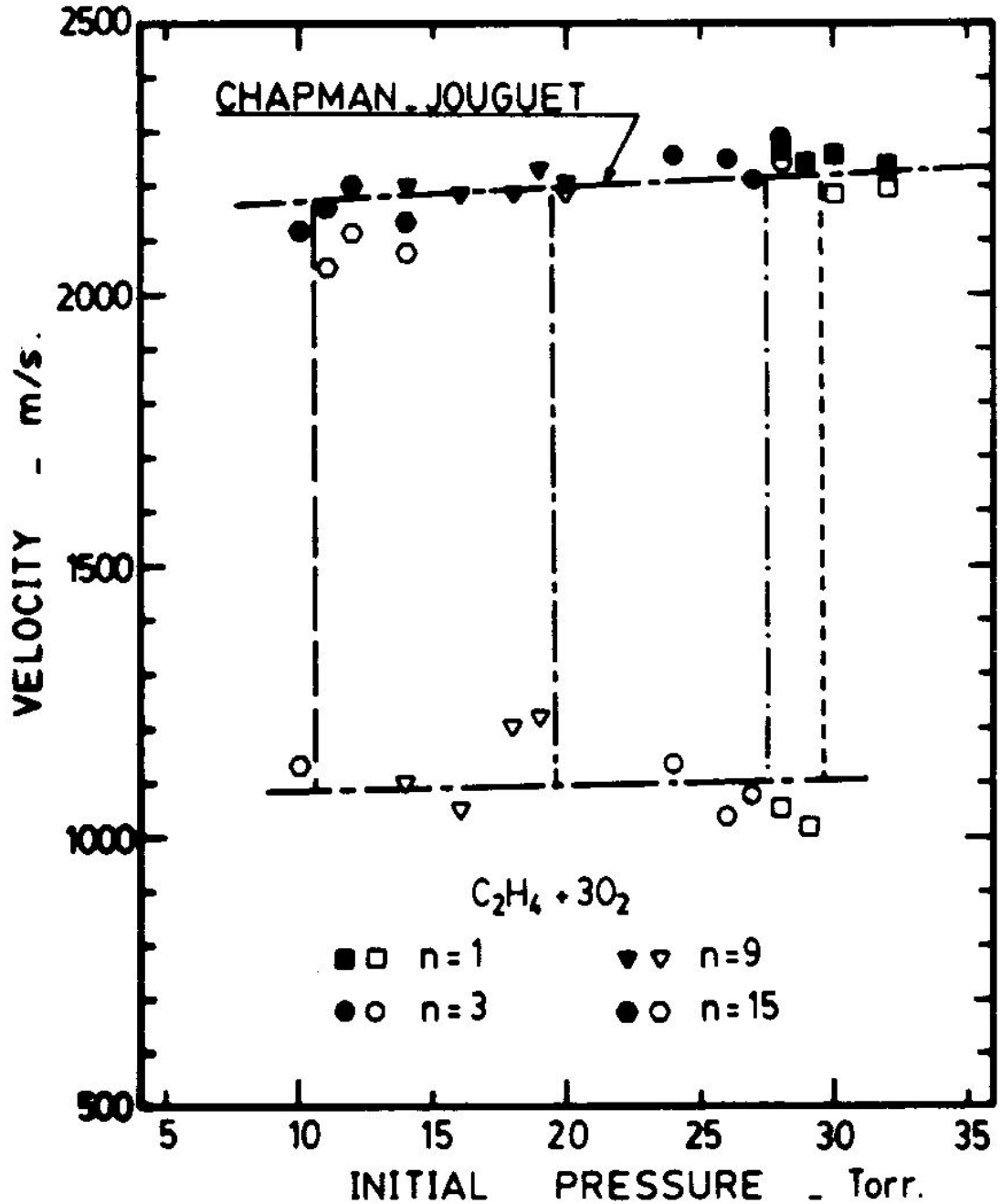
(confined) $0.33 \leq M_{crit} \leq 0.56\ M_{CJ}$ (unconfined)


