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by

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SUMMARY

A new metal foam material was examined for its effectiveness in absorbing the pressures formed by gas explosions in a sealed 2.8 litre (1/10 ft^3) cubic vessel.

A range of different porosity grades of the metal foam were examined in conjunction with (a) Propane, (b) Ethylene and (c) Hydrogen/air flammable gas mixtures.

The finest grade (porosity 80) when present to the extent of 50 per cent by volume, reduced the explosion pressure from approximately 620 kN/m^2 (90 psi) to 83 kN/m^2 (12 psi) for all three gases tested. The results obtained were found to be very lose to the values predicted by a theoretical expression derived.

This effect is considered to be valuable in the protection of electrical equipment used in flammable atmospheres.

KEY WORDS: Explosion; Flammable gas; Flame Arrester; Foam, Metallic.

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DEPARTMENT OF THE ENVIRONMENT AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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INTRODUCTION

A new metal foam material 'RETIMET' has recently been made commercially obtainable and has been found to exhibit certain flame arresting properties[1]. This report describes an investigation carried out to examine the possibility of reducing explosion pressure within a totally sealed vessel using this metal foam to absorb and cool the expanding, hot, gaseous products produced by a gas explosion.

EQUIPMENT AND MATERIALS

Explosion Vessel

The explosion vessel consisted of a cubical steel container having a wall thickness of 12.5 mm (½ inch) and an internal volume of 2.8 litres (1/10 cubic ft). A similar vessel with a perspex wall used for photographic purposes is shown in Fig 1. The test vessel was fitted with the following.

(a) A gas supply and venting system

The gas mixtures were produced by Rotameter flow meters followed by a packed column mixing tube 37 mm (1.5 inch) diameter 455 mm (18 inches) long.

The gas mixture was fed into the test vessel via a manually operated 'inlet' valve which was connected to a flame arrester, a non return valve and finally a manually operated valve close to the wall of the vessel to seal the enclosure.

The first three items were incorporated for safety reasons.

The waste gases were vented through a thin (150 gauge) polyethylene tube 125 mm (5 inches) diameter connected to the test vessel by a manually operated 'outlet' valve situated in the centre of the wall directly opposite the inlet valve.

(b) An Ignition Source

Ignition was achieved by a spark from a pair of electrodes 2 mm apart, situated in the centre of the vessel.

The spark was produced by a 12 volt automotive induction oil situated close to the test vessel.

(c) A Pressure Detection System

A pressure sensitive transducer was screwed into the centre of one wall of the test vessel. This was connected via a charge amplifier to a cathode ray oscilloscope from which pressure changes were recorded by means of a polaroid camera. See Fig. 2.

GAS MIXTURES

The gas mixtures used during the experiments were as follows:

(i) Propane/air 4.2% vol/vol.
(ii) Ethylene/air 6.5% vol/vol.
(iii) Hydrogen/air 32% vol/vol.

These mixtures were chosen to give the highest explosion pressures.

METAL FOAM (RETIMET)

The porosity of the metal foam is graded nominally by the supplier in pores per inch and the grades used were 10, 30, 45, 60 and 80 grade. A close up photograph of one of the specimens used is shown in Fig. 3.

The retimet material was arranged symmetrically inside the enclosure; 12 mm ($\frac{1}{2}$ inch) sheets having the same cross sectional area as the vessel were placed against the opposite walls containing the gas inlet and outlet, so that gases going through the vessel had to pass through the retimet before being vented. In some of the tests additional small pieces were placed at the bottom of the vessel so as to produce a U shaped cross section of metal foam with the ignition electrodes situated in the centre of the free volume.

The density of some of the specimens had been determined previously and was found to vary between 0.35 and 0.65 g/cm^3.

PROCEDURE

A number of experiments were carried out with the vessel empty and the remainder with a varying percentage of the total internal volume occupied by the metal foam. In each case the experimental procedure was the same:

The inlet and outlet valves were opened and the flammable gas mixture was passed through the apparatus until 100 complete volumes had passed through the vessel. Both inlet and outlet valves were then closed and the flammable mixture in the vessel ignited by the spark electrodes in the centre of the vessel.

The pressure developed inside the vessel was measured by the pressure transducer and recorded photographically from a cathode ray oscilloscope.

RESULTS

The results obtained are contained in two graphs. Fig. 4 shows the pressures obtained with various proportions of 80 grade Retimet with Hydrogen/air, Ethylene/air and Propane/air flammable mixtures.

Fig. 5 shows the pressures obtained with 10, 30, 45, 60 and 80 grades with Propane/air mixture.

Specimen pressure traces showing characteristic pressure rise rates in an empty vessel are shown in Fig. 6. Similar pressure traces obtained with 23 per cent of the total volume occupied by 80 grade metal foam are given in Fig. 7.

It can be seen from Fig. 4 that the 80 grade retimet gave similar pressure values for all three flammable mixtures used.

The experimental results shown in Fig. 5 show that grades 30, 45, 60 and 80 gave similar results but grade 10 gave distinctly higher pressures.

DISCUSSION

A simple theoretical relationship between the volume of metal and the maximum pressure can be produced by considering the effects of thermal expansion of the gases present inside the vessel.

Consider a vessel partly filled with metal foam and with flammable mixture occupying both the free volume and the voids inside the metal foam.

If the mixture in the free volume is ignited it will burn and expand thus compressing the unburnt gas in front of it until the flame reaches the surface of the metal foam whereupon the reaction stops leaving the free volume occupied by combustion products and the remainder of the mixture unheated and compressed inside the metal foam.

Let the free volume = V (expressed as a proportion of the total volume) and the amount of flammable mixture reacted = n (expressed as a proportion of the total mass).

Consider the effect of heating proportion n of the gas at constant volume from T_o to T_1 (from the original temperature to the flame temperature).

Then, approximately $P_1 = P_o . \frac{T_1}{T_o}$ Where P_o is the original pressure and P_1 is the pressure at T_1.

