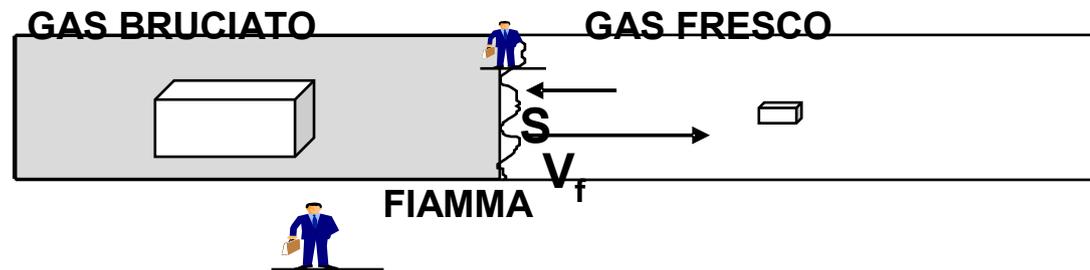


# PROPAGAZIONE

## SCHEMA DI PROPAGAZIONE PIANA

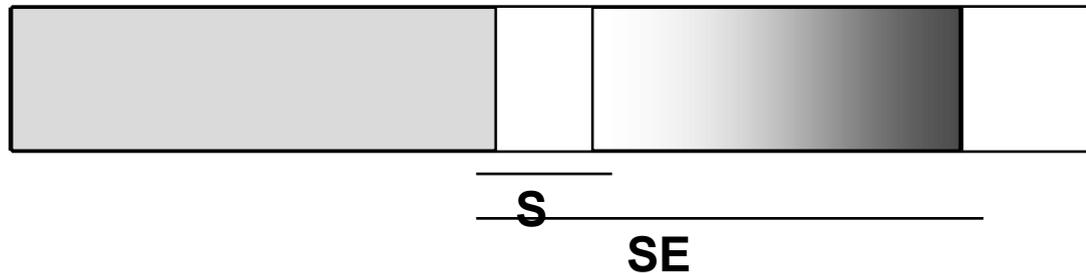


$$V_f = S E$$

$V_f$  = VELOCITA' DELLA FIAMMA

$S$  = VELOCITA' DI BRUCIAMENTO

$E$  = FATTORE DI ESPANSIONE =  $(T_f/T_i) (N_b/N_u)$



$$\rho_u u_u = \rho_b u_b$$

$$P_u + \rho_u u_u^2 = P_b + \rho_b u_b^2$$

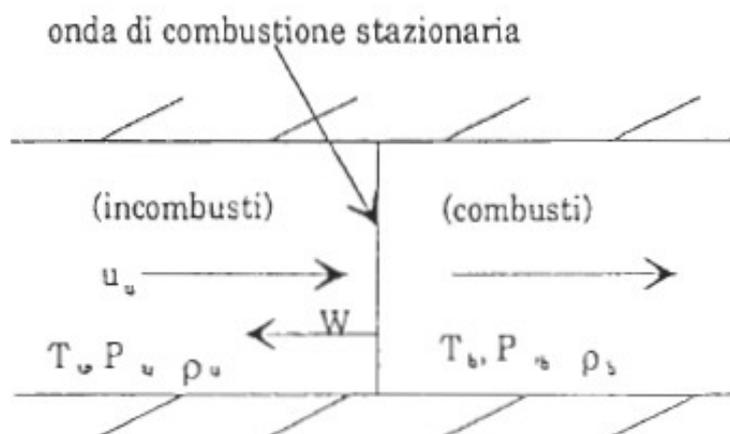
$$\frac{u_u^2}{2} + C_p T_u + q = \frac{u_b^2}{2} + C_p T_b$$

Le equazioni di bilancio sono state scritte con riferimento ad un sistema di coordinate solidale con l'onda di combustione (che si assume con velocità costante, uguale in modulo e opposta in verso alla velocità  $u_u$  dei gas incombusti); si è inoltre assunto che i calori specifici dei gas combustibili e di quelli incombusti siano uguali e costanti nel corso del processo. L'introduzione di tali

bilancio della massa (7.29.)

bilancio della quantità di moto (7.30.)

bilancio dell'energia (7.31.)



$W$  = velocità dell'onda rispetto ad un sistema fisso di coordinate.  
 $u$  = velocità del gas relative all'onda.

Fig. 7.7. Diagramma schematico di un'onda piana e stazionaria di combustione.

Le equazioni (7.29.) e (7.30.) possono essere combinate per ottenere la cosiddetta *equazione di Rayleigh*:

$$\frac{P_b - P_u}{\left(\frac{1}{\rho_u}\right) - \left(\frac{1}{\rho_b}\right)} = \rho_u^2 u_u^2 = \rho_b^2 u_b^2 \quad (7.32.)$$

che definisce una retta nel piano  $(1/\rho, P)$ , nota comunemente come *retta di Rayleigh*. Fissate le condizioni iniziali  $(P_u, \rho_u, u_u)$ , le soluzioni  $(1/\rho_b, P_b)$  della (7.32.) tali che<sup>1</sup>:

$$\frac{P_b - P_u}{\left(\frac{1}{\rho_u}\right) - \left(\frac{1}{\rho_b}\right)} \geq 0 \quad (7.33.)$$

individuano gli stati finali  $(P_b, \rho_b, u_b)$  del sistema fluidodinamicamente possibili.

L'equazione (7.31.), riferita a gas ideali (per i quali è  $C_p = (\gamma/\gamma - 1)R$ ) e utilizzando la (7.29.), può porsi nella forma:

$$\frac{\gamma}{\gamma - 1} \left( \frac{P_b}{\rho_b} - \frac{P_u}{\rho_u} \right) - \frac{1}{2} (P_b - P_u) \left( \frac{1}{\rho_b} + \frac{1}{\rho_u} \right) = q \quad (7.34.)$$

comunemente nota come *equazione di Rankine - Hugoniot*. Essa, assegnate le condizioni iniziali  $(P_u, \rho_u, T_u)$  e dato il calore di reazione  $q$ , fornisce i valori finali  $(P_b, \rho_b, T_b)$  del processo possibili dal punto di vista energetico.

La (7.34.) nel piano  $(1/\rho, P)$  è rappresentata da una curva ad andamento iperbolico che è detta *curva di Rankine - Hugoniot* relativa al processo con calore di reazione  $q$ . Il punto di coordinate  $(1/\rho_0, P_0)$  viene comunemente chiamato origine della curva di Hugoniot; esso appartiene alla cosiddetta *curva adiabatica*, o curva di Hugoniot relativa alle stesse condizioni iniziali e al calore di reazione nullo.