6"
2.5"
1"
Acoustic Damping Wall

FIBER GLASS #3



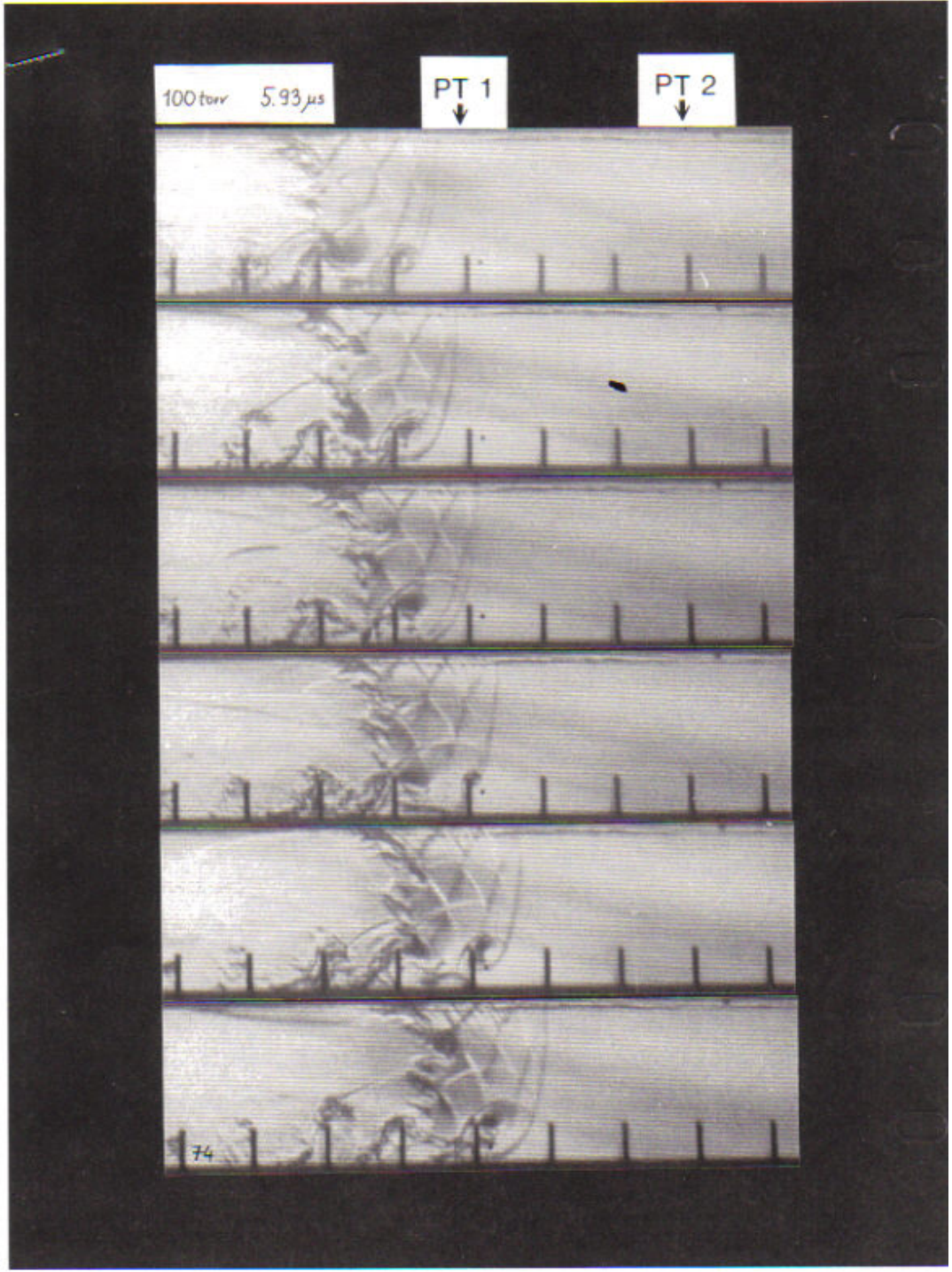
FIG·1a

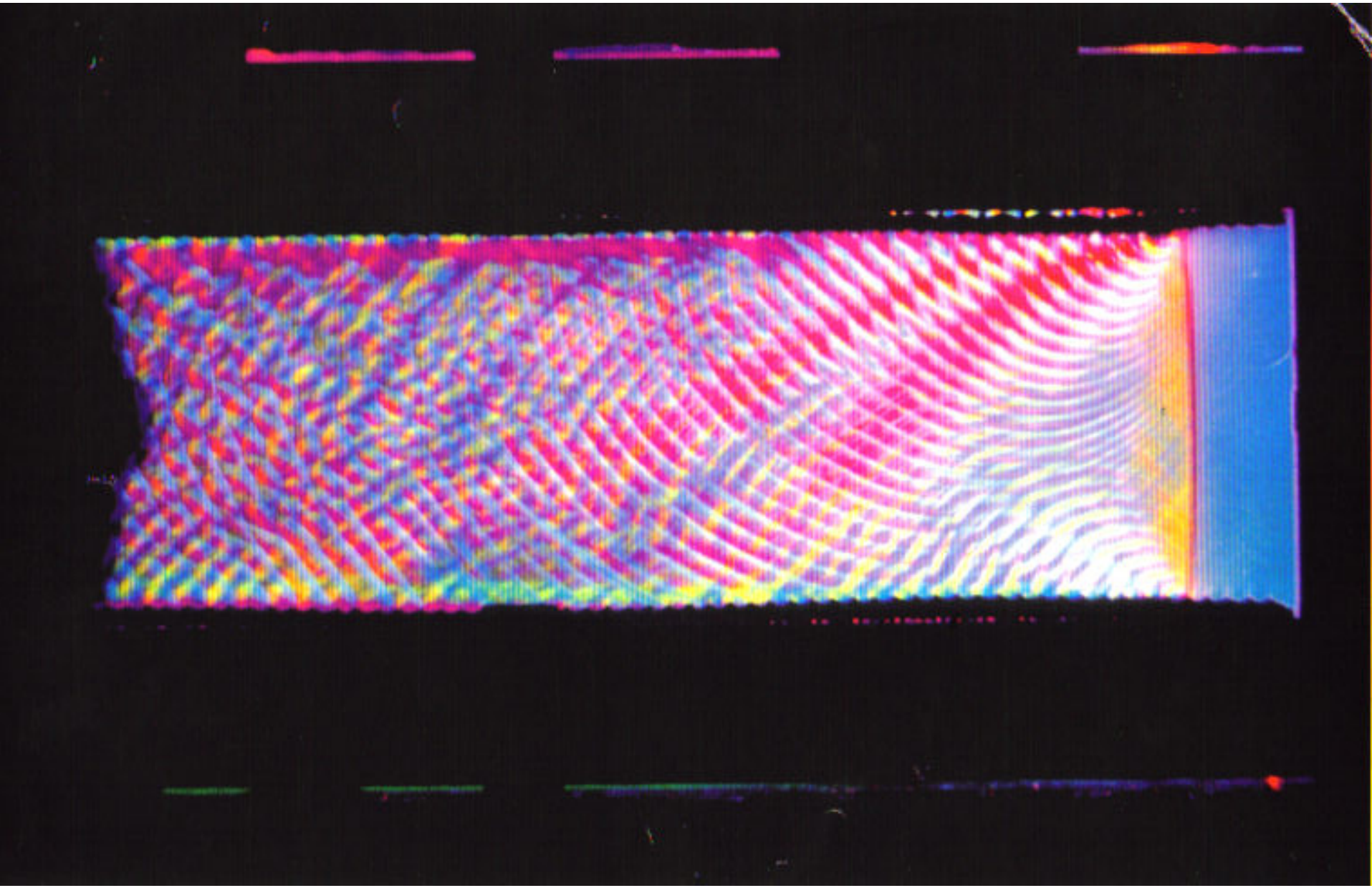

CHAPMAN-JOUGUET
VELOCITY - m/s.
2500
2000
1500
1000