When allowed to expand into the remaining unreacted gas at P_o the final pressure will be

$$P = (n . P_o \frac{T_1}{T_o}) + (1 - n).P_o \qquad \text{........ (1)}$$

neglecting the small volume occupied by the metal in the foam.

By definition, the free volume V is the same as the volume occupied by fraction n after heating and expansion.

Then

$$V = n. \frac{P_1}{P} = \frac{n(T_1/T_o)}{(T_1/T_o - 1).n + 1} \qquad \ldots\ldots\ldots (2)$$

From (2)

$$n = \frac{V}{T_1/T_o - (T_1/T_o - 1).V} \qquad \ldots\ldots\ldots (3)$$

Substituting into (1) and rearranging

$$P = P_o . \left[\frac{V}{\left(\frac{T_1/T_o}{T_1/T_o - 1}\right) - V} + 1 \right] \qquad \ldots\ldots\ldots (4)$$

Where

P = Maximum pressure

V = $\frac{\text{Volume not occupied by foam}}{\text{total volume of vessel}}$

T_o = Original gas mixture temperature

T_1 = Flame temperature

This expression gives a very close approximation to the actual values obtained with the finer grades of metal foam (below 30). It does not, however, take into account any cooling of hot gases by the metal foam, see below.

The expression above does not take into account any change in the number of molecules of reactants and products e.g. for the burning of hydrogen in air.

$$2H_2 + O_2 + 4N_2 \rightarrow 2H_2O + 4N_2$$

$$7 \text{ mols} \rightarrow 6 \text{ mols}$$

This produces an effective shrinkage in the total volume of 6/7. Therefore in calculating the resultant pressure increase for such a reaction equation (1) becomes:

$$P = \left\{ n.P_o \left(\frac{T_1}{T_o} \right) .f \right\} + (1 - n)P_o \qquad \text{........ (1A)}$$

where $f = \dfrac{\text{Number of molecules of products*}}{\text{numbers of molecules of reactants*}}$ (including inerts e.g. N_2)

Subsequently equation (2) becomes:

$$V = \frac{\left({T_1}/{T_o} \right) .f.\ n}{\left({T_1}/{T_o} \right) .f.n - n + 1} \qquad \text{........ (2A)}$$

and equation (4) becomes:

$$P = P_o . \left(\frac{V}{\dfrac{\left({T_1}/{T_o} \right)^f}{\left({T_1}/{T_o} \right)^{f-1}} - V} + 1 \right) \qquad \text{........ (4A)}$$

This gives an even closer approximation to the actual results obtained. It does not significantly alter the lower pressures when V is 0.5 or less.

Until now the volume occupied by the metal foam has been considered as a volume of gas with no account taken of the volume of metal within the foam (normally around 6%). This can be accounted for by introducing a factor representing the total volume of gas (m) i.e. the volume of the vessel less the volume of the metal in the foam.

where $m = 1 - (1 - V)\dfrac{D}{d}$

Where D is the density of the foam and d is the density of the metal.

Equation (1) then becomes

$$P = \frac{n.P_o. {}^{T}/T_o}{m} + \frac{(1 - n)\ P_o}{m} \qquad \text{........ (1B)}$$

which makes equation (4)

$$P = P_o \left[\frac{V}{\left\{ \dfrac{T_1/T_o}{\left(T_1/T_o\right) - 1} \right\} m - V} + 1 \right] \qquad \text{........ (4B)}$$

The introduction of this factor m has only a marginal effect upon the calculated pressure in the mid range e.g. where $V = 0.5$ the effect of m was a 3% increase in P for nickel foam with 6% metal.

The combination of both f and m factors gives

$$P = P_o \left[\frac{V}{\left\{ \dfrac{(T_1/T_o)f}{(T_1/T_o)f-1} \right\} m - V} + 1 \right] \qquad \text{........ (5)}$$

The following values for f, T_1 and $\dfrac{\{T_1/T_o\}f}{\{T_1/T_o\}f-1}$ are given below:

	f	T_1	$\dfrac{\{T_1/T_o\ f\}}{\{T_1/T_o\ f-1\}}$
Propane:	1.045	2260[2]	1.141
Ethylene:	1.00	2350[2]	1.142
Hydrogen:	0.856	2390[3]	1.167

Equation 5 compares very closely to the results obtained with the finer grades, see Fig. 8 which shows a comparison between results obtained with 80 grade using three different gases and the calculated values using equation (5).

This equation does not take into account the cooling of the hot gases before the maximum pressure is achieved. An equation including such cooling was found to give results much lower than actually experienced. It was assumed therefore that no substantial cooling occurs before the maximum pressure is developed.

CONCLUSIONS

The presence of Retimet metal foam in a totally enclosed vessel has been found to reduce the maximum pressure developed during gas explosions within the vessel.

The degree of pressure reduction depends on the percentage of the internal volume occupied by the metal foam. The presence of 50 per cent by volume of 45 grade Retimet was found to reduce pressures from 620 kN/m^2 (90 psi) to approximately 83 kN/m^2 (12 psi).

The high porosity grades tend to reduce pressures more effectively than the coarsest grade. All except the 10 grade gave approximately the same result with propane/air flammable mixtures.

This investigation has shown that it may be possible to utilize this effect in the construction of small enclosures for use in flammable atmospheres. It would be particularly valuable when the use of flame arrester vented enclosures might be unsuitable owing to the possibility of arrester blockage due to atmospheric pollution.

The pressure obtained with the finer grades (above 30) were in close agreement with the theoretical expression derived equating pressure with proportion of metal foam present.