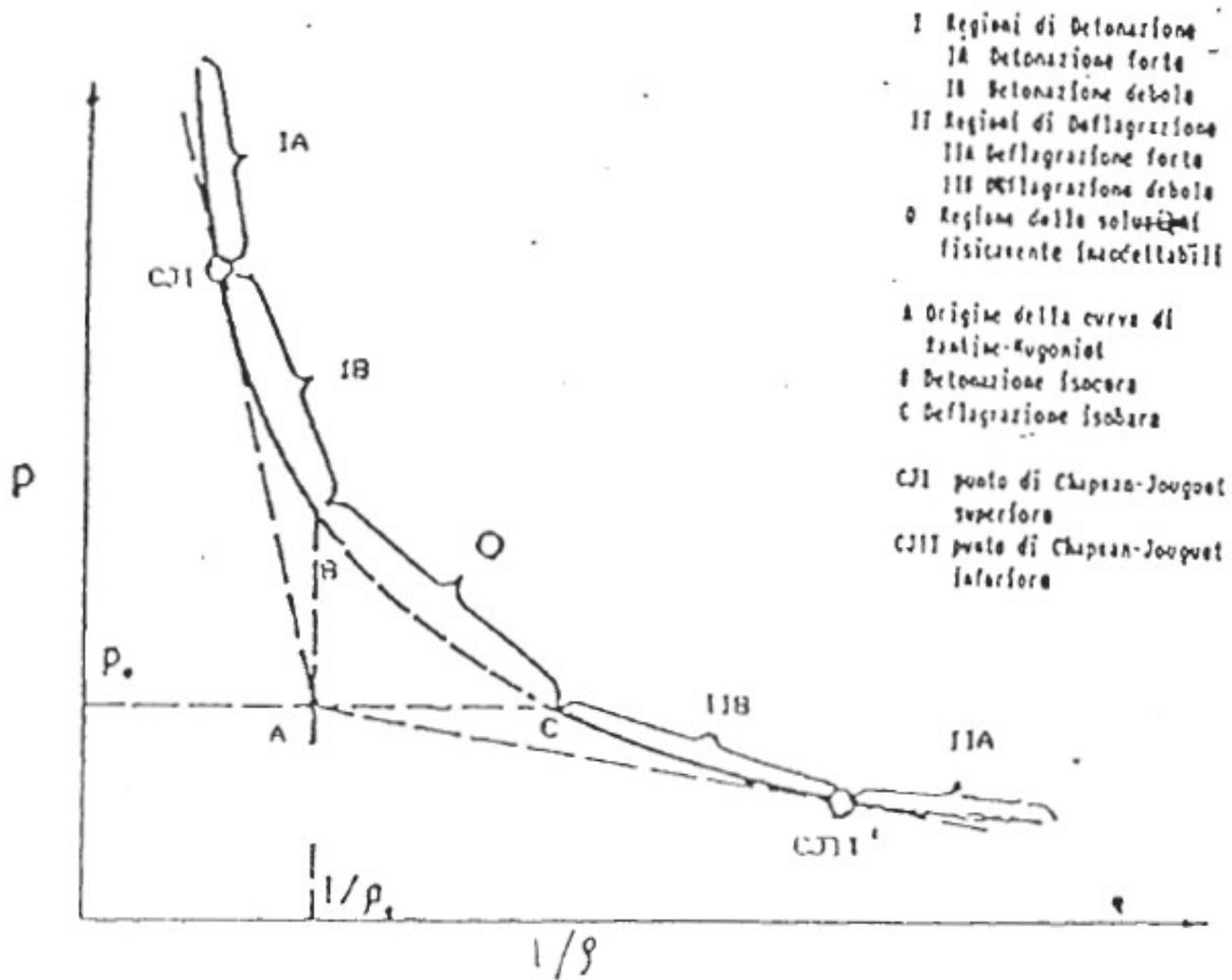
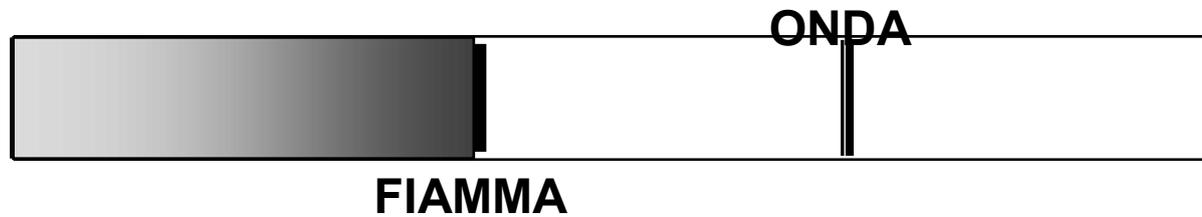


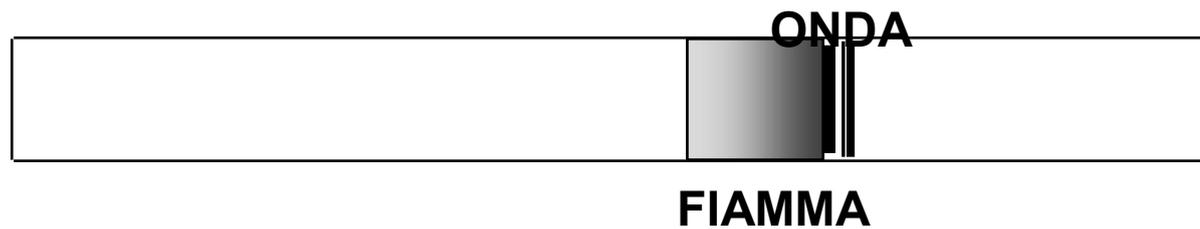
Fig. 7.8. Curva di Rankine-Hugoniot

# *DETONAZIONE*

## DEFLAGRAZIONE



## DETONAZIONE

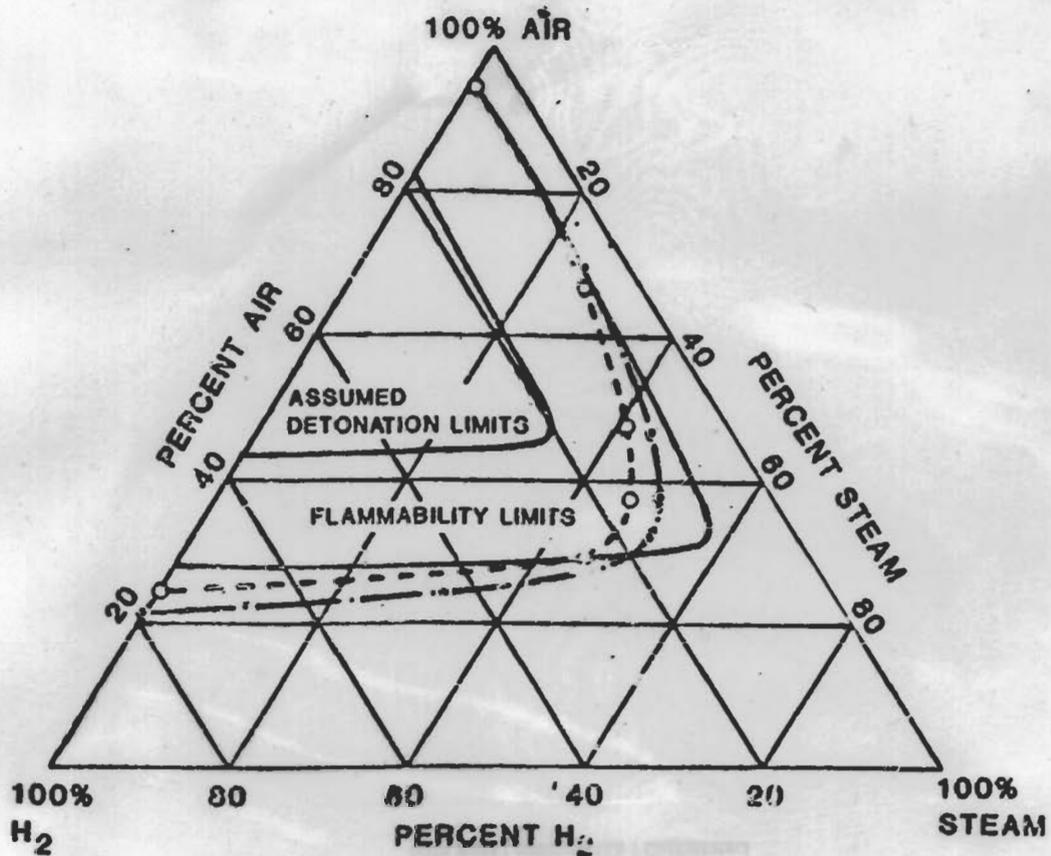


# BURNING VELOCITY

**EFFECT OF GAS CONCENTRATION ON BURNING VELOCITY**  
Results from Gibbs and Calcote<sup>10</sup>—see table 1.2 for recommended maximum values for different fuels