500
5
10
15
20
25
30
35
INITIAL PRESSURE - Torr.
$C_2H_4 + 3O_2$
n=1
n=3
n=9
n=15

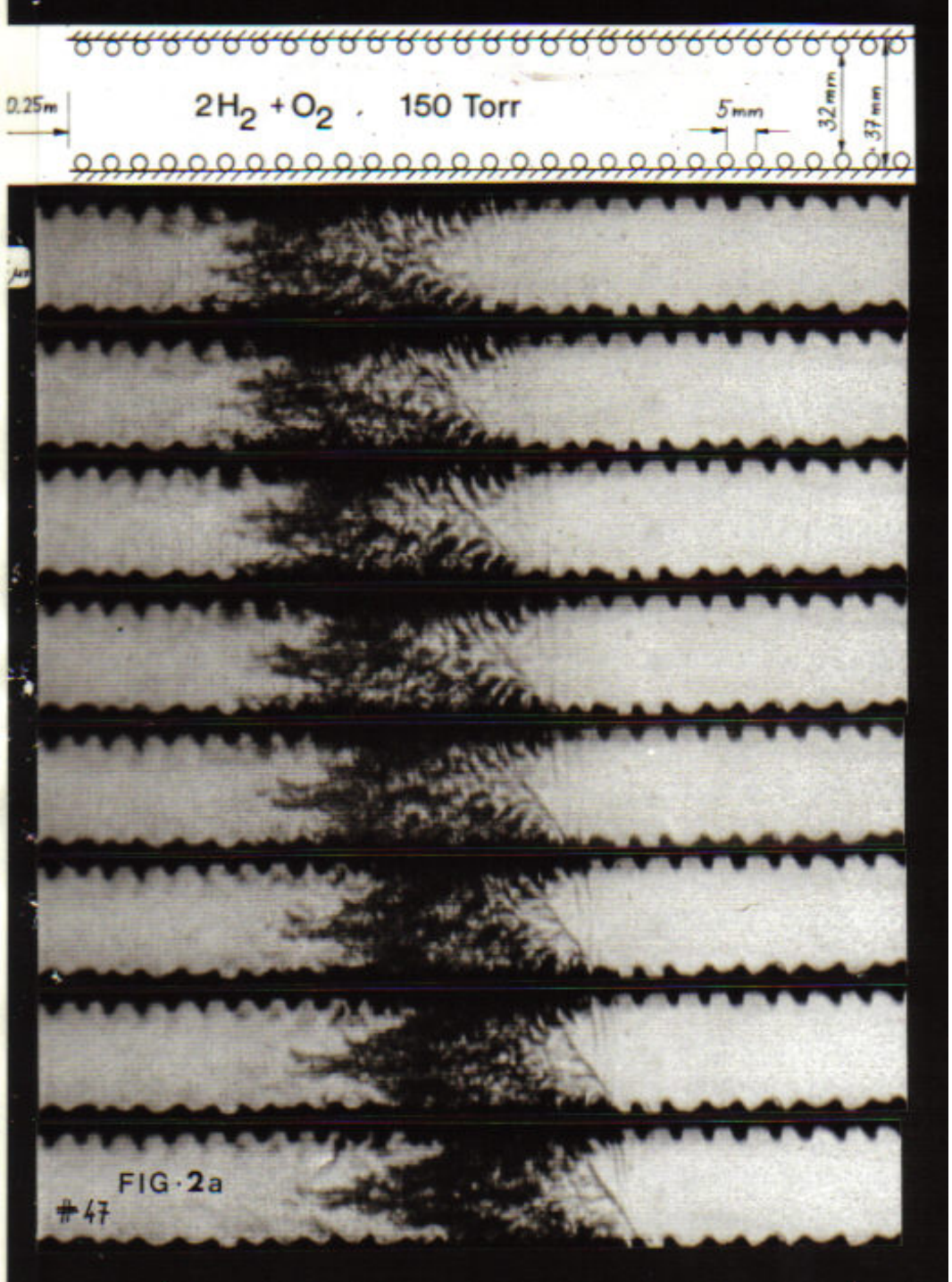
Mechanism of Onset of Detonation in Rough (Obstacle-Filled) Tubes