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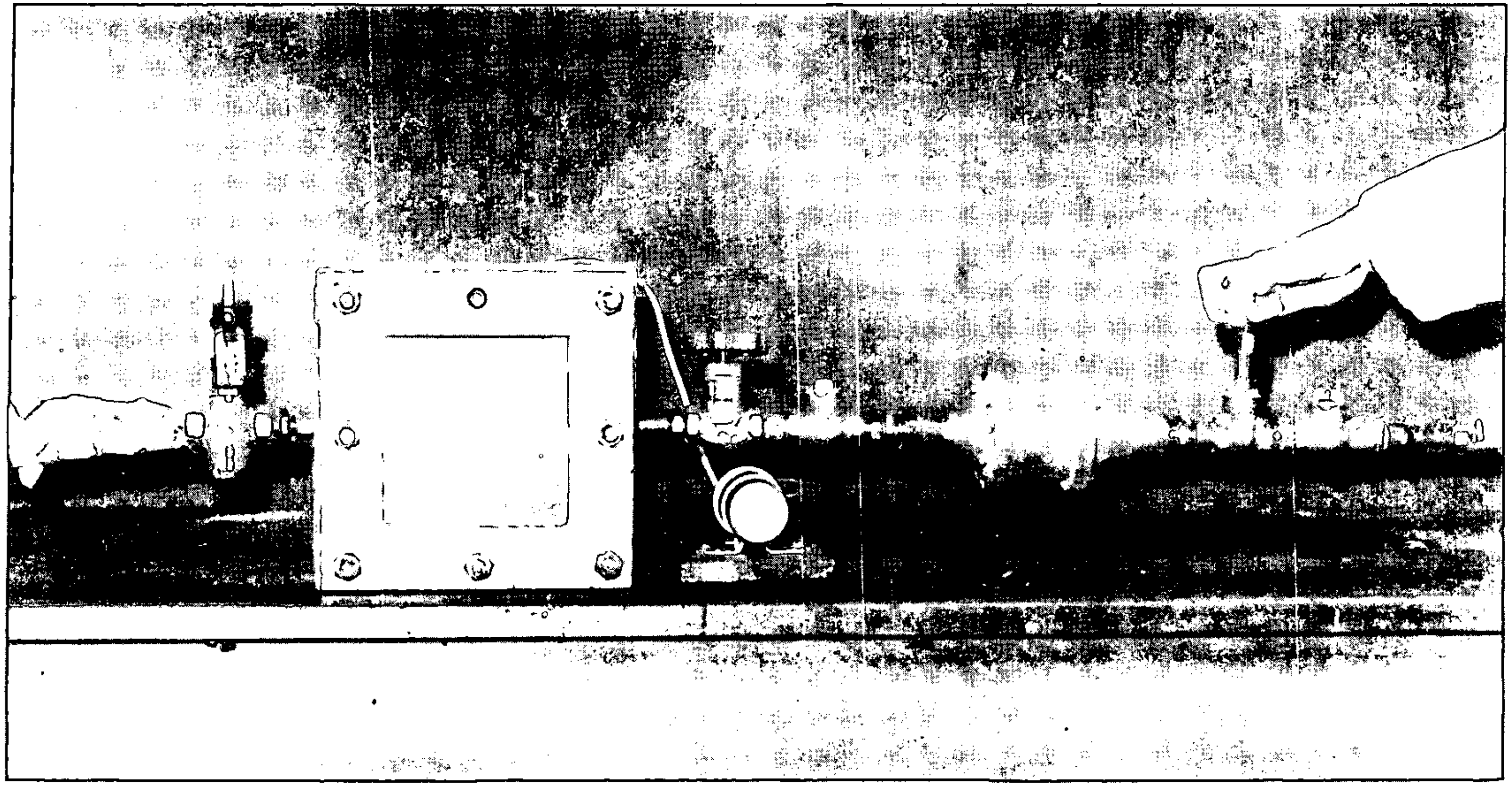

