COMBUSTION STUDIES AT HIGH HYDROGEN CONCENTRATIONS

AND

THE EFFECT OF OBSTACLES ON COMBUSTION

INTERIM PROJECT REPORT
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1. INTRODUCTION

Combustion of hydrogen-steam-air mixtures is important in connection with the effect of loss-of-coolant type of accidents on nuclear reactor containment systems. During certain hypothetical events, hydrogen may be released in quantitites such that the resulting containment atmosphere is capable of sustaining a combustion wave propagating through the mixture. Various experimental investigations have been made into the combustion of relatively low hydrogren concentration mixtures using glow plug igniters in support of the selection of a Distributed Ignition System for post-accident gas control. Although the likelihood of formation of relatively high hydrogen concentration mixtures inside reactor containment is considered remote, it was felt that investigation into the effects of combustion of rich mixtures would supplement existing knowledge of combustion phenomena while providing further evidence of the improbability of detonations.

Though combustion of hydrogen-air systems has been studied in the past in connection with burning velocity measurements, very little work appears to have been done with hydrogen steam-air systems, particularly in large volumes at high hydrogen concentrations.

Furno et al[1] have done some hydrogen combustion experiments in a 3.66 metre diameter sphere. The experiments were concerned mainly with limit flames of hydrogen in air and concentrations investigated were less than 15% hydrogen by volume. Kumar et al(2) have performed combustion experiments in a 2.3 m sphere with hydrogen-air-steam mixtures near the lower flammability limit. The concentrations investigated were 4-10% hydrogen and 0-30% steam by volume. This appears to be the only large scale hydrogen combustion work reported so far.

Liu et al[3] have done experiments in a 2-litre vessel with hydrogen-steam-air mixtures. The concentration range investigated included up to 15% steam and 10% hydrogen by volume.

The combined works of Furno, Kumar, and Liu appear to be the only published material involving the combustion of hydrogen-steam-air mixtures to date.

In view of the above, a series of experiments has been undertaken to improve our understanding of combustion of hydrogen-steam-air mixtures at high (10-42%) hydrogen concentrations in the 2.3 m sphere. Specific objectives include the comparison of the measured pressure transients with those calculated by simple adiabatic combustion models using burning velocity correlations and the confirmation that detonations do not occur readily in relatively open volumes for mixture concentrations considered to be detonatable.

This report also includes some scoping experiments on the effects of obstacles in the flame path. These may be present in the reactor buildings in the form of equipment, machinery, gratings, steam pipes, etc., and may act as heat sinks and, as has been demonstrated by Moen et al(4), may also accelerate the flame. In this study, obstacles in the form of gratings were placed in the sphere.

All experiments were performed using a spark ignitor as the ignition source.

2. DESCRIPTION OF THE TEST FACILITY AND INSTRUMENTATION

2.1 Test Facility

The test facility consists of three units that may be interconnected: a sphere, a pipe and a vertical cylinder. Their dimensions are given in Table 1. The sphere alone was used for the series of experiments reported here. The sphere (see Figure 1) has three large openings and several smaller ones. The smaller openings are used for mounting instruments and probes. The sphere is insulated and trace heated with steam and its temperature can be maintained at any desired value up to about 135°C. Steam may be injected into the sphere through one of the ports as required. Two fans driven by variable speed air motors are mounted diametrically opposite each other in the sphere as shown in Figure 2. Fan details are given in Table 2.

2.2 Instrumentation

A schematic of the instrumentation is shown in Figure 3. Transient pressures in the sphere during combustion were measured by four piezo-electric transducers with a rise time of 2 micro-seconds and by a Rosemount capacitance pressure transmitter with a response time of 0.2 seconds. Since, at high hydrogen concentrations, the combustion was complete in far less than 0.2 seconds, the Rosemount transmitter was used only for partial pressure measurements while introducing the gases into the sphere. Two of the four transducers were coated with an RTV compound and recess mounted. The other two transducers mounted flush with the surface were also coated with RTV. For a selected few experiments a fine wire, E type, thermocouple of 0.001 in. wire diameter was used to measure the transient temperature of the gases close to the wall. The ion probes previously used to detect flame front arrival did not perform satisfactorily and were discarded.

The signals from the transducers were processed by an ADC with a scan time of 1.5 millisecond per scan. A 2-channel transient recorder which could acquire 4800 data points with a faster scan rate was also used for recording of transient pressures.

The gases in the sphere, before and after combustion, were analyzed using a gas chromatograph (GC) employing a Hydrogen Transfer System. The details of the chromatograph, its calibration, and sampling technique are given in Reference (5). A schematic of the sampling loop is shown in Figure 4.

3. EXPERIMENTAL PROCEDURE

3.1 Mixture Preparation

First, the vessel was evacuated to a pressure of about 10 kPa. Then hydrogen was introduced to the desired partial pressure followed by steam and air. To insure mixing, the fans were kept operating during the time in which steam and air was introduced. This procedure produced a uniform mixture.

3.2 Sampling

Before any sampling, at least two calibration mixtures bracketing the test mixture concentrations, were run through the gas chromatograph. This was necessary because of the slight day to day shift in the calibration of the chromatograph. The sampling line from the sphere to the chromatograph was steam trace heated to prevent any condensation of water vapour in the line.

The sampling line was thoroughly flushed for at least five minutes with the mixture in the sphere to ensure a representative sample. As many samples as required were analyzed until two consecutive GC measurements agreed within specified limits. The same procedure was followed when sampling the combustion products. Table 3 shows the precision of the chromatograph. Since the GC was not calibrated for moisture content, the concentration of steam was inferred from the measured concentrations of hydrogen and air. For some experiments, residual steam left over from the previous experiments contributed to the uncertainty in the estimated steam concentrations. In general, the error in steam concentrations were 0 to +5%, maximum.

3.3 Combustion Experiments Involving Turbulence

In these experiments, the fans were turned on for approximately 1 minute before ignition and were kept operating during the test. Though the fan speed is variable, the present series of experiments have been done at a constant fan speed of about 1500 rpm.

4. RESULTS AND DISCUSSION

4.1 Combustion at 10% Hydrogen Concentration

All experiments were done at 100°C and slightly below atmospheric pressure, between 96 to 98 kPa.

Complete combustion of mixtures containing 10% hydrogen and 0-40% steam was observed by noting that all of the hydrogen was consumed. Figure 5 shows the pressure-time history for mixtures containing 10% hydrogen and various amounts of steam, under quiescent conditions. As the steam concentration is increased from 0 to 40%, the peak pressure decreases and the overall combustion time increases. The increase in combustion time is expected since the presence of steam reduces the burning velocity. Further, as the steam concentration is increased from 0 to 40%, the measured peak pressure rise decreases from 214 kPa to 110 kPa whereas the adiabatic theory predicts only about 25 kPa decrease in peak pressure. Several explanations are possible.

First, the radiation heat losses during combustion are higher with steam due to its large emissivity. This not only reduces the peak pressure but also decreases the flame speed due to cooling of the burnt gas. Second, since the burning velocity is reduced at higher steam concentrations, the longer time available for heat losses further decreases the peak pressure. Third, with slower burning velocities, buoyancy effects may become important which may make the fireball asymmetric, touching the top surface before the bottom surface. This can result in rapid conduction heat transfer to the wall while combustion is still proceeding, again decreasing the peak pressure.

The shape of the curves of pressure-time history in Figure 5 changes as the steam concentration is increased from 0 to 40%. This may be due to the increased effects of buyoyancy at reduced burning velocity. Complete combustion was observed at all concentrations of steam up to and including 40%.

4.2 Combustion at Higher Hydrogen Concentrations

Figure 6 shows the peak combustion pressure plotted as a function of hydrogen concentration for various amounts of steam. For a given steam concentration, the peak pressure increases as the hydrogen concentration is increased, reaching a maximum at nearly stoichiometric composition. Beyond this, the peak pressure drops. Below stoichiometric composition all of the hydrogen is consumed; above stoichiometric composition all of the oxygen is consumed. Thus, combustion proceeds until one of the reactants is completely consumed for steam concentrations up to 30%.

Figure 7 shows the fraction of hydrogen burned as a function of initial hydrogen concentration. As can be seen, beyond a certain low (∿ 7%) hydrogen concentration, the burn fraction rapidly increases and stays at 100% until the stoichiometric composition is reached. As expected, beyond this concentration the burn fraction decreases linearly with hydrogen concentration since all the oxygen present is consumed.

Figures 8, 9, 10 and 11 show the theoretically(7,8) predicted peak pressures compared with the measured values. The discrepancy between the theoretical and experimental values increases as the hydrogen concentration is increased. For example, in Figure 8 the dash line is for a simple adiabatic combustion model without accounting for disssociation and the chained line includes dissociation effects. Dissociation is most important near stoichiometric compositions due to the high temperature reached.

As mentioned earlier, there is some uncertainty in the concentrations of steam present in the mixture, the large discrepancy occurring at or beyond stoichiometric compositions. This is due to large amounts of steam produced by prior experiments with high hydrogen concentrations which may not have been fully removed when evaluating the vessel. For examp [illegible] er a 24% hydrogen and 30% steam burn, nearly 60% stea [illegible] sent in the products. The effect of any uncertainty in steam concentration is more pronounced for rich mixtures than for lean mixtures. This is because there is less oxygen available for combustion when extra steam is present and thus less hydrogen is burned.

Figures 12 and 13 show temperature-time and pressure-time histories for 20% hydrogen concentration. The thermocouple was mounted close to the vessel wall, in a cavity. As the flame propagates from the center outwards, the unburned gases ahead of the flame front are compressed nearly adiabatically, increasing the temperature of the unburned gases. When the flame reaches the thermocouple, the temperature increases rapidly. Though the increase is more gradual than expected, due to response of the thermocouple, the instant at which the front reaches the thermocouple is clearly discernable. Since combustion is complete at the instant the flame reaches the thermocouple and the flame arrival time of 0.13 seconds agrees well with the time for peak combustion pressure, it demonstrates that .001" thermocouples can be used as flame front detectors.

At all concentrations investigated, it was found that the combustion was smooth and regular. There was no detonation. The highest mean flame speed was of the order of 20 m/s and was observed for a stoichiometric, dry hydrogen air mixture. Figure 14 shows pressure histories-time for 29.5% and 41.7%

hydrogen-air mixtures. It has been observed(5) that the burning velocity for hydrogen-air mixture attained its highest value at 42% hydrogen, nearly 1.5 times as large as that at 29.5%. Combustion at 42% hydrogen should, therefore, be complete in about 30% less time than that required at 29.5% hydrogen but, in fact, the peak pressure is reached slightly earlier at 29.5% hydrogen than that at 42%. The reasons for this are not clear.