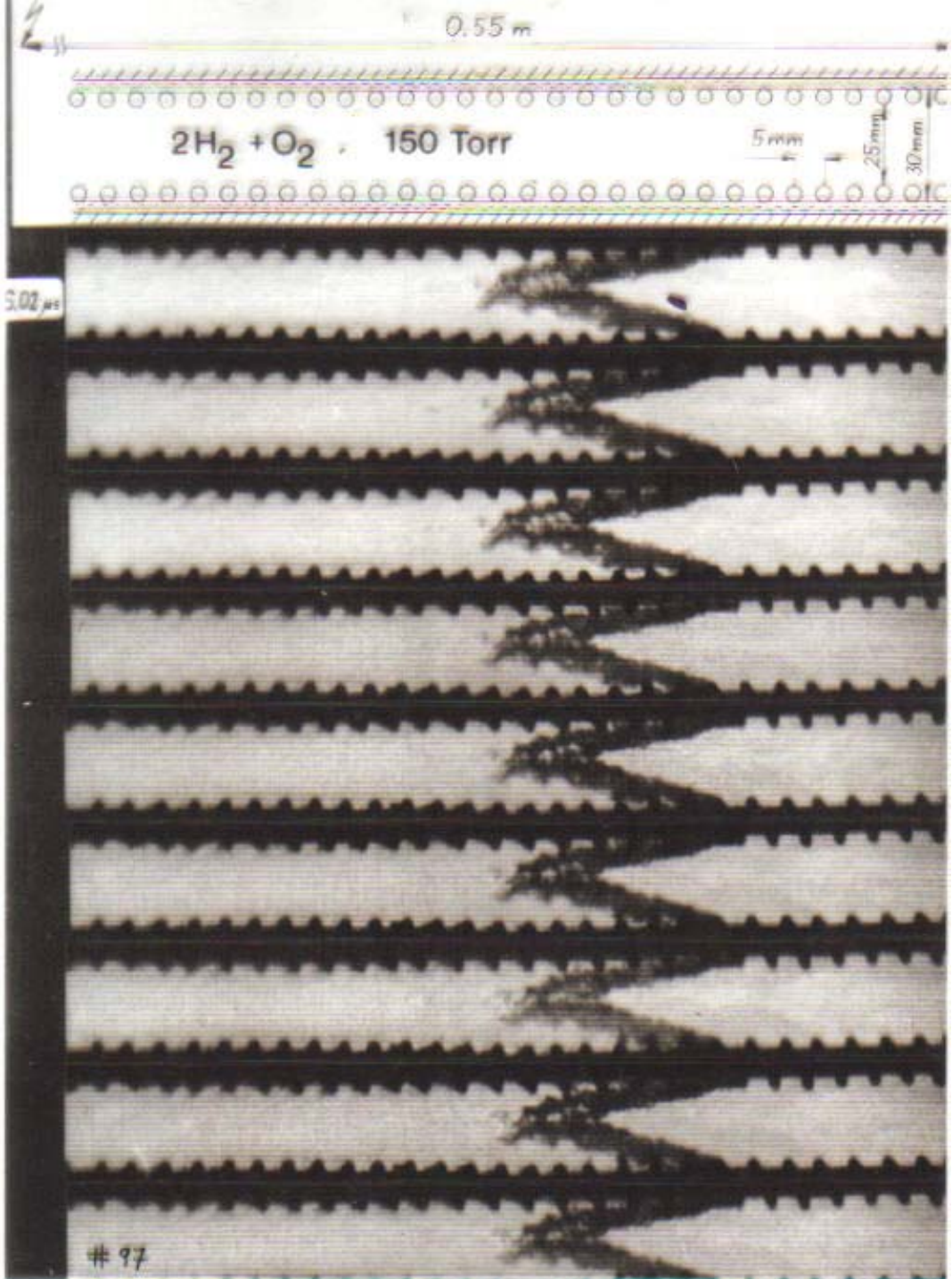
- turbulence from obstacles
- pressure waves