FIG. 1 THE TEST ENCLOSURE SHOWING INLET AND OUTLET VALVES

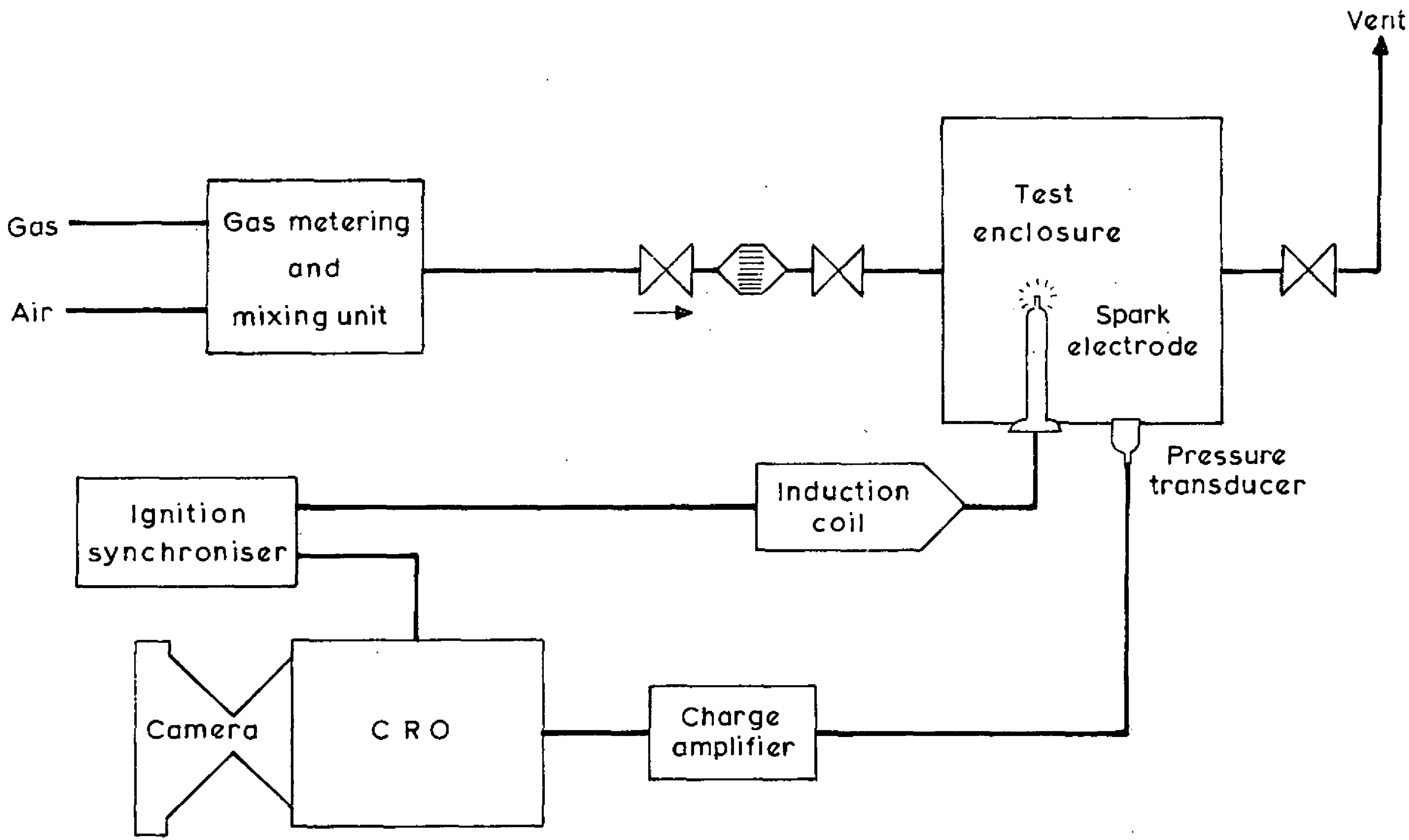

FIG. 2 DIAGRAM OF THE APPARATUS

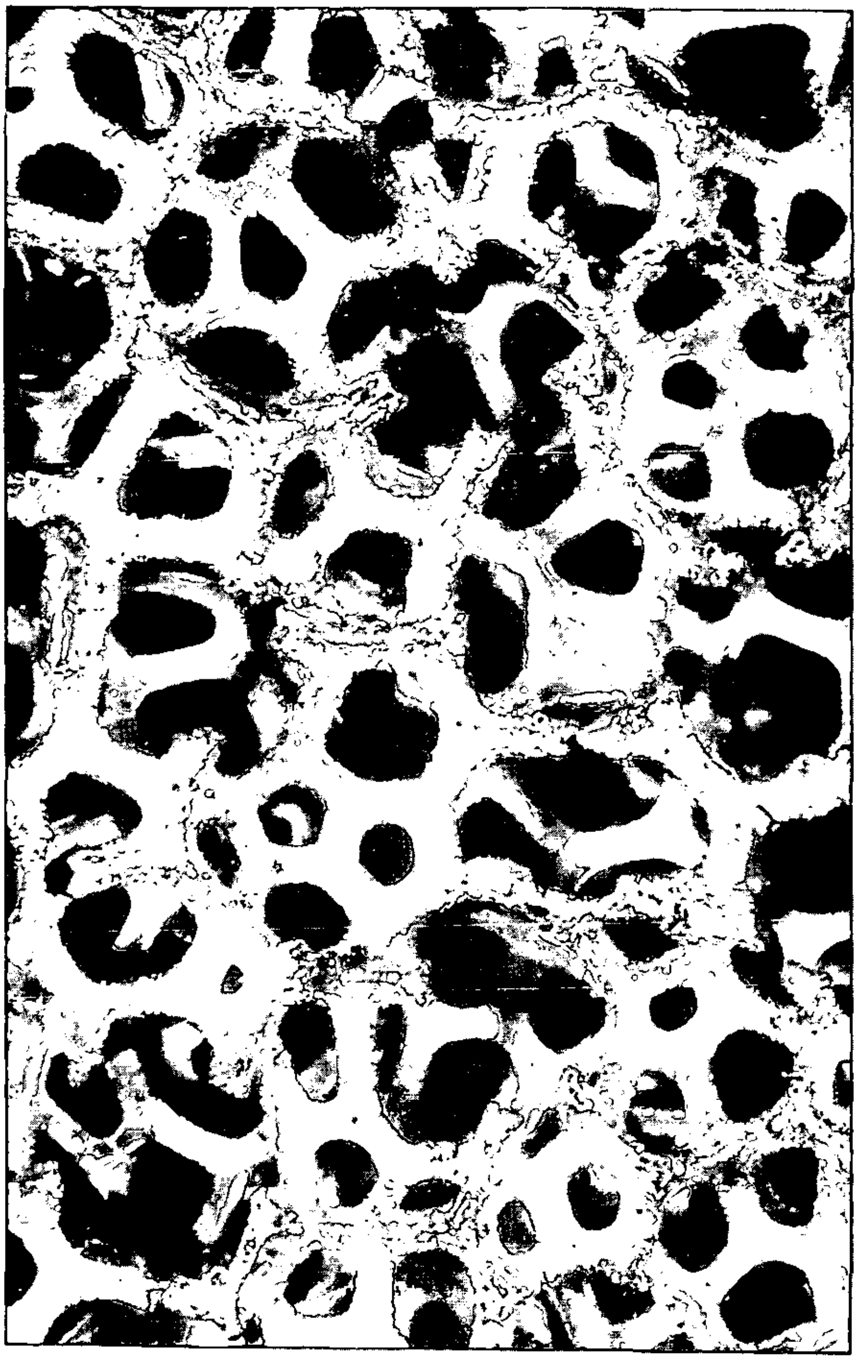