— Propane—Air  
- - - Ethylene—Air  
..... Methane—Air





**FLAMMABILITY LIMITS**

- 68°F - 187°F AT 0 psig (20°C - 86°C AT 101 kPa)
- - - - 300°F - 0 psig (149°C - 101 kPa)
- ⊙- - - - 300°F - 100 psig (149°C - 892 kPa)

**Figure 2-16. Flammability and Detonation Limits of Hydrogen:Air:Steam Mixtures**

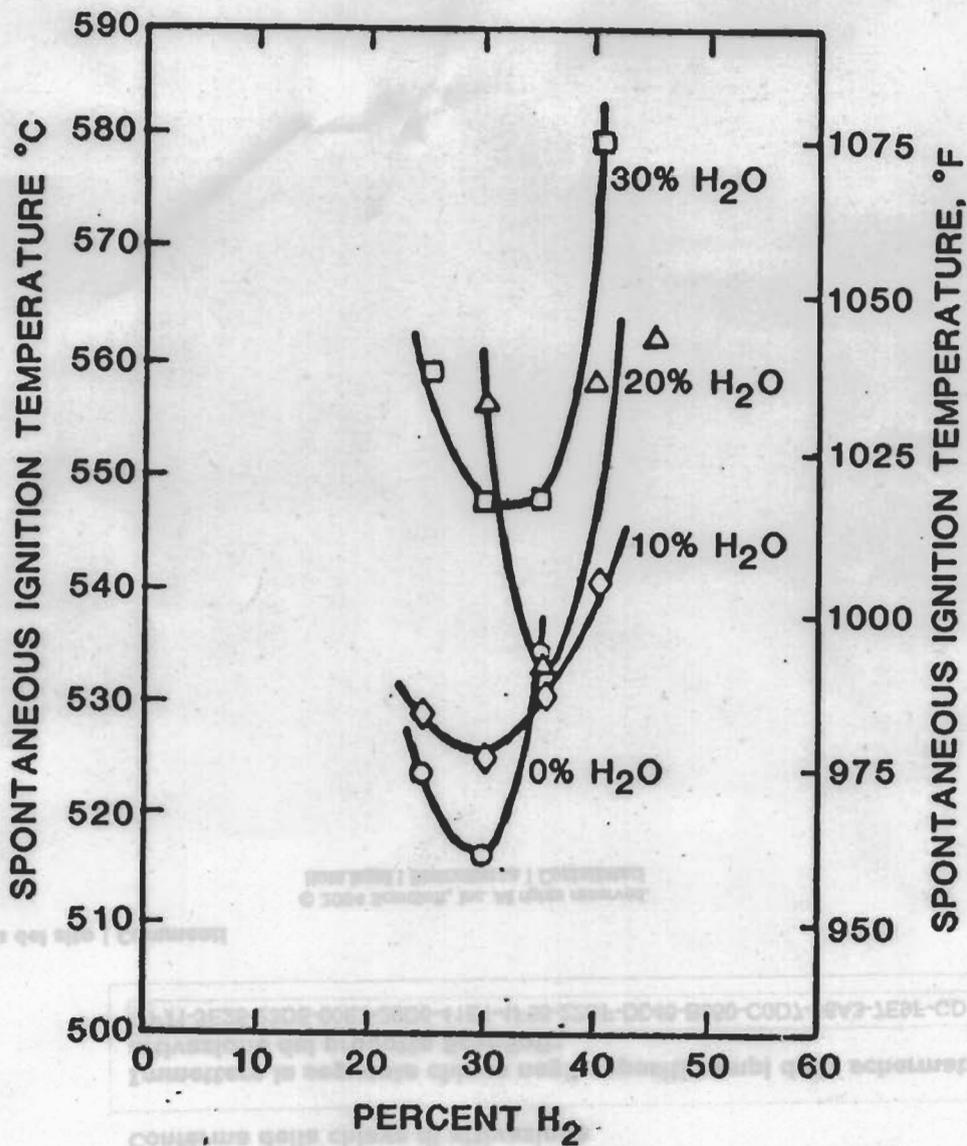


Figure 2-21. Minimum Spontaneous Ignition Temperature of Hydrogen:Air:Steam Mixtures