0.1ms
10cm


100 torr 5.93 μs
PT 1
PT 2
74



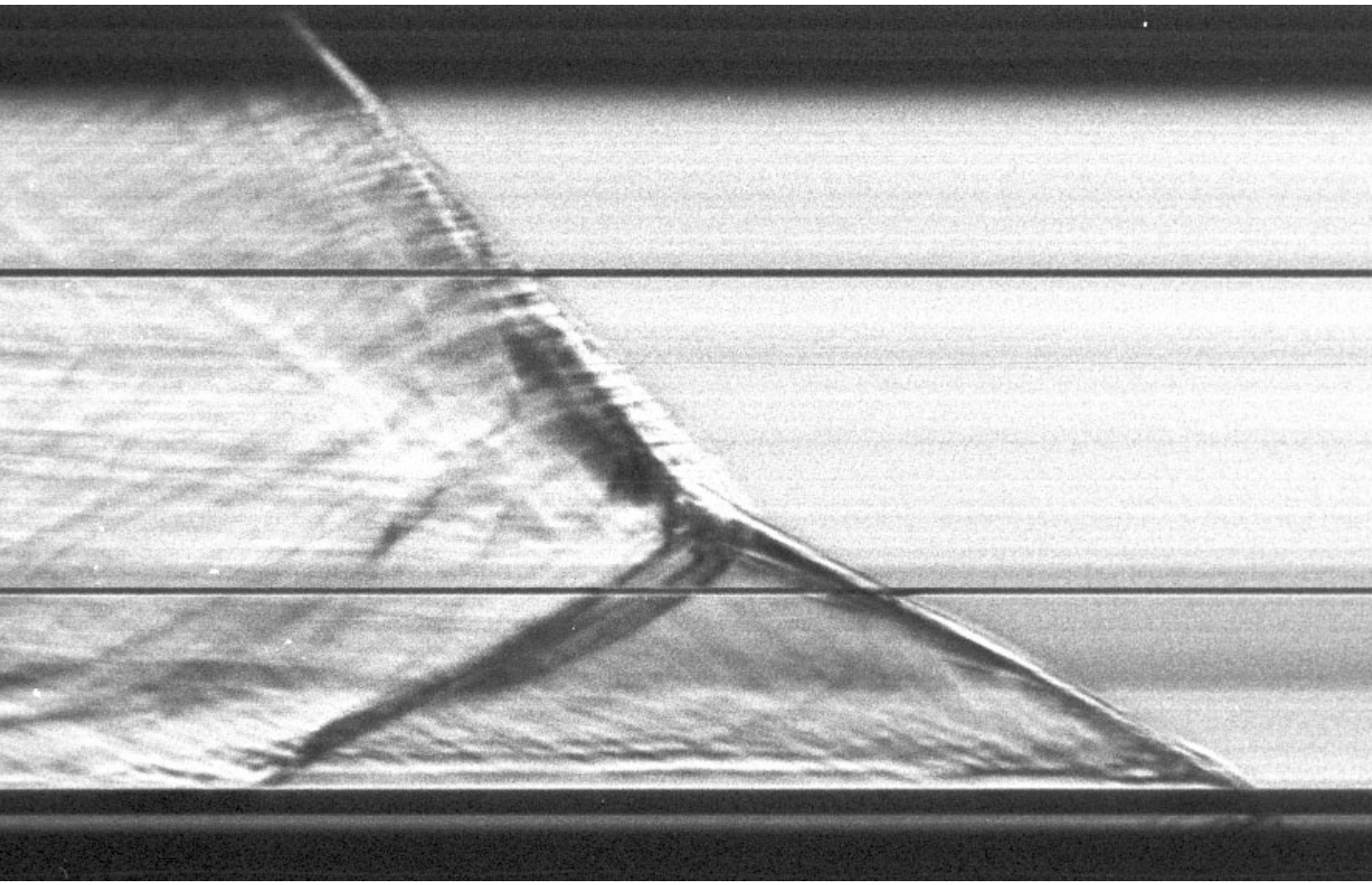

0.25m
$2H_2 + O_2$, 150 Torr
5mm
32mm
37mm
FIG·2a
#47