FIG.3 RETIMET METAL FOAM MAGNIFICATION 20

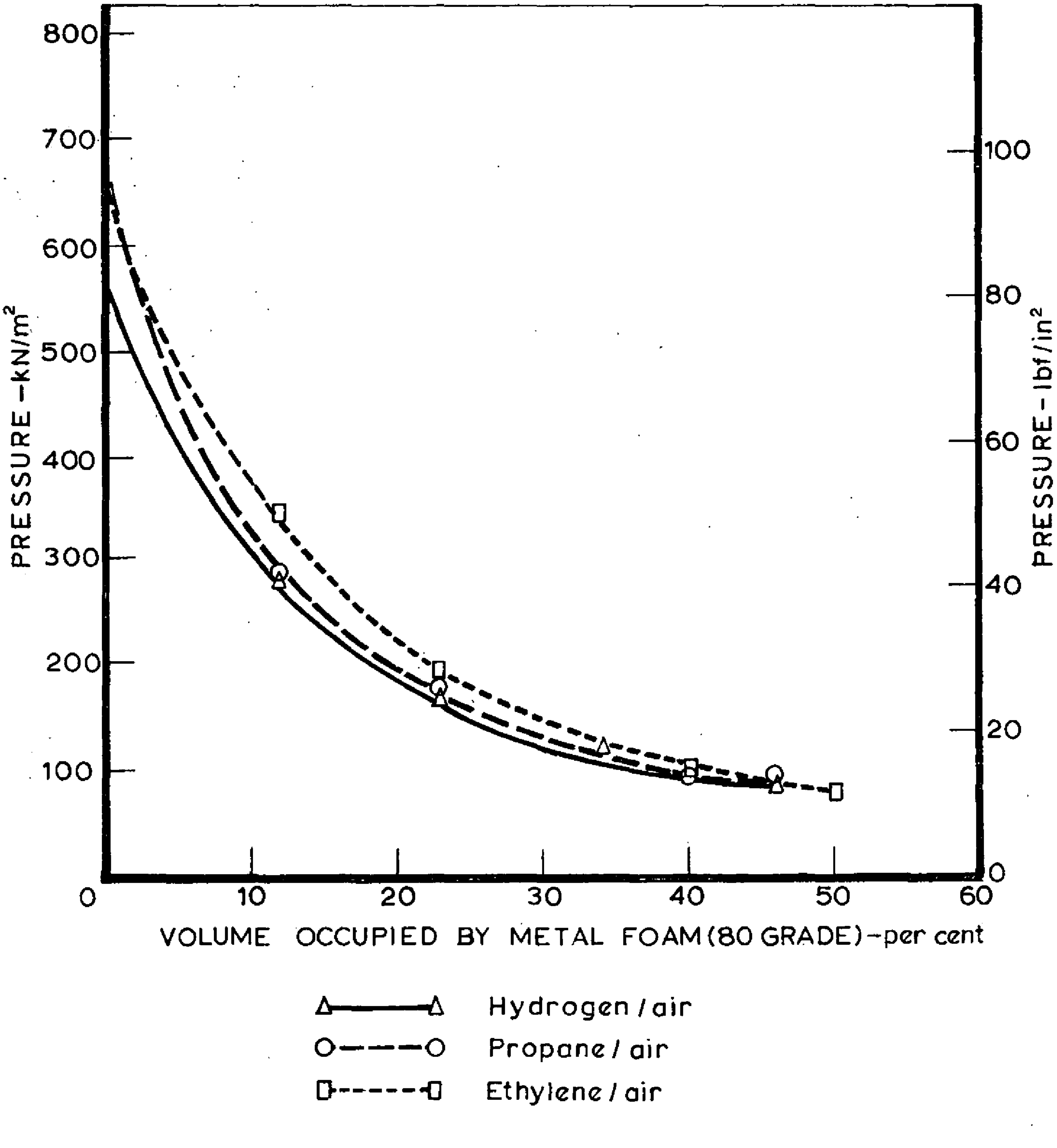

FIG.4 RESULTS OBTAINED WITH 80 GRADE RETIMET USING DIFFERENT GAS MIXTURES