4.3 The Effect of Turbulence

Earlier investigations(2) in the Containment Test Facility at low hydrogen concentrations near lower flammability limits have revealed that turbulence significantly affects combustion. It not only increased the extent but also the rate of combustion. The effect of turbulence at a high hydrogen concentration is shown in Figure 15. For this case, the combustion was complete even without turbulence. The fan-generated turbulence accelerated the combustion only slightly. Without turbulence the combustion was complete in 0.09 seconds and with turbulence the combustion was complete in about 0.065 seconds. The ratio of combustion times is only 1.5 as compared to 6 at 5.5% hydrogen (not shown here). This marginal effect of turbulence is understandable because, at high concentrations, the burning velocities are already high and turbulent intensities less than the burning velocity itself may not significantly accelerate the combustion.

4.4 Effect of Gratings on Combustion

Two gratings of the type shown in Figure 16, were placed horizontally at one third elevations in the vessel as shown in Figure 17. The sheets are perforated with 2.54 cm (1 inch) diameter holes. The holes occupy approximately 50% of the grating area. The experiments were done at 100°C.

Figure 18 shows the pressure-time history with and without gratings for a mixture with 6% hydrogen in air with bottom ignition. It is seen from the figure that combustion is accelerated as the flame passes through the gratings. Gas chromatographic measurements indicated that nearly 60% of the hydrogen was burned when gratings were present as compared to 30% without gratings. When the fire ball passes through the gratings, it splits up into several smaller flame balls, effectively increasing the conical volume burnt. On the other hand, gratings also act as heat sinks due to their large surface area and mass.

Figure 19 compares the pressure-time histories at a hydrogen concentration of 20% with central ignition. Although gratings accelerate the rate of combustion slightly, the quenching effect is very pronounced. The measured peak pressures with gratings is slightly lower (∿ 5 Psi) than without gratings. Further, the accelerating effect of gratings is small.

Figure 20 shows the effect of fan turbulence on combustion with and without gratings at 7% hydrogen. The peak pressure is smaller with grates as is the rate of pressure rise in the early stages. This is probably because the turbulence is confined to the central region between the gratings. The strength of the eddies may be considerably reduced when they penetrate through the perforation. Further, turbulence enhances the rate of heat transfer to the gratings and vessel wall thus reducing the peak pressure.

5. CONCLUSIONS

From the experiments, the following conclusions can be made for mixtures with hydrogen concentration between 10% and 42%.

1. Detonations did not occur for mixtures considered to be detonable.
2. Combustion proceeds until one of the reactants is completely consumed.
3. The measured peak pressures are lower than theoretically predicted by current Whiteshell models.
4. The effect of fan induced turbulence is considerably less for rich mixtures than that for lean mixtures. For the cases investigated, combustion with turbulence was only 50% faster than with quiescent cases with no significant effect on the peak pressure.
5. The addition of steam considerably reduces the peak pressures attainable in the system. This effect is more pronounced for fuel-rich than for fuel-lean mixtures.
6. Combustion time is shortest for dry stoichiometric hydrogen-air mixture.

Some tentative conclusions that can be made for the effect of gratings are as follows:

1. At low hydrogen concentrations without fan induced circulation, around 6%, gratings increase the degree of combustion and to a lesser extent the rate.
2. At high hydrogen concentrations (> 10%), gratings act like heat sinks, reducing the peak pressure.

3. In the presence of fan turbulence, gratings not only reduce the rate of combustion but also the peak pressure.

The conclusions on the effects of gratings are tentative due to the scoping nature of the experiments. An insufficient number of tests were performed to allow for quantification of grating effects or formulation of general conclusions as the effects observed may be specific to the grating chosen. However, the data reported herein does not reflect a dramatic effect of gratings on peak pressure developement or pressure rise time.

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ACKNOWLEDGEMENTS

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TABLE 1

CTF VESSEL DIMENSIONS

	Sphere	Interconnecting Pipe
Internal diameter (ft)	7.5	0.95
Length (ft)		19.7
Wall thickness (inch)	2.14	.67
Volume (ft^3)	223	17.7
Design pressure (psi)	1450	1450

TABLE 2

FAN DETAILS

Air Motor Speed	1850 RPM (Max)
Motor Horse Power	0.22
Fan tip Diameter	0.406 m
No. of Blades on the Fan	4
Fan Capacity,/min	42.47 cu meters at 1100 RPM
Continuously Variable Speed Motor	

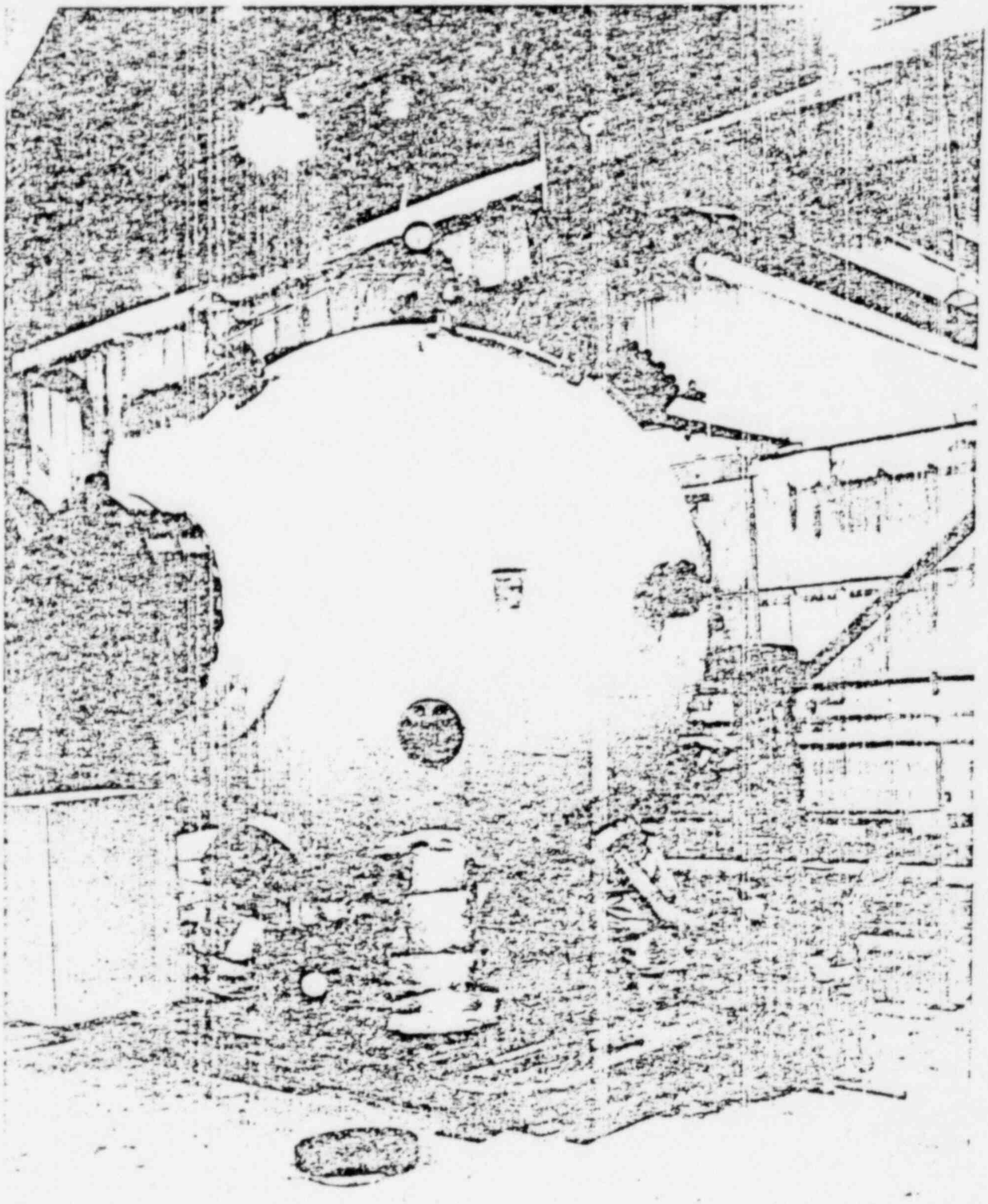
TABLE 2

Component	Concentration Range Volume %	Precision (2σ) Volume (%)
H_2	0.5 - 2.0	0.2
H_2	0 - 30	1.2
O_2	0 - 21	1.6
N_2	70 - 90	2.1
H_2O	3 - 8	0.7

Precision of Pressure Measurements

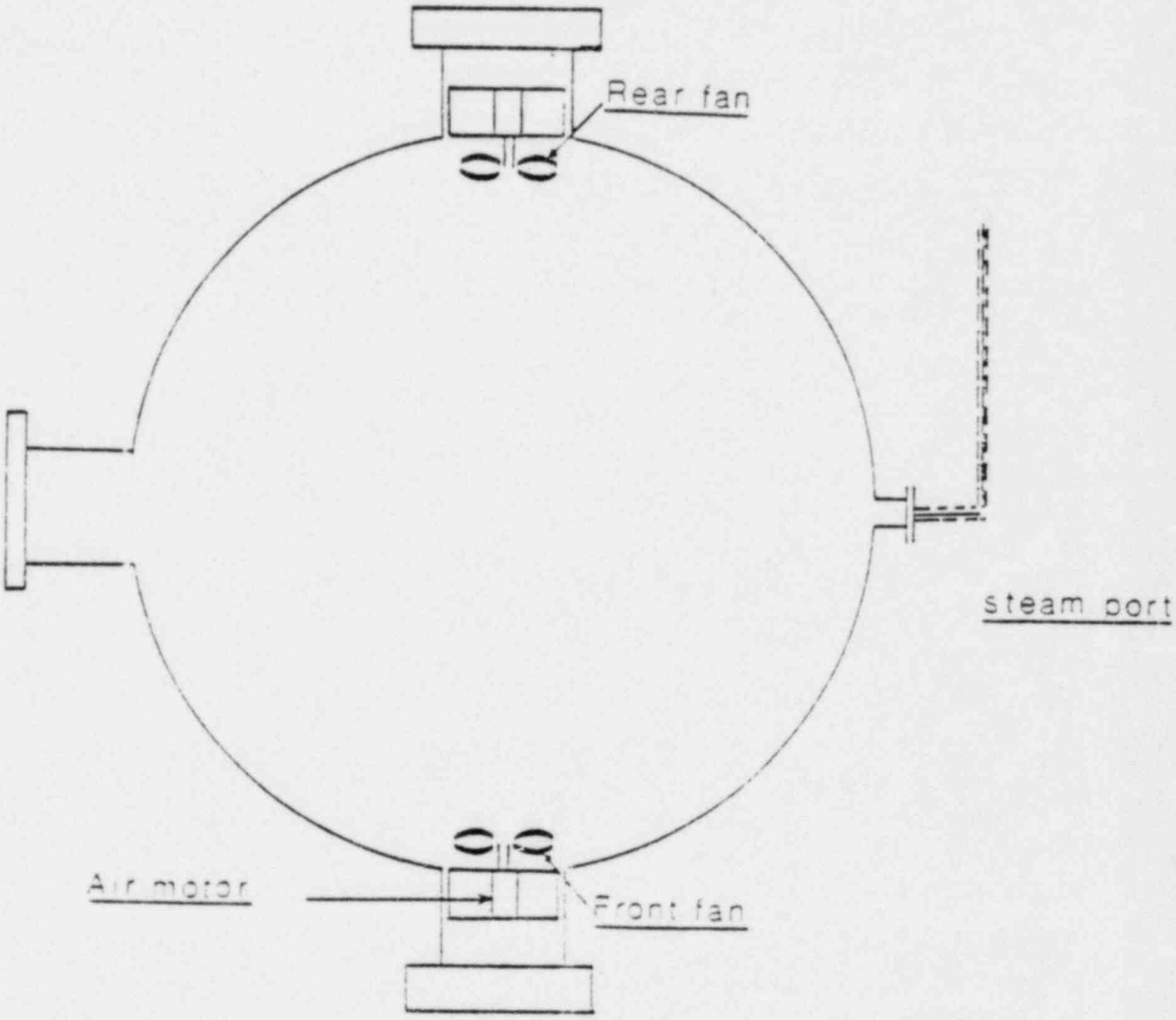
Rosemount Transmitter - 1 kPa (max)