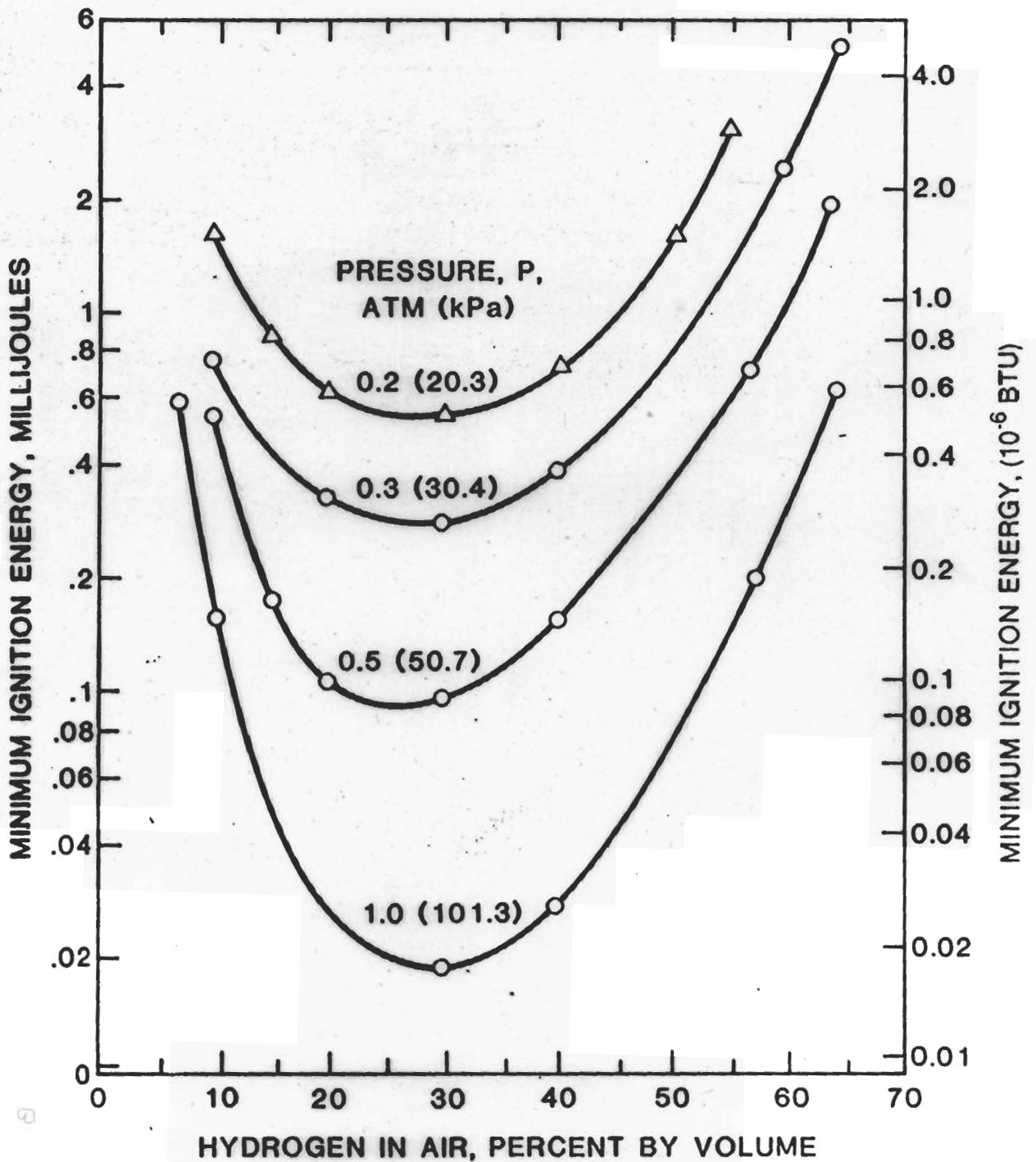
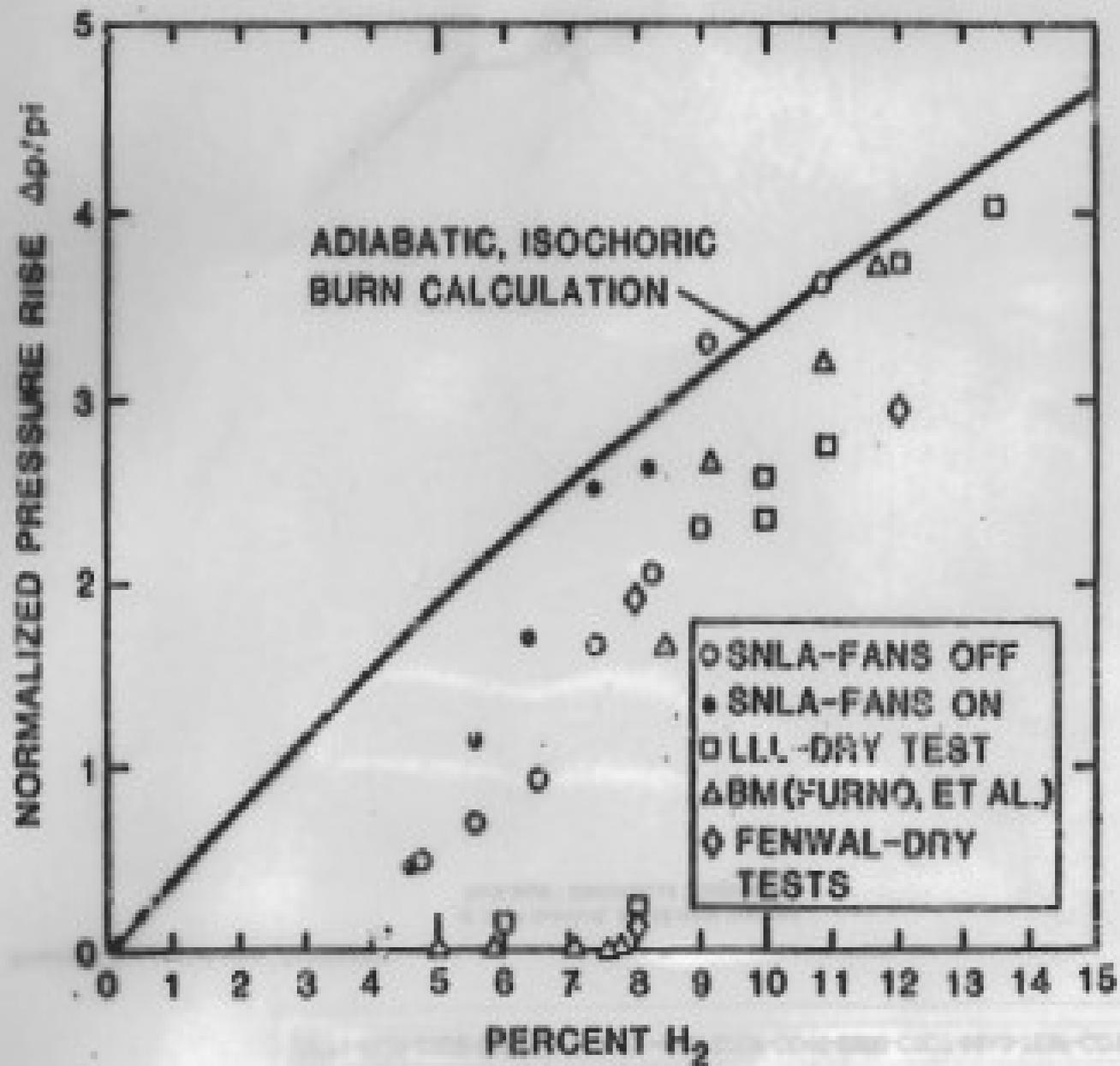
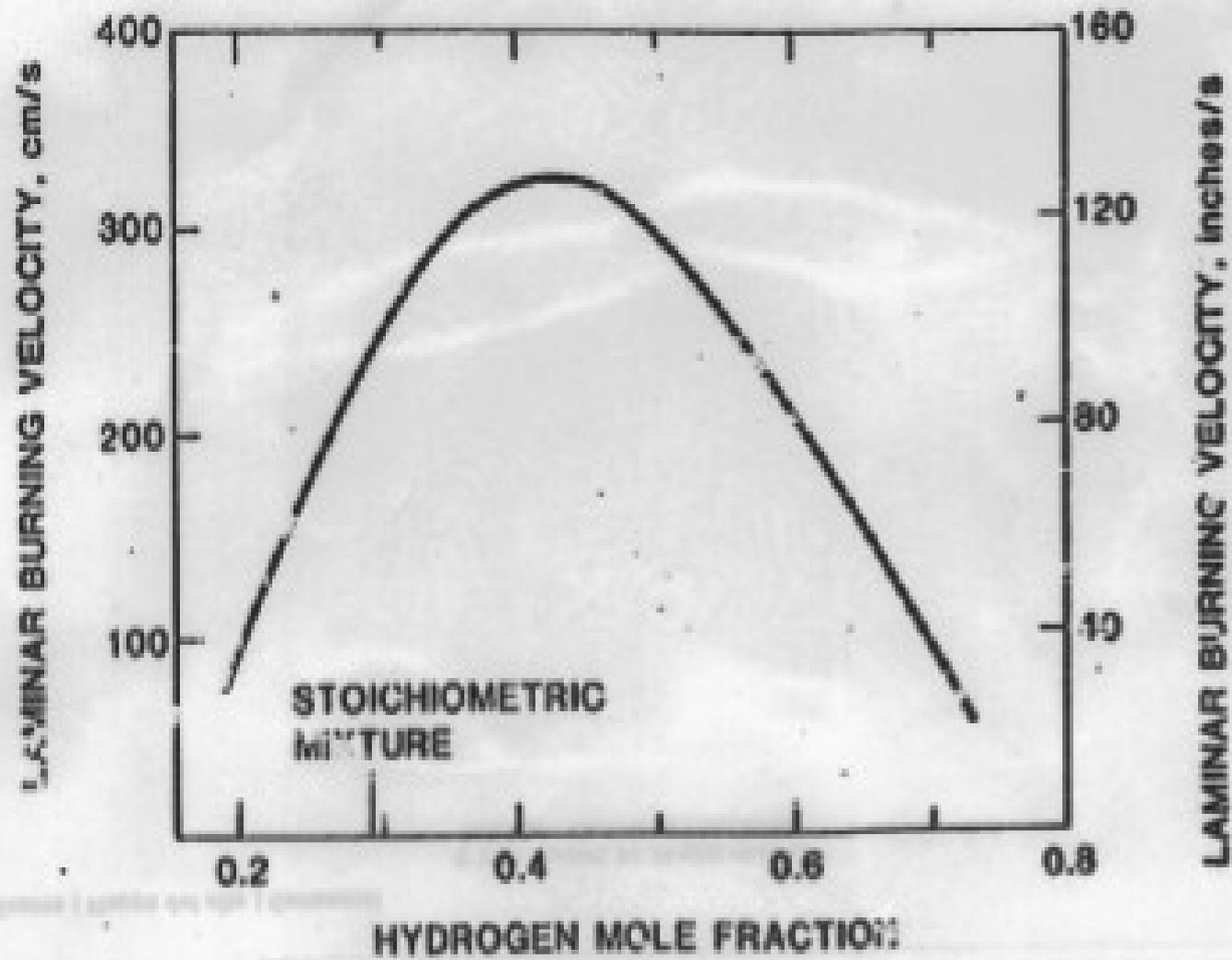