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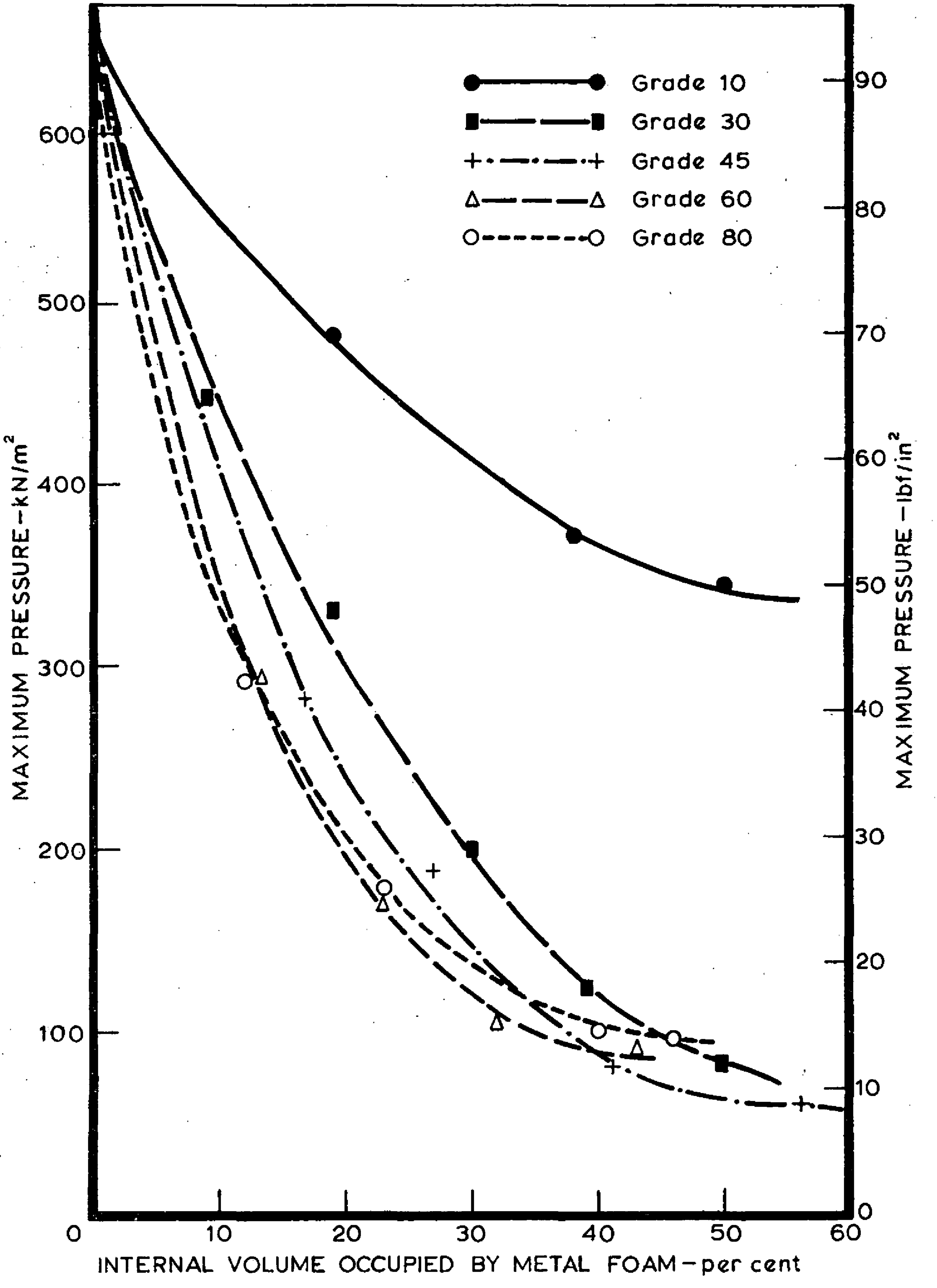
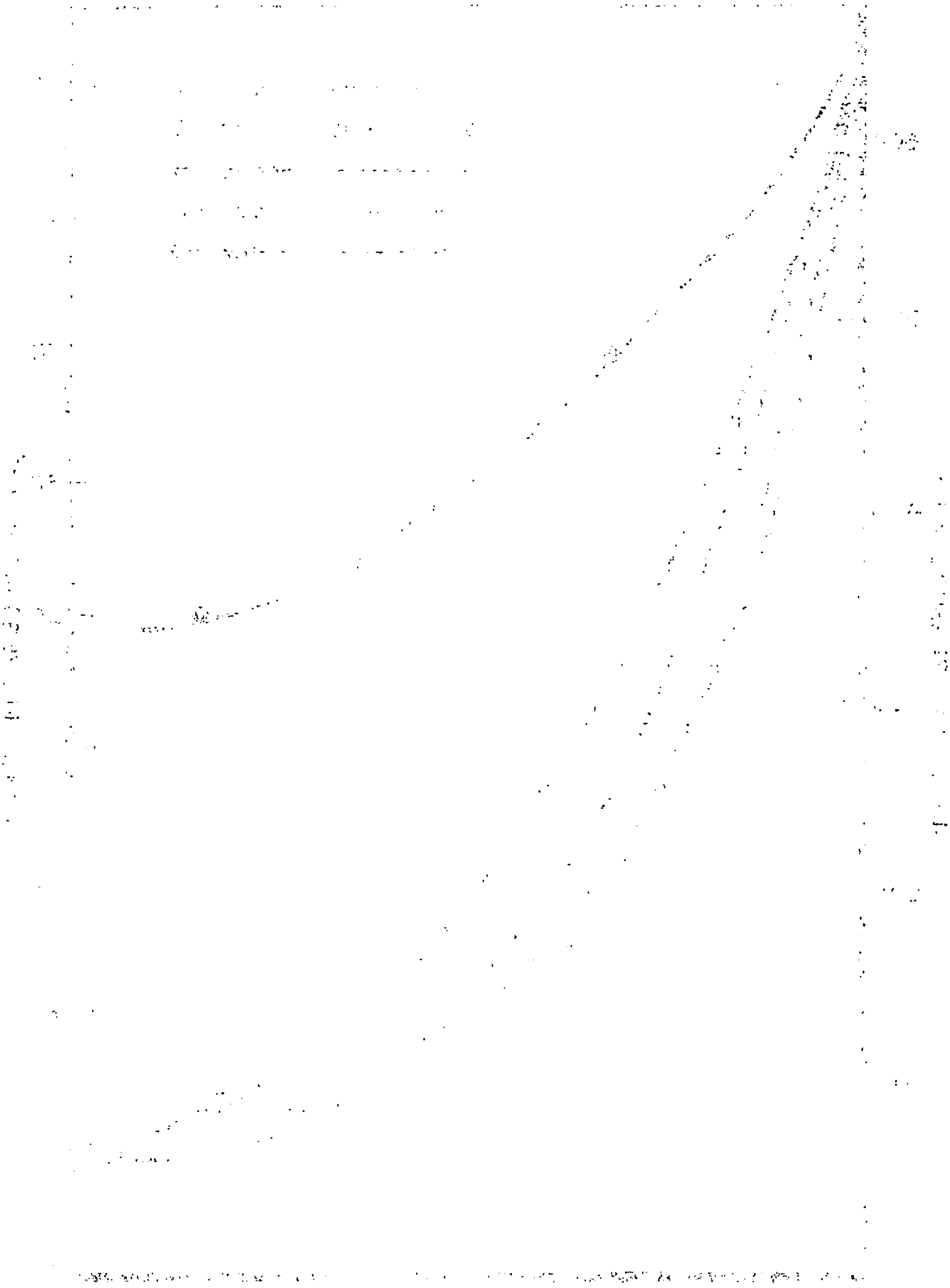