Piezoelectric transducer - 1 psi (max)



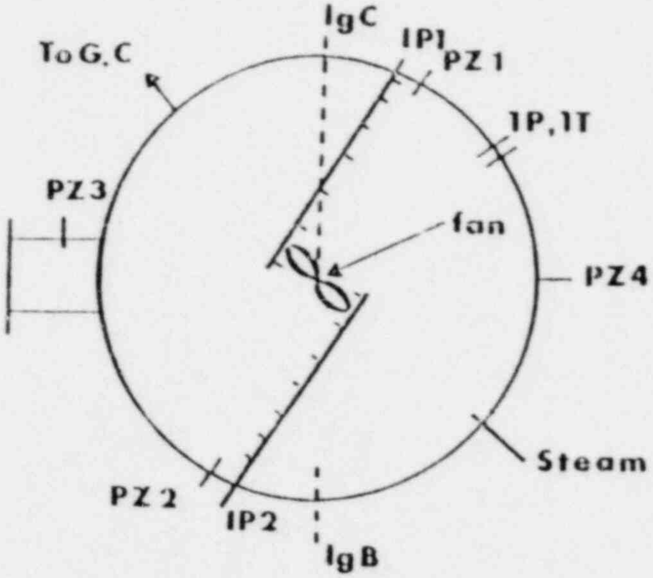
A VIEW OF THE SPHERE

Figure - 1



ARRANGEMENT OF FANS

Figure - 2



IgB, IgC – Ignitors

IP1, IP2 – Ion Probes

PZ1,2,3,4– Piezo electric transducer

1P – Process Pressure transducer

1T – RTD

SCHEMATIC OF INSTRUMENTATION

Figure -3

SCHEMATIC OF GAS SAMPLING LOOP

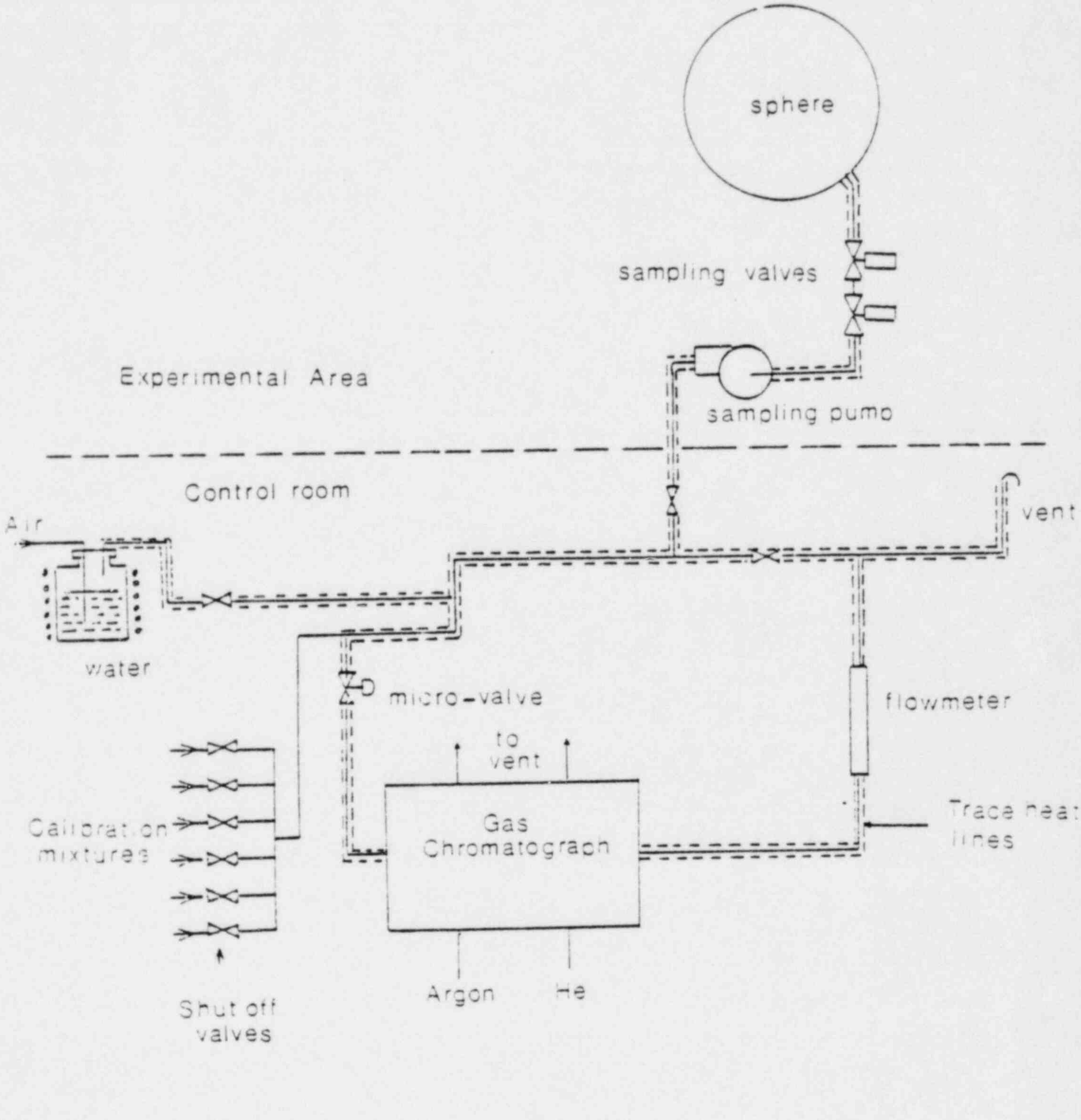


Figure - 4

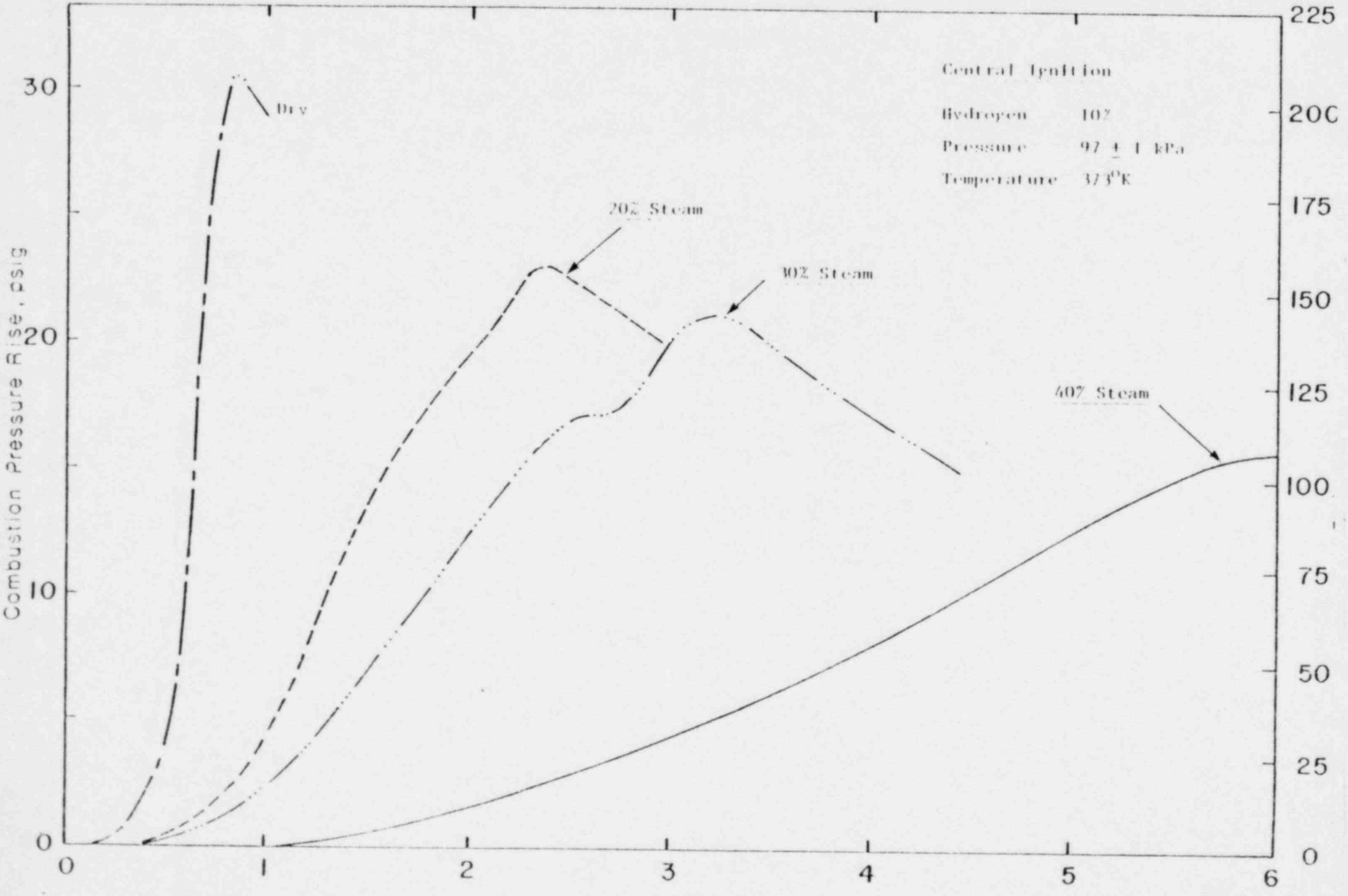

Combustion Pressure Rise, psig
0
10
20
30
0
25
50
75
100
125
150
175
200
225
0
1
2
3
4
5
6
Dry
20% Steam
30% Steam
40% Steam
Central Ignition
Hydrogen 10%
Pressure 97 ± 1 kPa
Temperature 373°K
TIME AFTER IGNITION, Sec.