Figure 2-18. Spark Ignition Energies For Dry Hydrogen: Air Mixtures





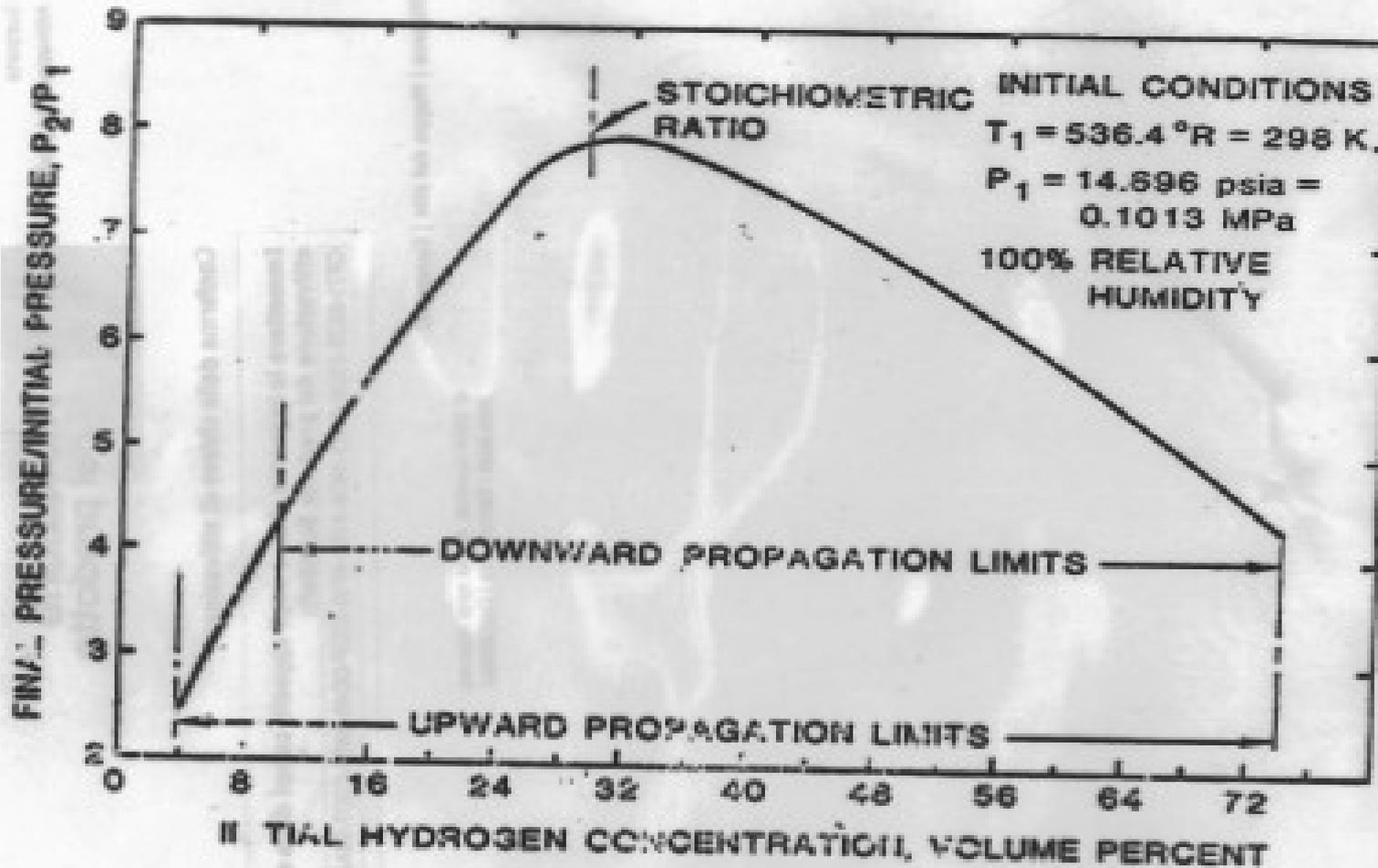


Figure 2-10. Theoretical Adiabatic, Constant-Volume Combustion Pressure for Hydrogen-Air Mixtures



**table 1.2 TYPICAL COMBUSTION PROPERTIES OF SOME HYDROCARBON GASES AND HYDROGEN IN AIR**

Fuel	Molecular weight	A Flammability limits % v/v gas		% Gas at stoichiometric ratio	B % Gas at maximum burning velocity	B Maximum laminar burning velocity $S_b$ (m/s)
		Lower	Upper			
Hydrogen $H_2$	2	4	75	30	54	3.5
Methane $CH_4$	16	5	15	9.5	10	0.45
Ethane $C_2H_6$	30	3	12.5	5.6	6.3	0.53
Propane $C_3H_8$	44	2.2	9.5	4.0	4.5	0.52
Butane $C_4H_{10}$	58	1.9	8.5	3.1	3.5	0.50
Pentane $C_5H_{12}$	72	1.5	7.8	2.6	2.9	0.52
Hexane $C_6H_{14}$	86	1.2	7.5	2.2	2.5	0.52
Heptane $C_7H_{16}$	100	1.2	6.7	1.9	2.3	0.52
Acetylene $C_2H_2$	26	2.5	80	7.7	9.3	1.58
Ethylene $C_2H_4$	28	3.1	32	6.5	7.4	0.83
Propylene $C_3H_6$	42	2.4	10.3	4.4	5.0	0.66
Butylene $C_4H_8$	56	1.7	9.5	3.4	3.9	0.57
Benzene $C_6H_6$	78	1.4	7.1	2.7	3.3	0.62
Cyclohexane $C_6H_{12}$	84	1.3	8.0	2.3	2.7	0.52

A From Coward and Jones<sup>5</sup>  
 B Value for  $H_2$  from Rose and Cooper<sup>3</sup>. Value for  $C_2H_2$  as recommended by Andrews and Bradley<sup>6</sup>  
 Other values based on comparative data from Gerstein *et al*<sup>7</sup> which have been corrected in line with a currently accepted value of 0.45 m/s for methane-air - See Andrews and Bradley<sup>6</sup>  
 C Values marked by \* from Lewis and Von Elbe<sup>1</sup>, other values from Perry and Chilton<sup>8</sup>