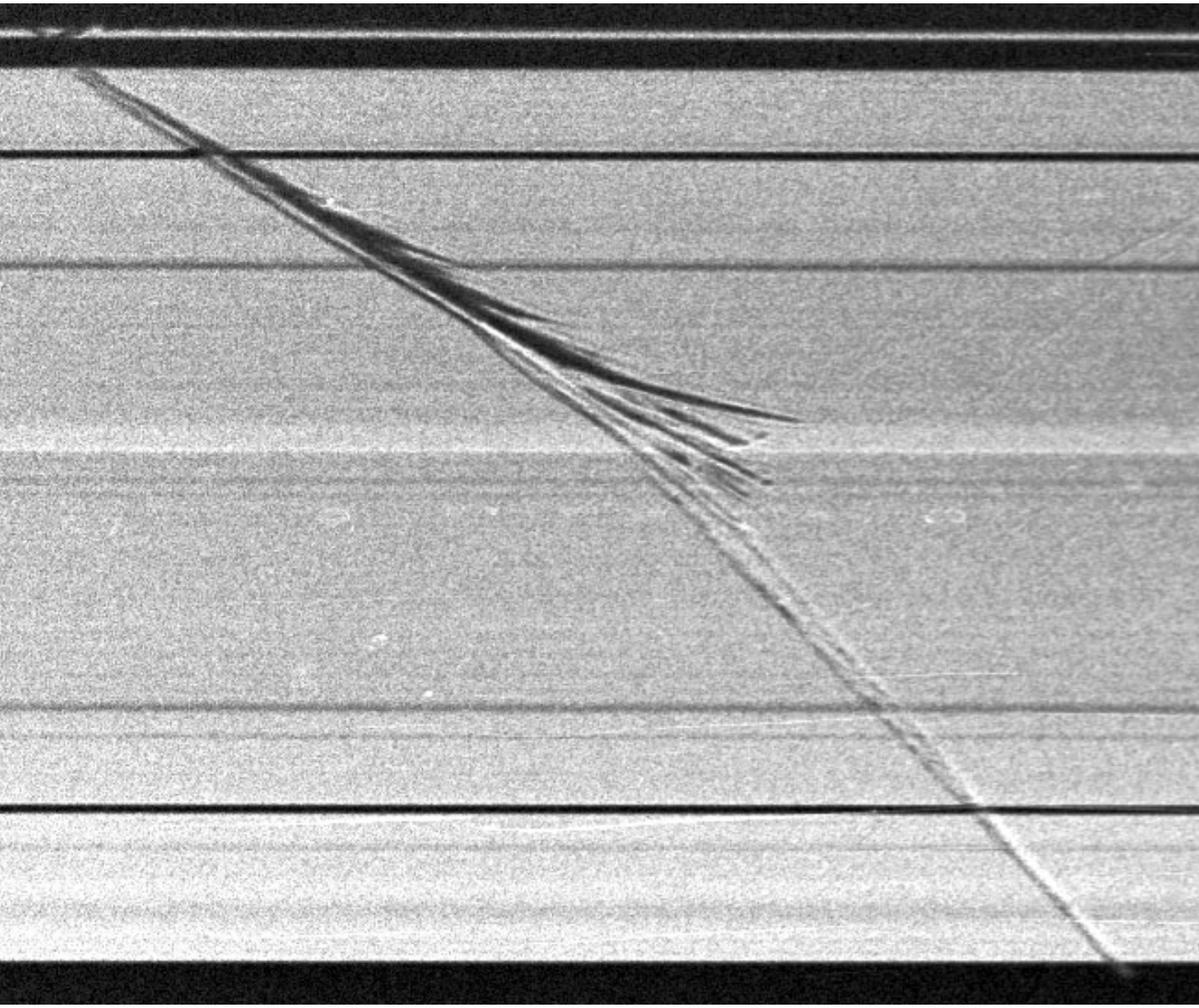

0.55 m
$2H_2 + O_2$. 150 Torr
5 mm
25 mm
30 mm
5.02 μs
97

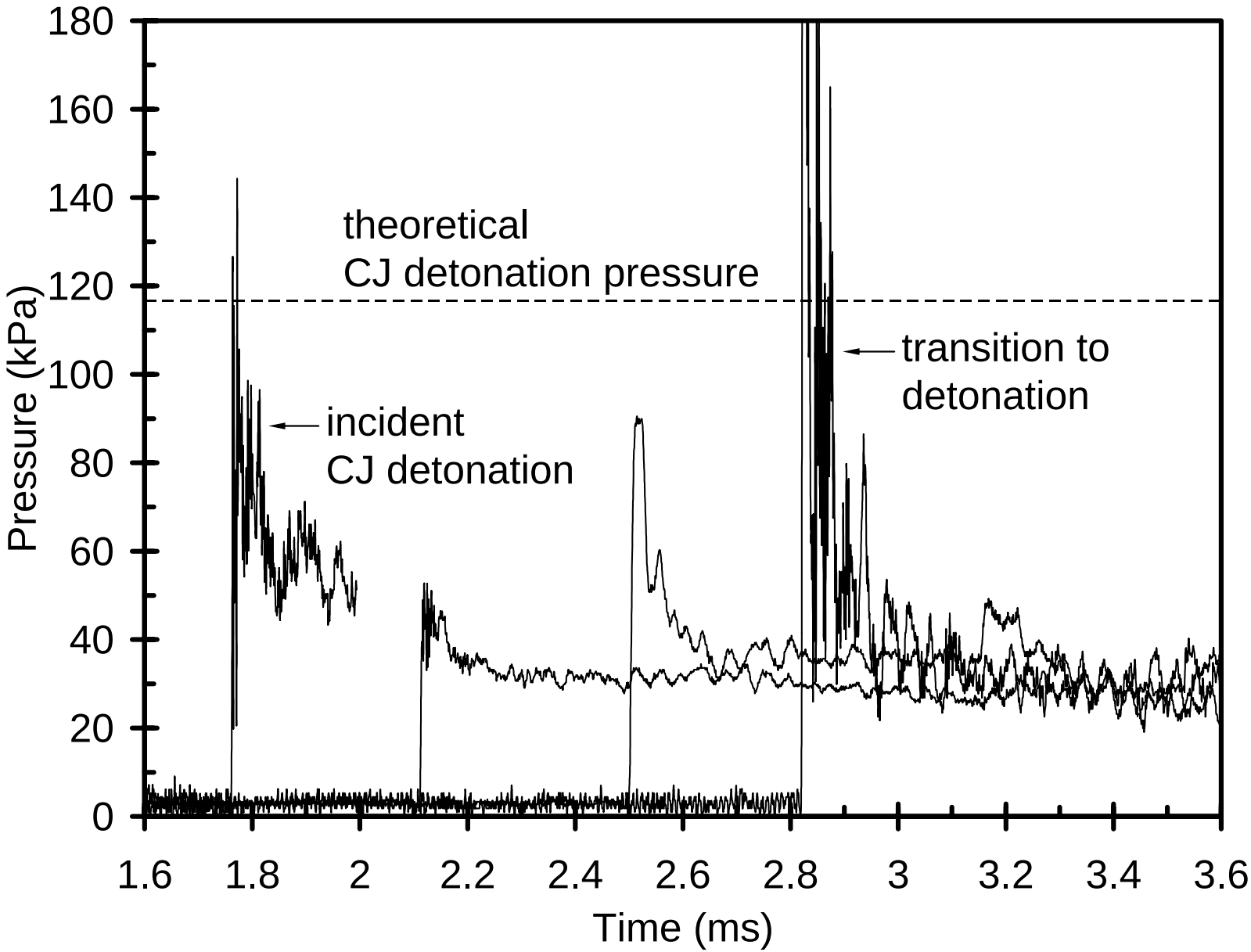
Two Modes of Onset of Detonation