FIGURE - 5

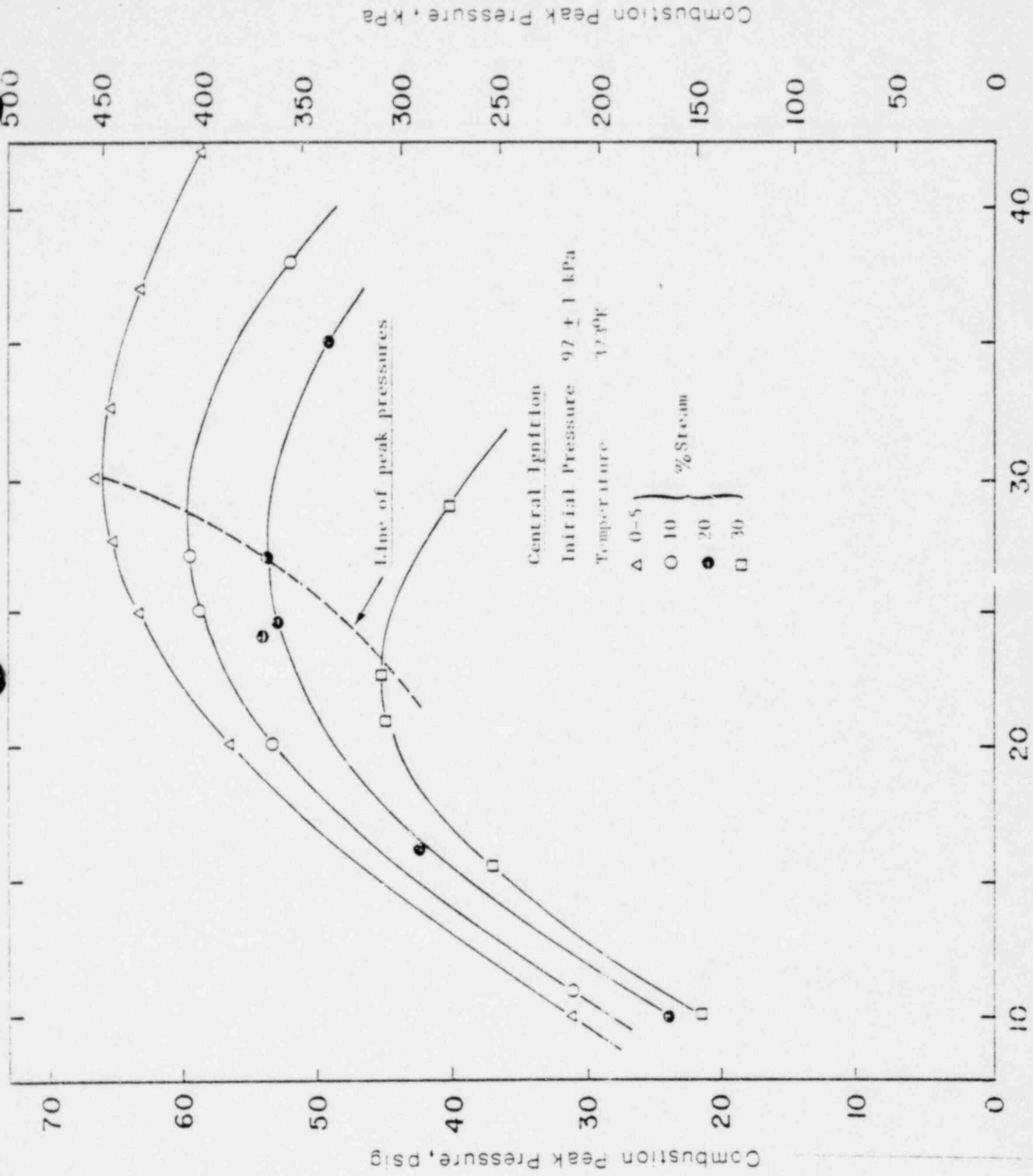
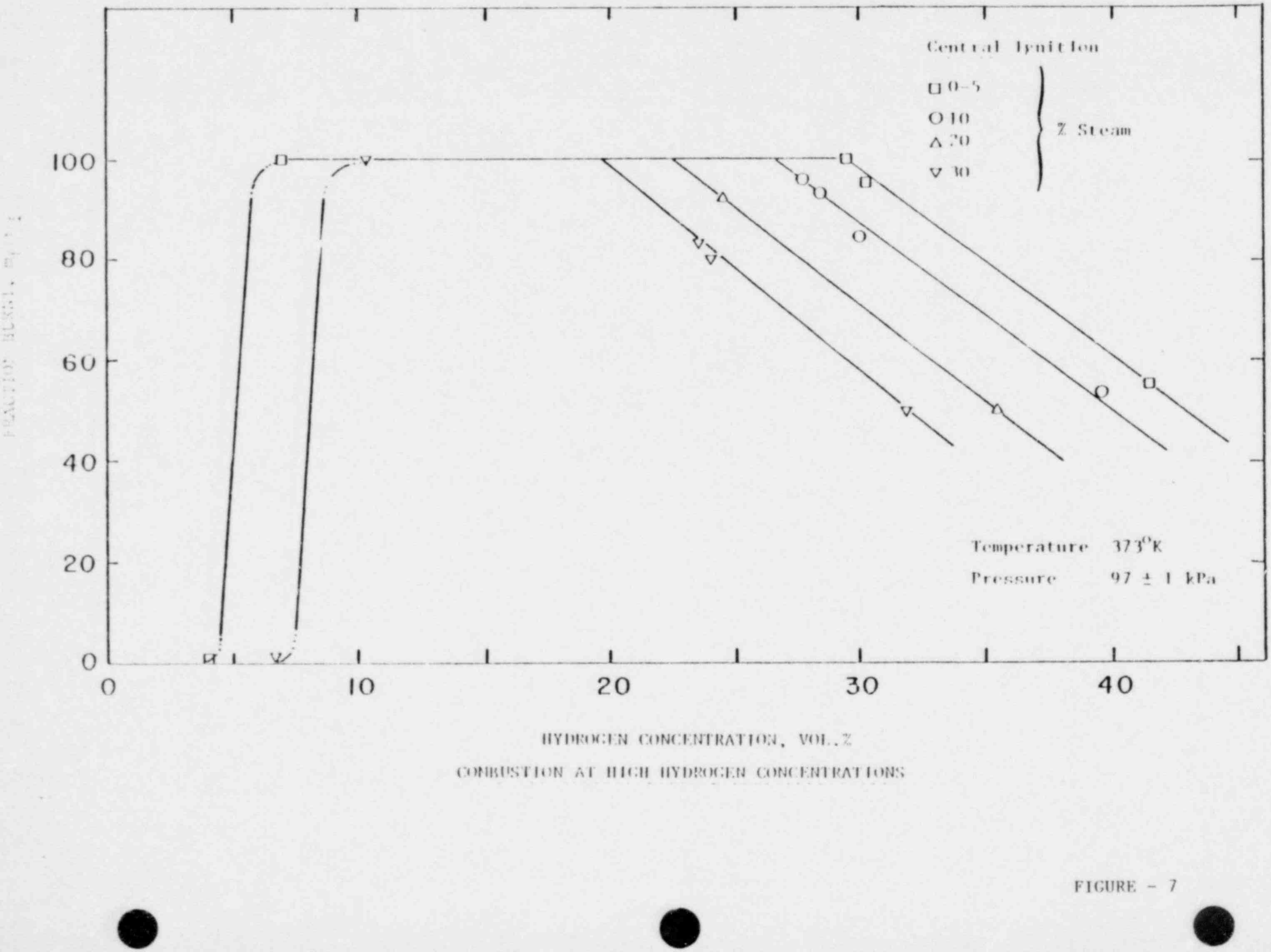
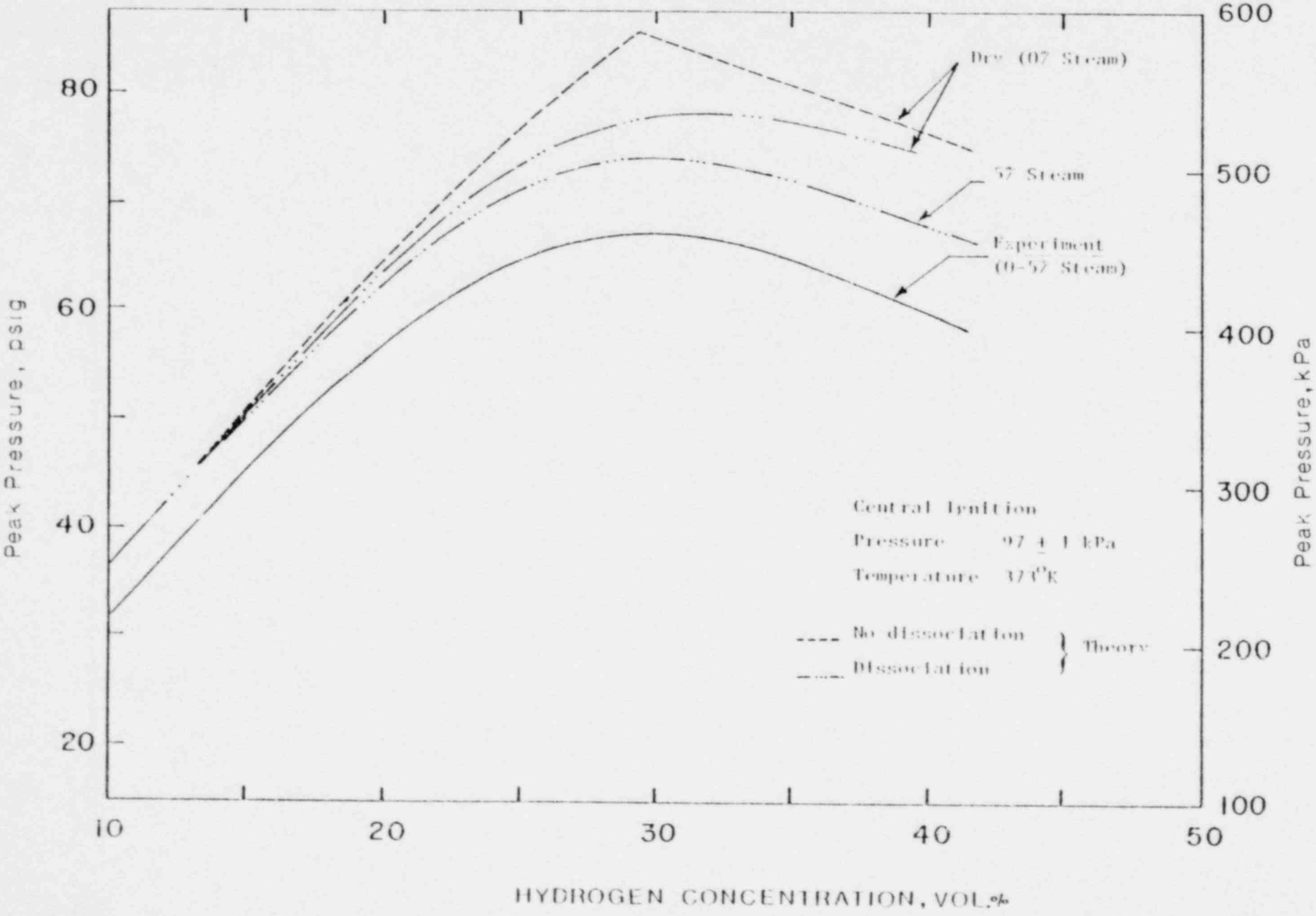