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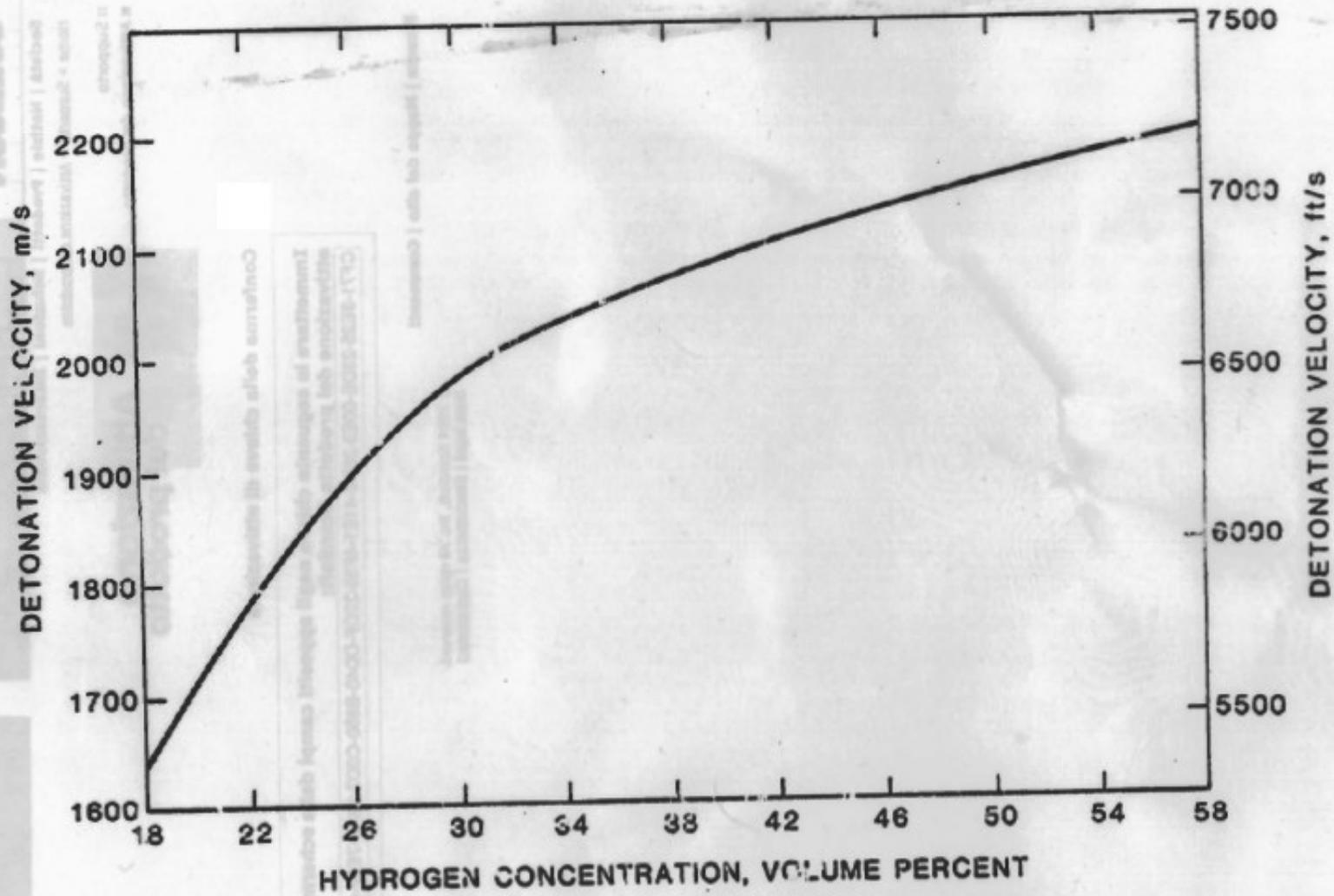


Figure 2-22. Theoretical Chapman-Jouguet Detonation Velocity for Hydrogen:Air Mixtures

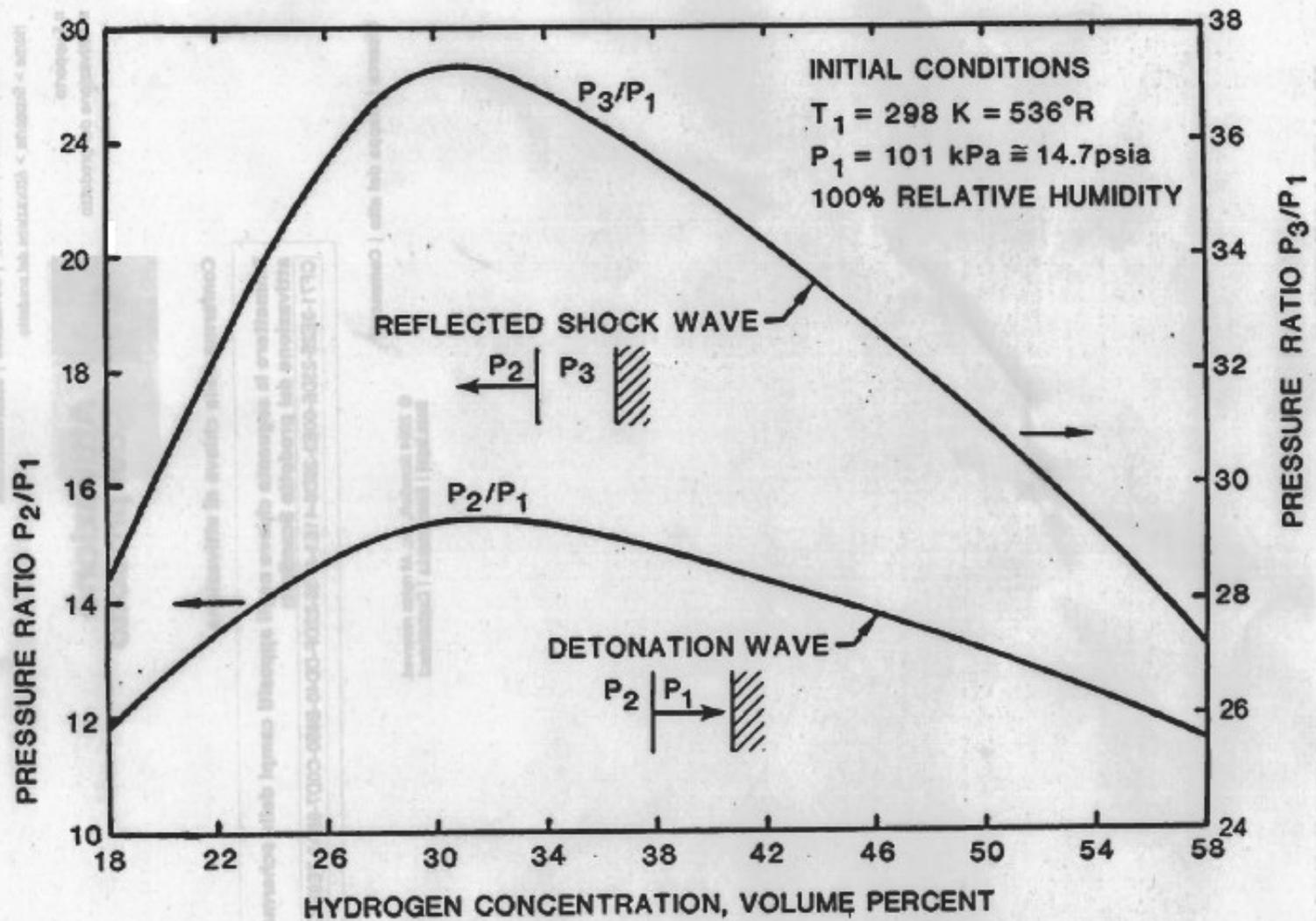
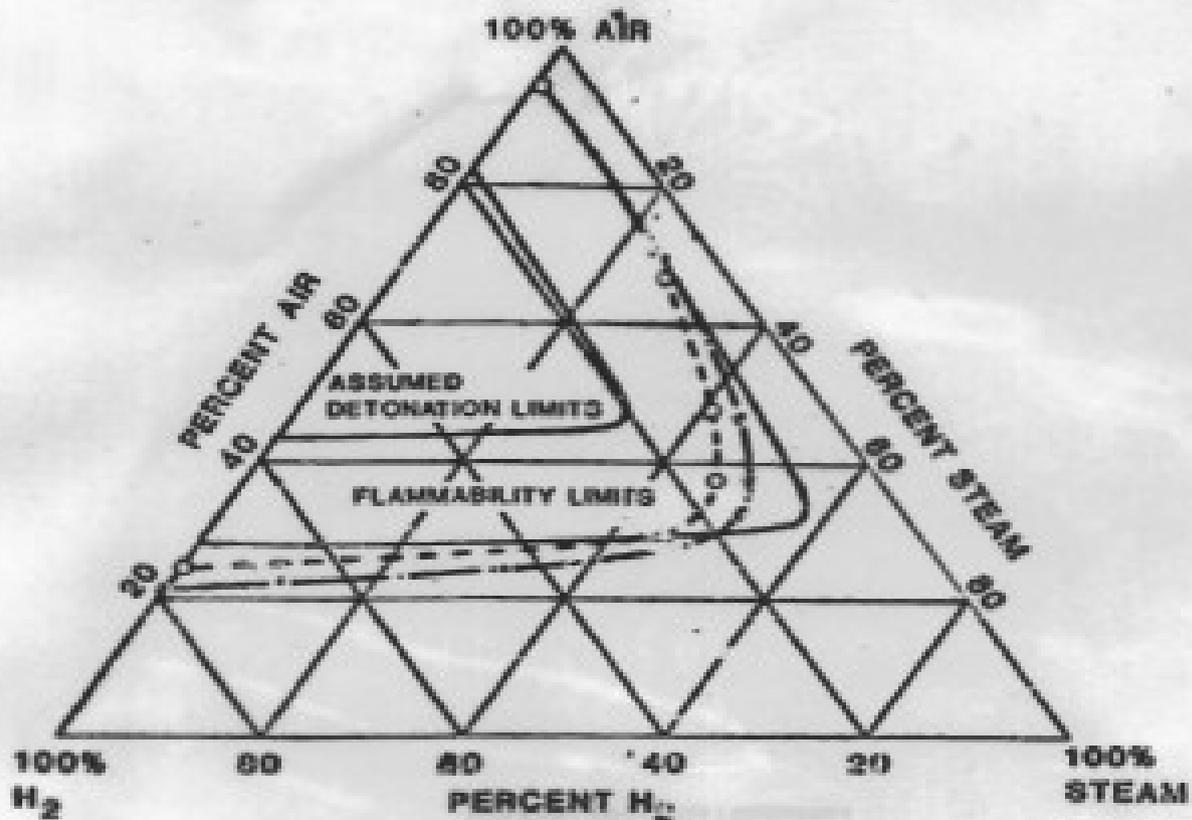