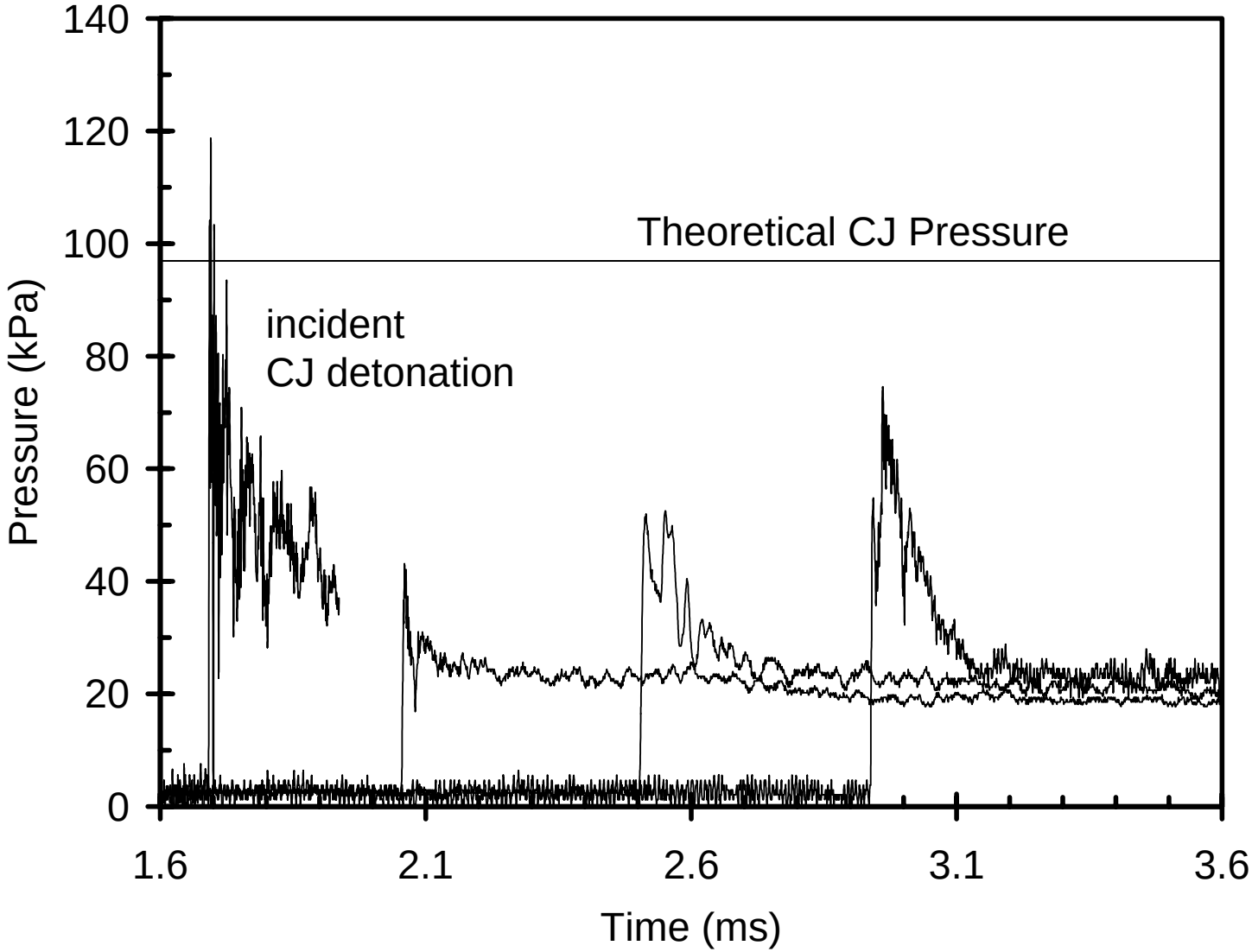
1. unstable mixture: local explosion, SWACER mechanism evidenced by formation of retonation waves