Combustion Peak Pressure, kPa
500
450
400
350
300
250
200
150
100
50
0
Combustion Peak Pressure, psig
70
60
50
40
30
20
10
0
10
20
30
40
Line of peak pressures
Central Ignition
Initial Pressure 97 ± 1 kPa
Temperature 373°K
Δ 0-5
O 10
● 20
□ 30
% Steam

FIGURE - 6



COMBUSTION AT HIGH HYDROGEN CONCENTRATIONS

FIGURE - 7



Peak Pressure, psig
20
40
60
80
Peak Pressure, kPa
100
200
300
400
500
600
10
20
30
40
50
HYDROGEN CONCENTRATION, VOL.%
Dry (0% Steam)
5% Steam
Experiment (0-5% Steam)
Central Ignition
Pressure 97 ± 1 kPa
Temperature 373°K
No dissociation
Dissociation
Theory

FIGURE - 8

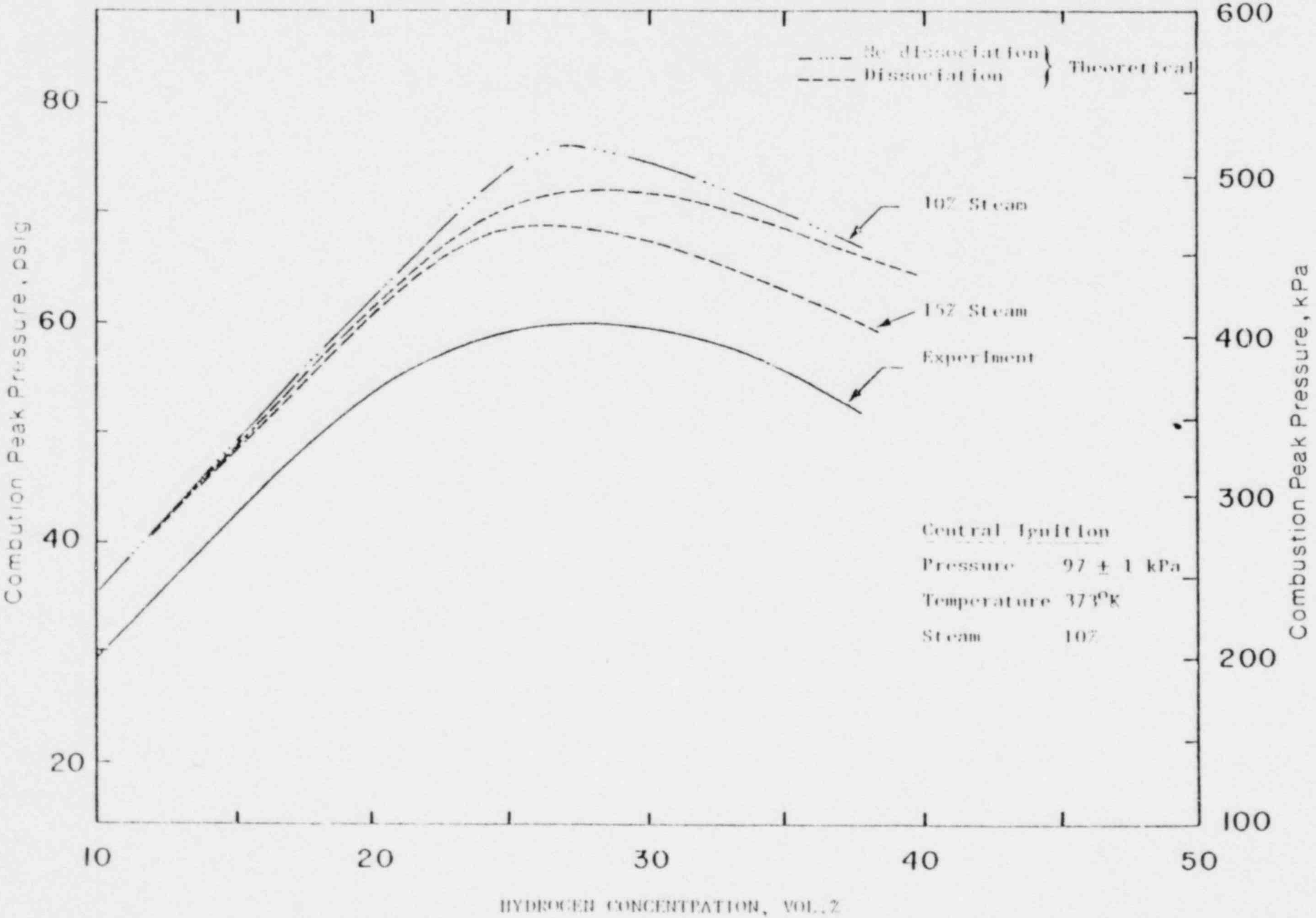

No dissociation
Dissociation
Theoretical
10% Steam
15% Steam
Experiment
Central Ignition
Pressure 97 ± 1 kPa
Temperature 373°K
Steam 10%
Combution Peak Pressure, psig
20
40
60
80
Combustion Peak Pressure, kPa
100
200
300
400
500
600
10
20
30
40
50
HYDROGEN CONCENTRATION, VOL.%

FIGURE -9

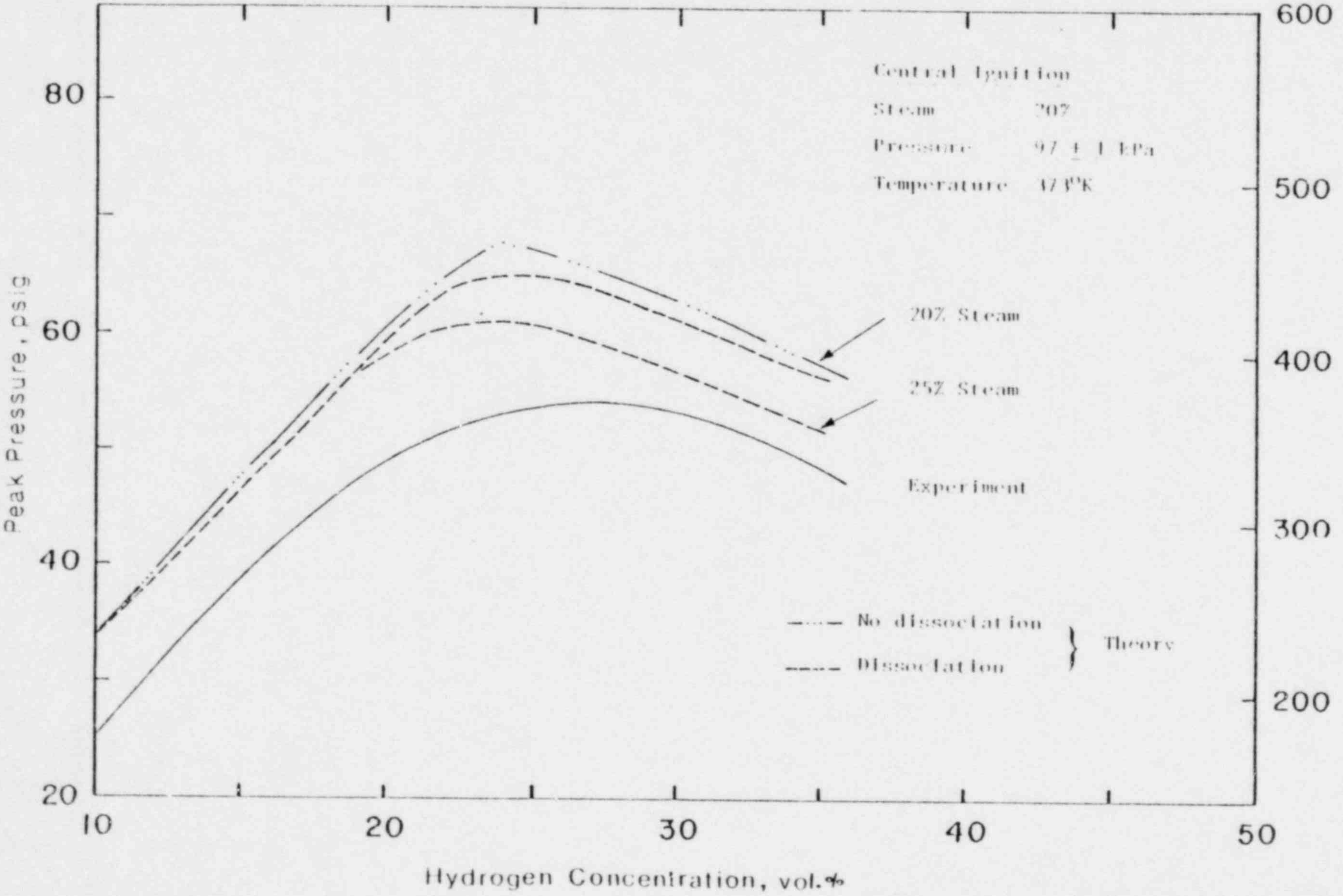

Peak Pressure, psig
80
60
40
20
Peak Pressure, kPa
600
500
400
300
200
10
20
30
40
50
Hydrogen Concentration, vol.%
Central Ignition
Steam 20%
Pressure 97 ± 1 kPa
Temperature 373°K
20% Steam
25% Steam
Experiment
No dissociation
Dissociation
Theory