FIG. 5 PRESSURES OBTAINED WITH VARIOUS GRADES OF RETIMET USING PROPANE / AIR MIXTURE



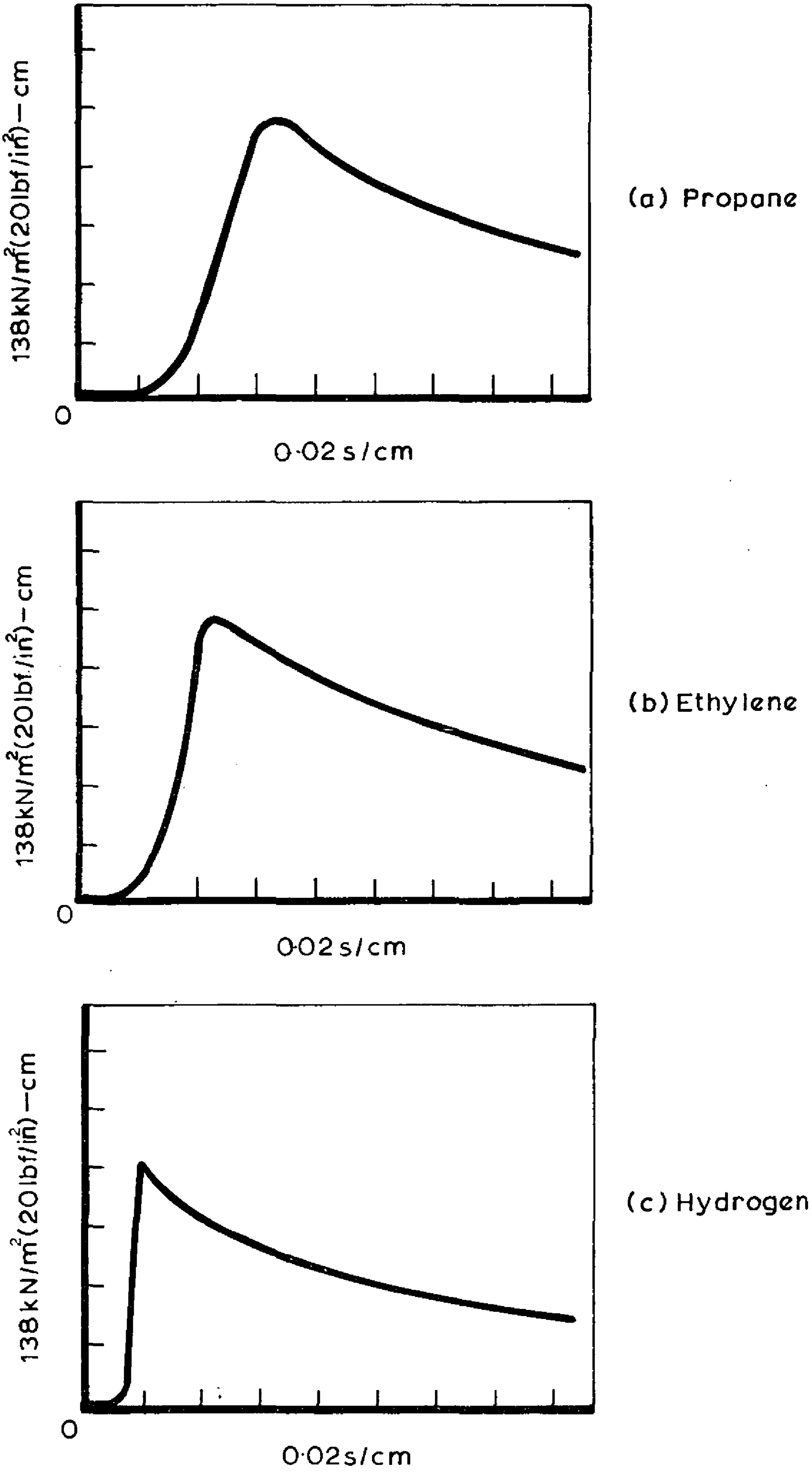


FIG.6 PRESSURE RECORDS WITH EMPTY BOX

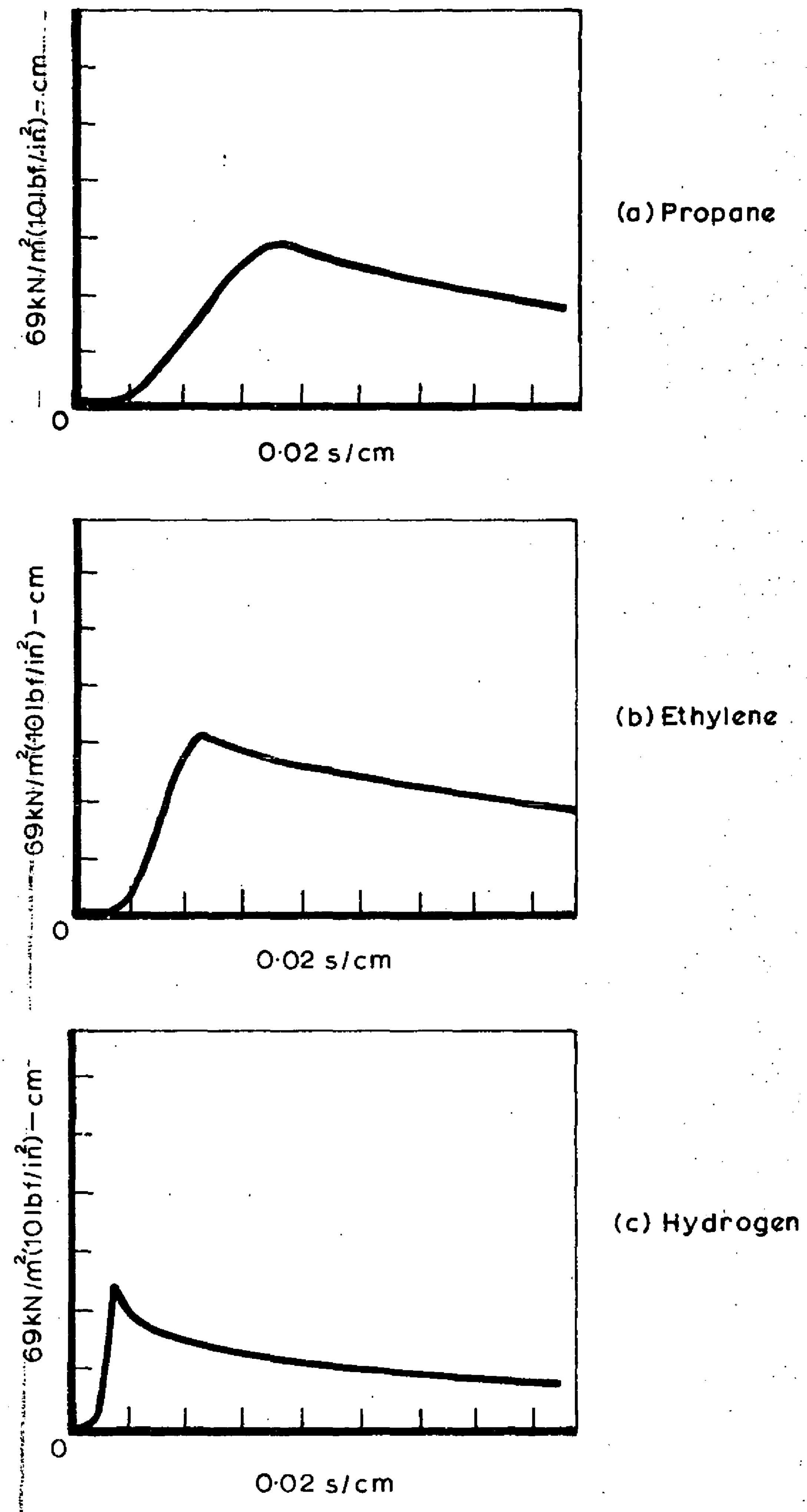