2. progressive wave amplification resonant coupling with turbulent reaction zone



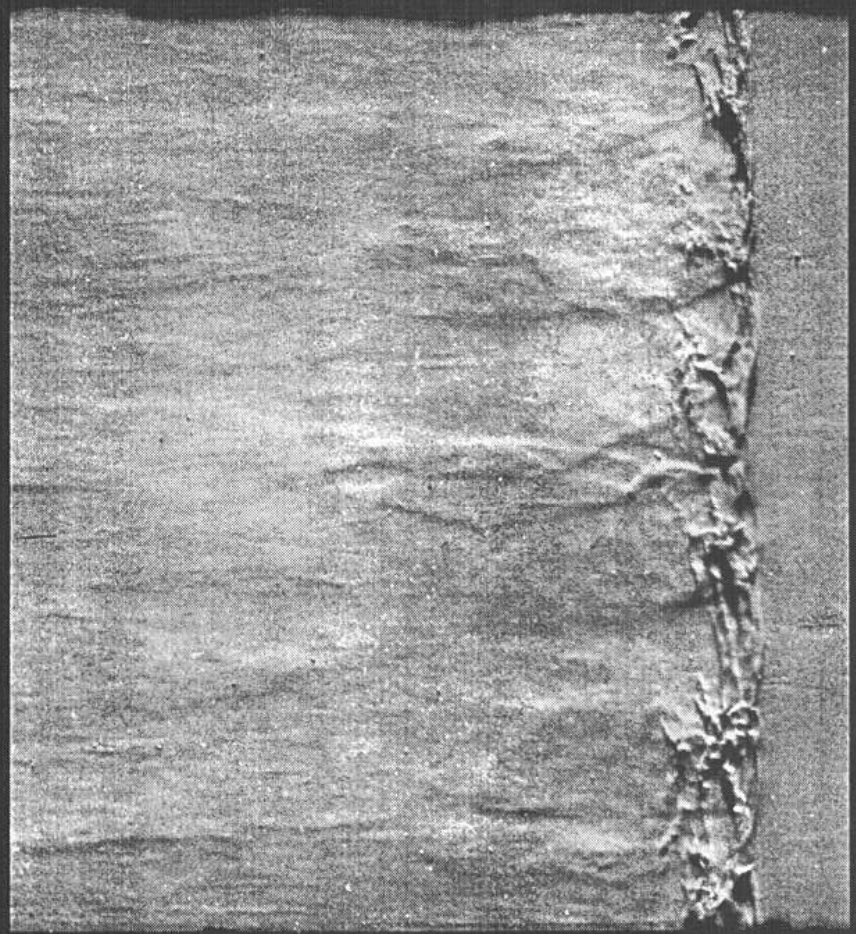



180
160
140
120
100
80
60
40
20
0
Pressure (kPa)
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
Time (ms)
theoretical
CJ detonation pressure
incident
CJ detonation
transition to
detonation

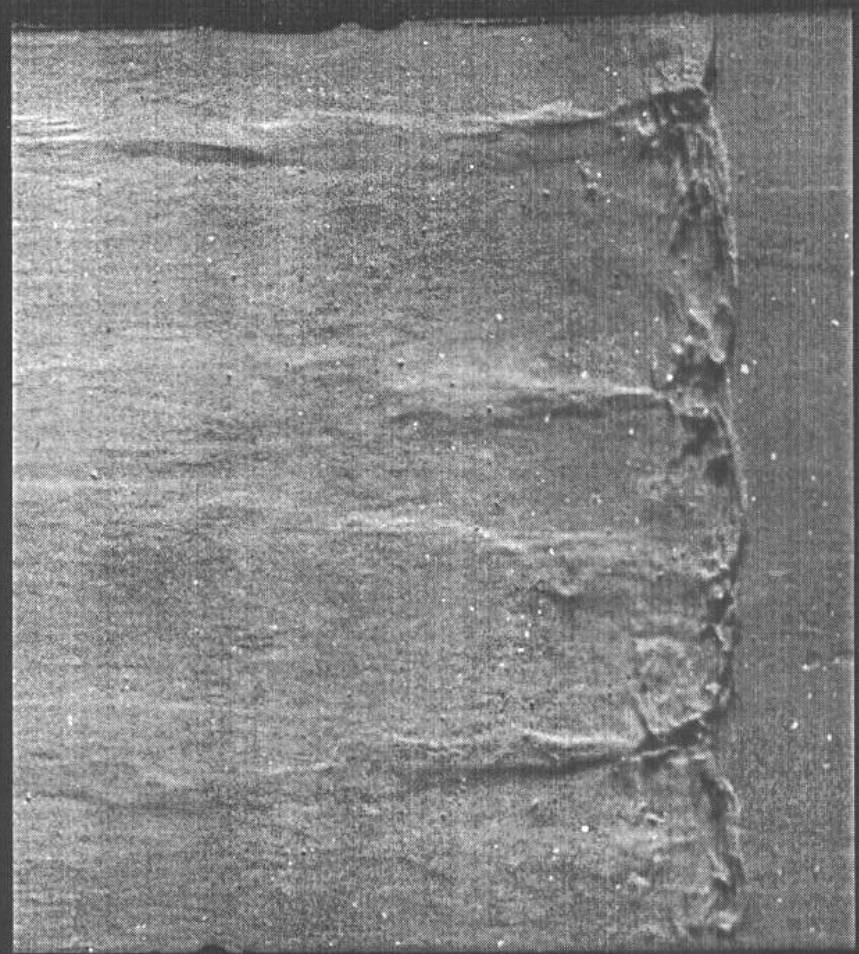

140
120
100
80
60
40
20
0
Pressure (kPa)
Theoretical CJ Pressure
incident
CJ detonation
1.6
2.1
2.6
3.1
3.6
Time (ms)

- detonation mechanism is resonant coupling between transverse pressure waves and chemical reactions

- transition means setting up the conditions for the resonant coupling to occur



$C_2H_2 + 9.5O_2$, 5.5kPa



$C_2H_2 + 2.5O_2 + 10.5Ar$, 5kPa

- turbulent combustion brings the deflagration to maximum speed; Chapman-Jouguet deflagration ~½ V_{CJ}

- transition to detonation requires the resonant coupling between transverse pressure fluctuations and the chemical reactions

- Chapman-Jouguet deflagration speed is not governed by reaction rate (hence turbulence)
- turbulent combustion rate must be fast enough to pressurize reaction zone
- gasdynamic expansion drives the deflagration like a CJ detonation
- hence, sound speed energetic parameters dominate and not turbulence

Outstanding Problems in DDT

- quantify the pre-detonation state
  (thermodynamic, turbulence, chemical kinetics)

- theory for the development of local explosions centers from hydrodynamic fluctuations

- condition for rapid amplifcation of pressure waves (SWACER)