FIGURE - 10

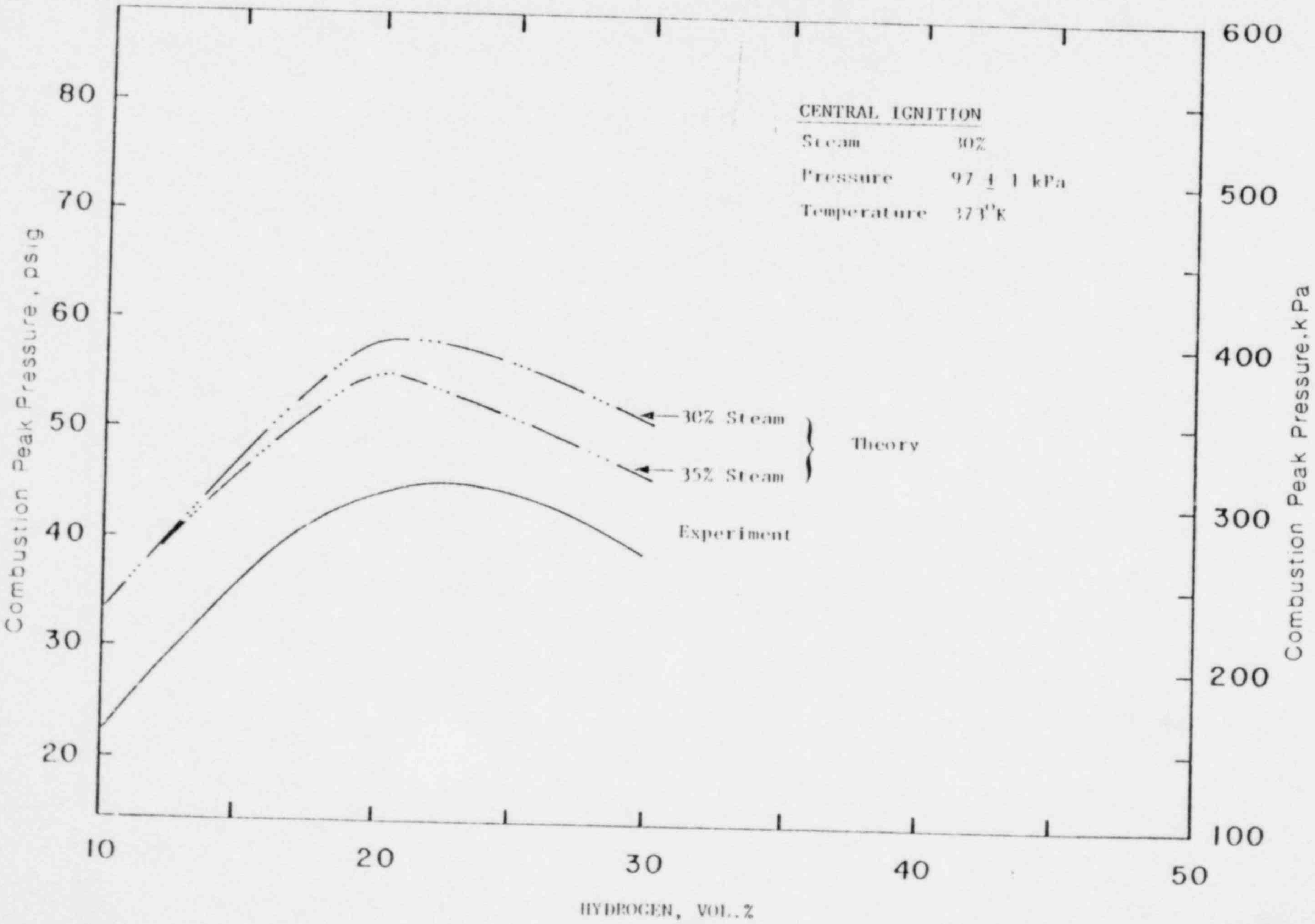

CENTRAL IGNITION
Steam 30%
Pressure 97 ± 1 kPa
Temperature 373°K
30% Steam
35% Steam
Theory
Experiment
Combustion Peak Pressure, psig
20
30
40
50
60
70
80
Combustion Peak Pressure, kPa
100
200
300
400
500
600
10
20
30
40
50
HYDROGEN, VOL.%

FIGURE - 11

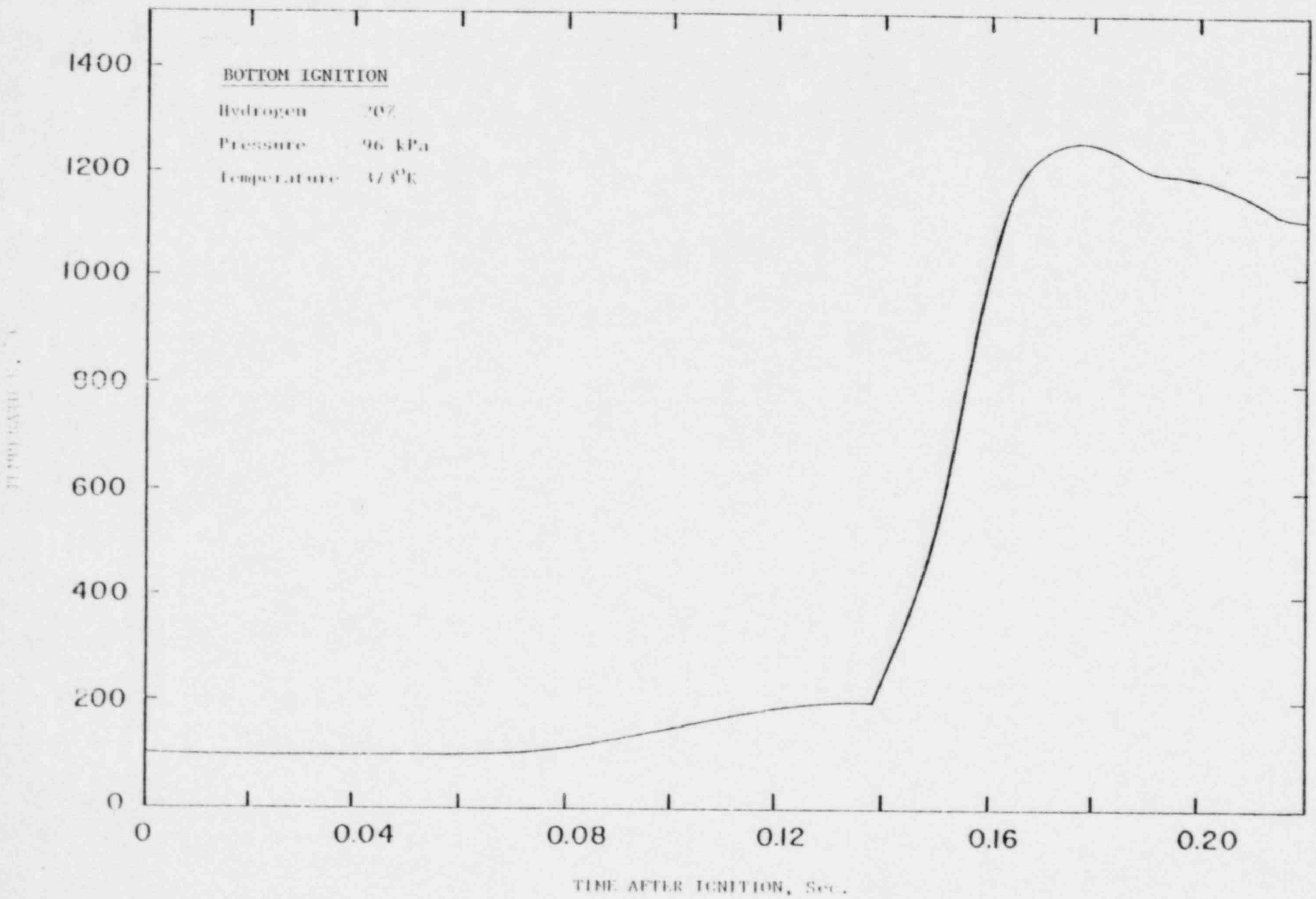

PRESSURE, kPa
1400
1200
1000
800
600
400
200
0
BOTTOM IGNITION
Hydrogen 20%
Pressure 96 kPa
Temperature 373°K
0
0.04
0.08
0.12
0.16
0.20
TIME AFTER IGNITION, Sec.

FIGURE - 12

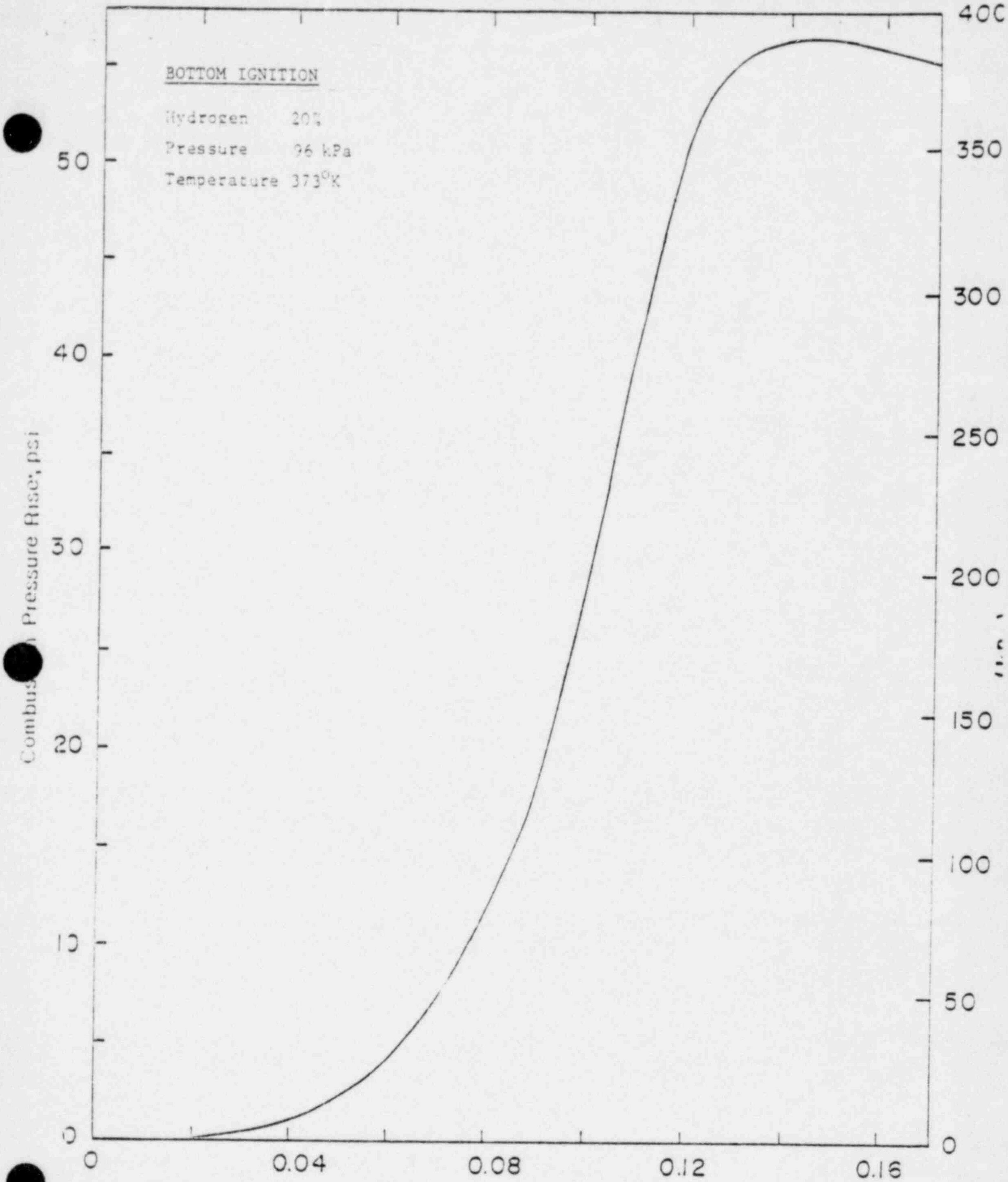

BOTTOM IGNITION
Hydrogen 20%
Pressure 96 kPa
Temperature 373°K
Combus... Pressure Rise, psi
0
10
20
30
40
50
0
50
100
150
200
250
300
350
400
0
0.04
0.08
0.12
0.16
TIME AFTER IGNITION, Sec.