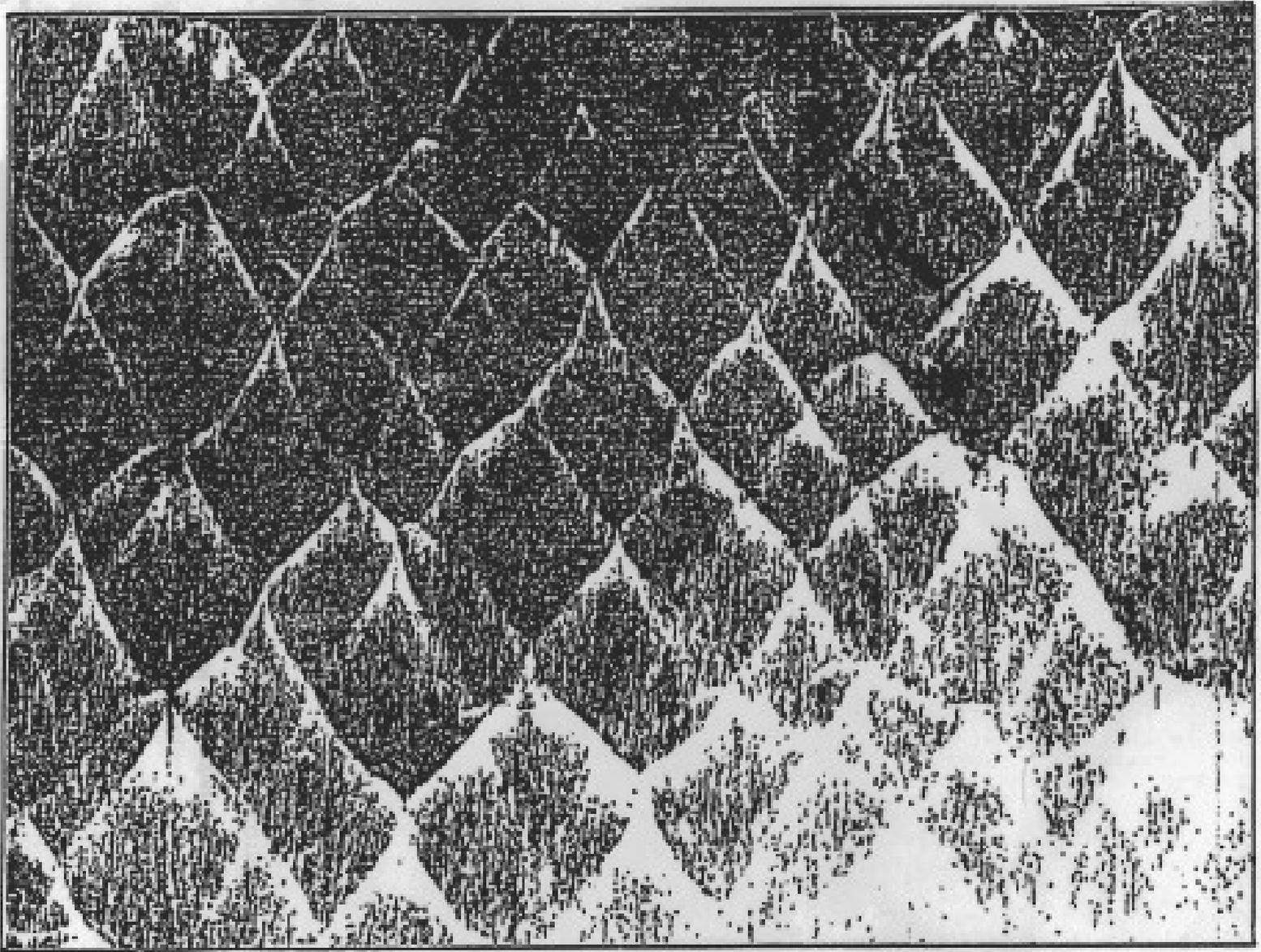
Figure 2-25. Theoretical Detonation Pressure and Normally Reflected Detonation Pressure for Hydrogen:Air Mixtures