FIG.7 PRESSURE RECORDS WITH 23 PER CENT 80 GRADE RETIMET

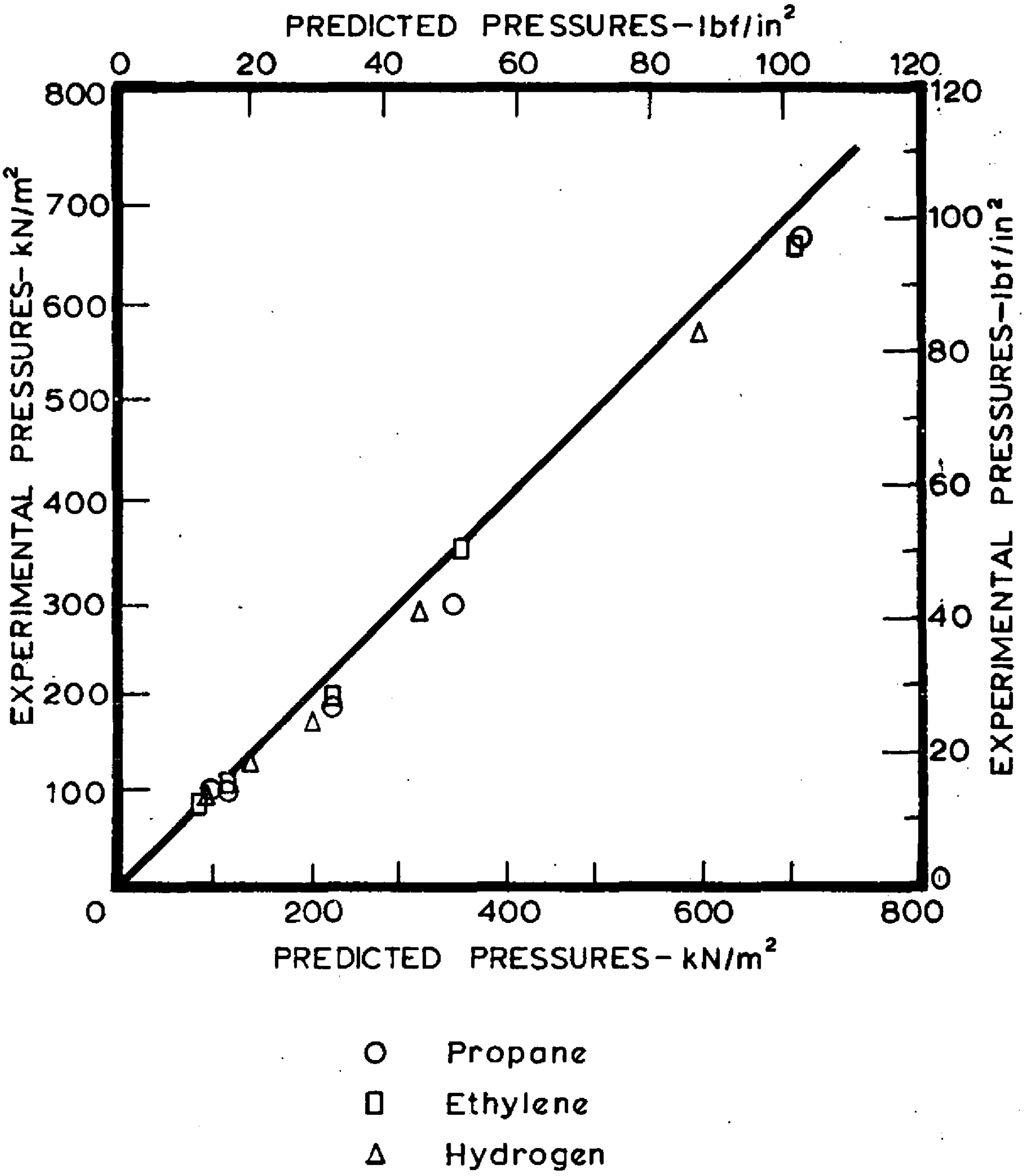


FIG. 8 COMPARISON BETWEEN PREDICTED AND EXPERIMENTAL PRESSURES (EQUATION 5) USING 80 GRADE RETIMET