FIGURE - 13

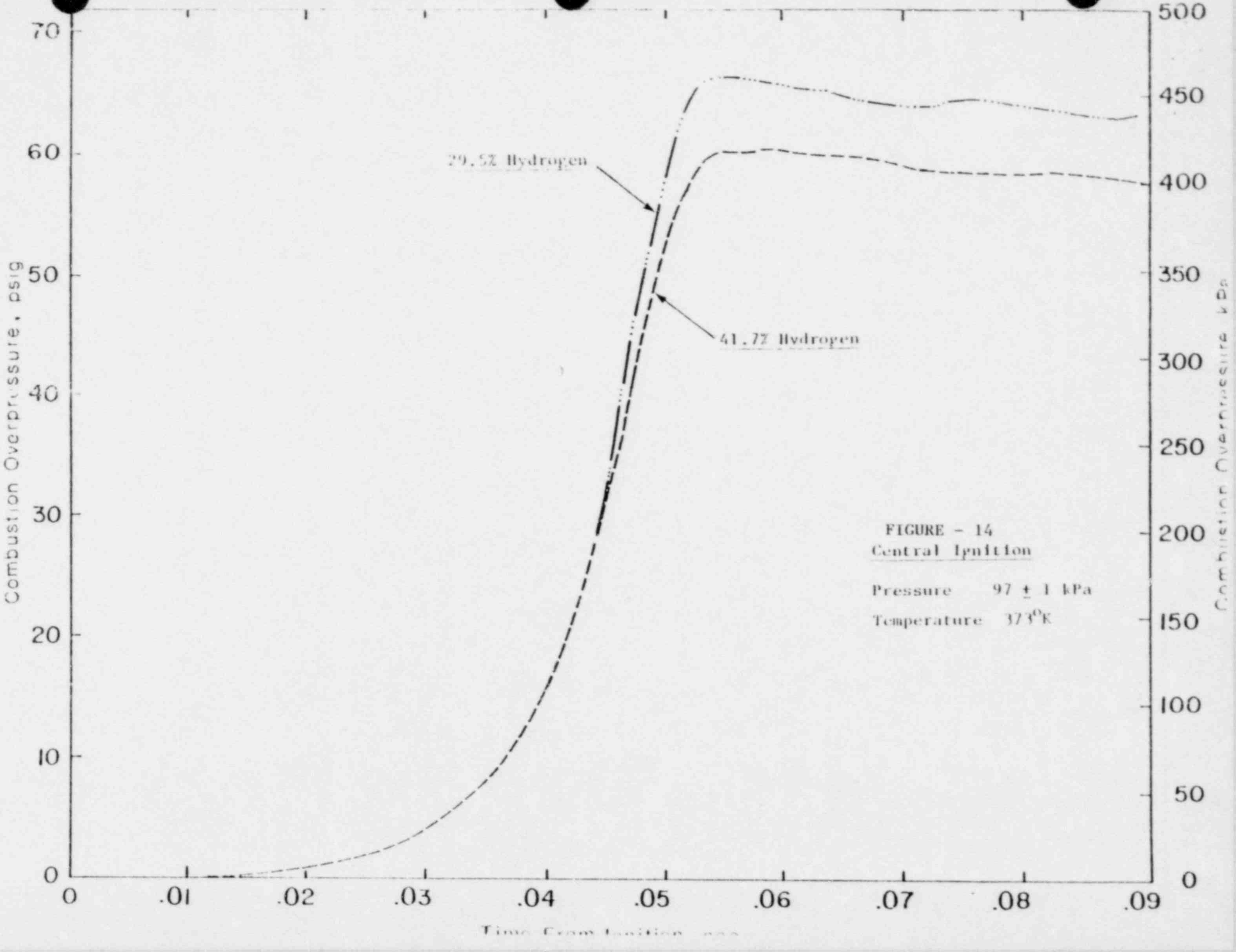


FIGURE - 14
Central Ignition

Pressure 97 ± 1 kPa

Temperature 373°K

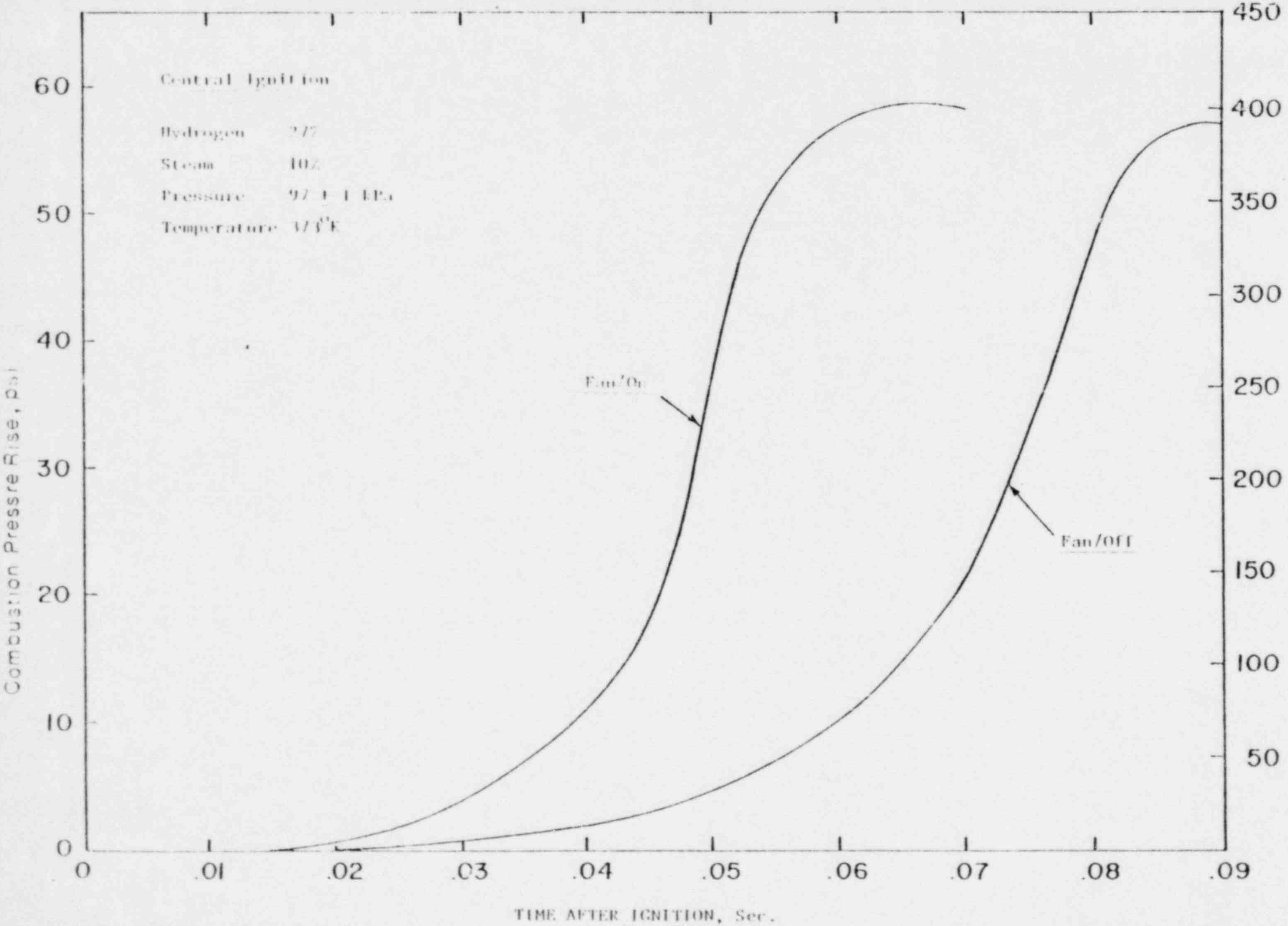
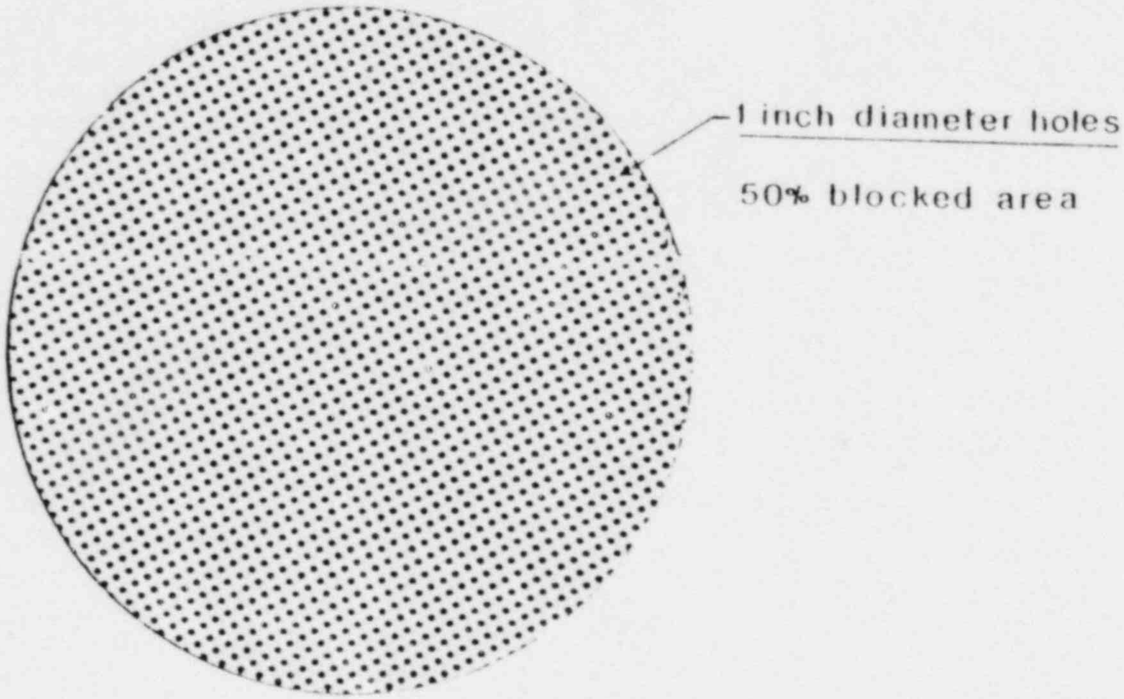

Central Ignition
Hydrogen 27%
Steam 10%
Pressure 97 ± 1 kPa
Temperature 373°K
Fan/On
Fan/Off
Combustion Pressre Rise, psi
0
10
20
30
40
50
60
Combustion Pressure Rise, kPa
50
100
150
200
250
300
350
400
450
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
TIME AFTER IGNITION, Sec.