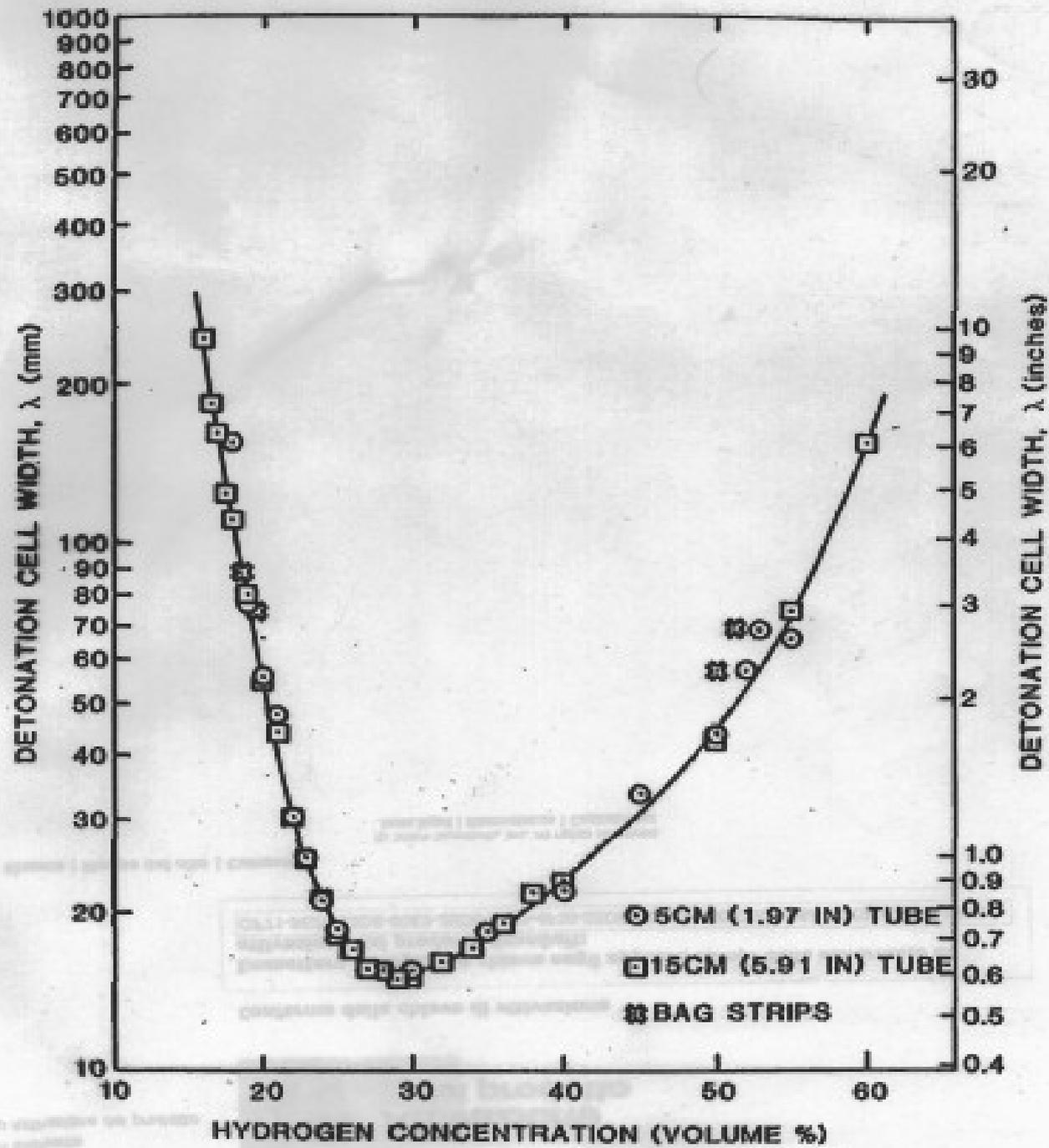


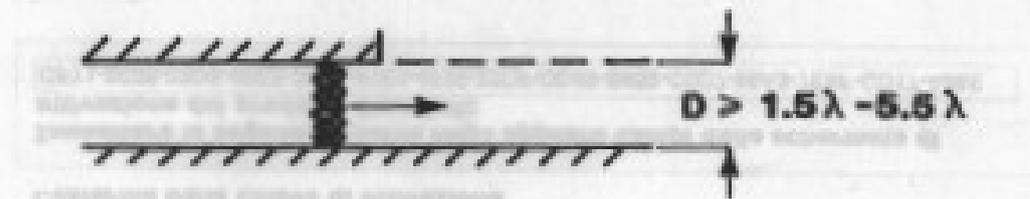
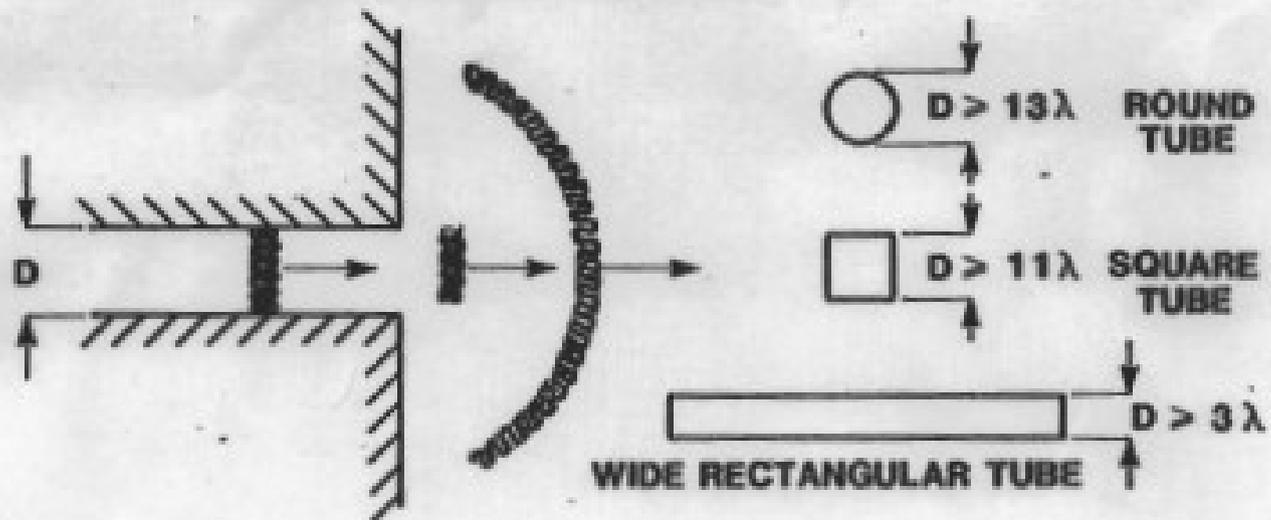
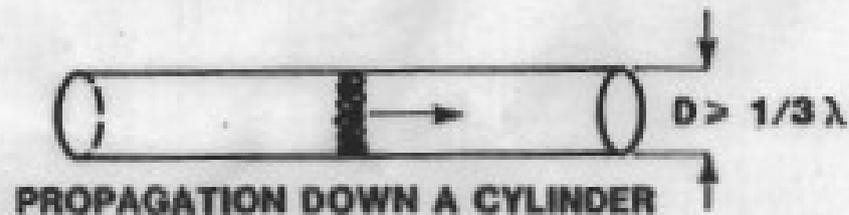
**FLAMMABILITY LIMITS**

- 68°F - 167°F AT 0 psig (20°C - 66°C AT 101 kPa)
- - - - - 300°F - 0 psig (149°C - 101 kPa)
- - - - - 300°F - 100 psig (149°C - 692 kPa)

Figure 2-16. Flammability and Detonation Limits of Hydrogen:Air:Steam Mixtures







**MINIMUM CLOUD THICKNESS FOR PROPAGATION CONFINED  
ON ANY ONE SIDE**