FIGURE _ 1



SCHEMATIC OF GRATINGS USED

FIGURE - 16

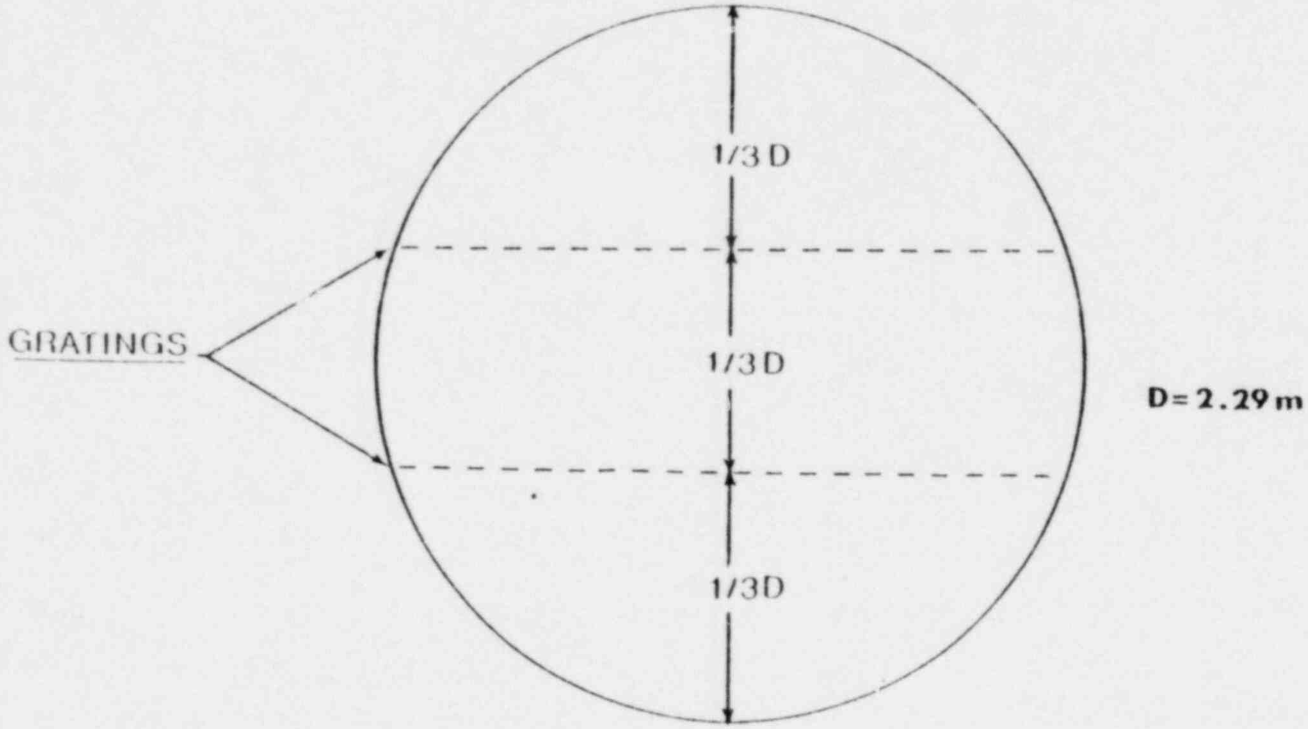


FIGURE-17: ARRNGEMENT OF GRATINGS IN THE SPHERE

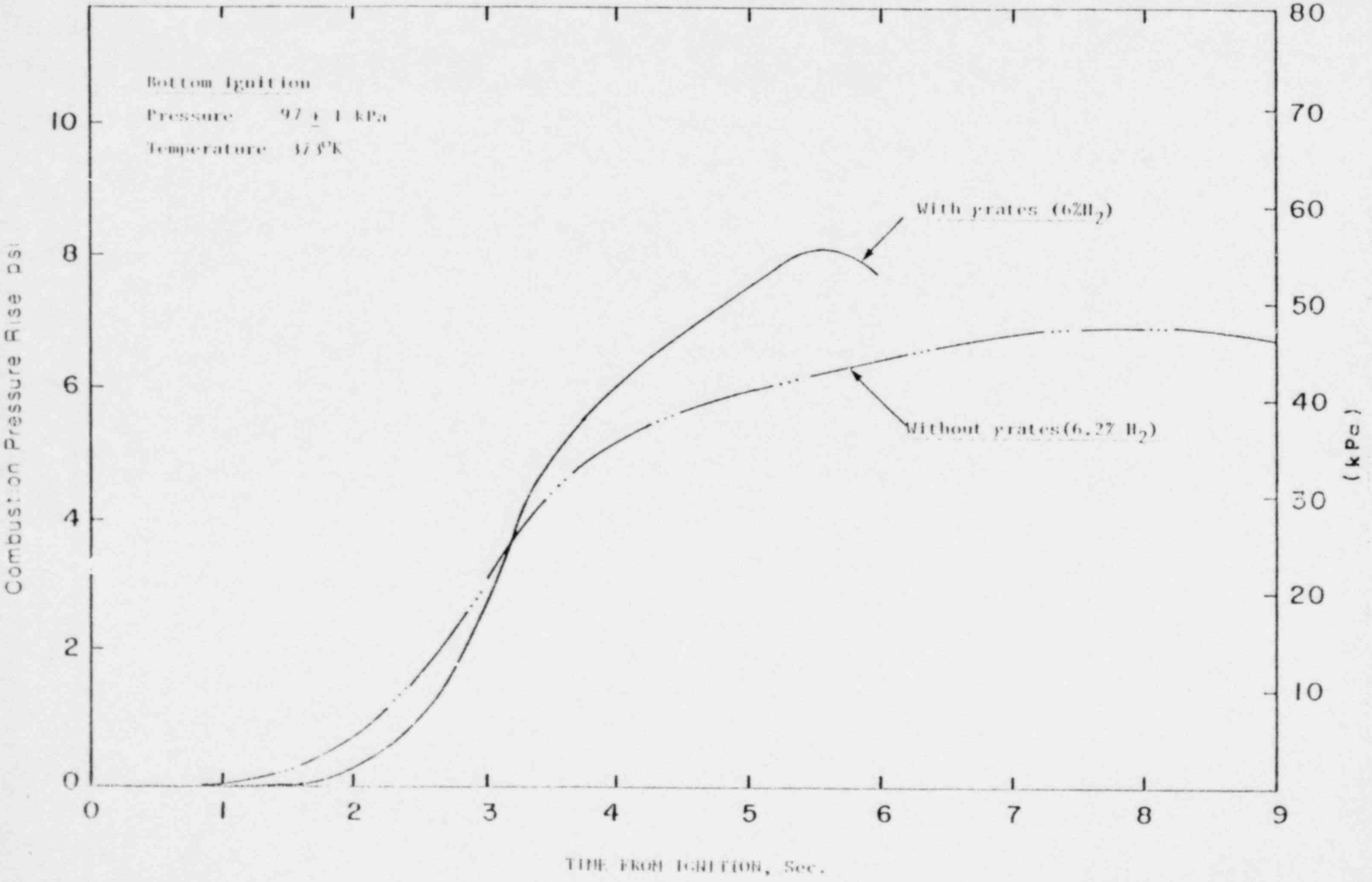
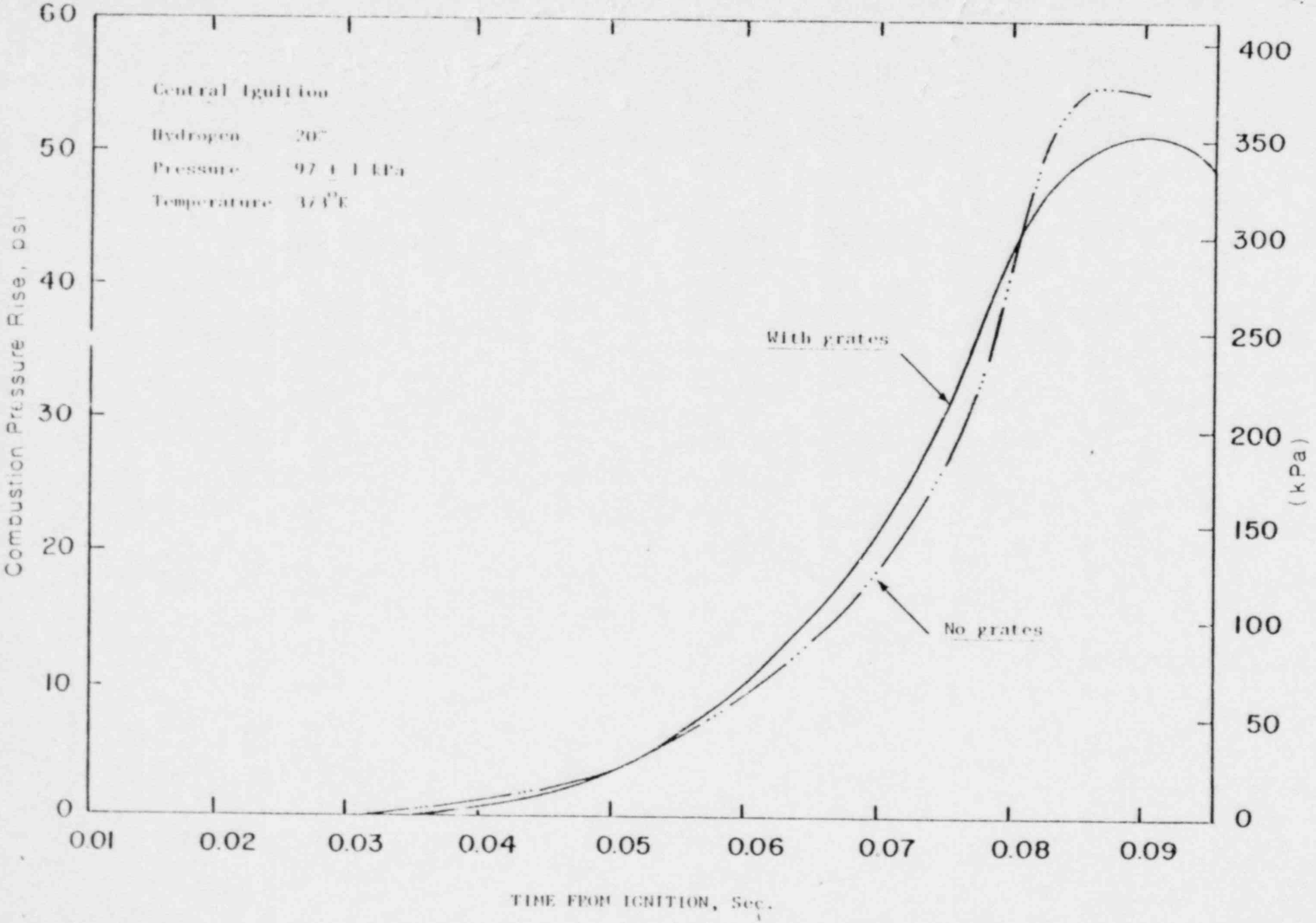

Bottom Ignition
Pressure 97 ± 1 kPa
Temperature 373°K
With grates (6%H_2)
Without grates (6.2% H_2)
Combustion Pressure Rise psi
0
2
4
6
8
10
(kPa)
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
TIME FROM IGNITION, Sec.

FIGURE - 18



Central Ignition
Hydrogen 20%
Pressure 97 ± 1 kPa
Temperature 373°K
With grates
No grates
Combustion Pressure Rise, psi
0
10
20
30
40
50
60
(kPa)
0
50
100
150
200
250
300
350
400
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
TIME FROM IGNITION, Sec.

FIGURE - 19

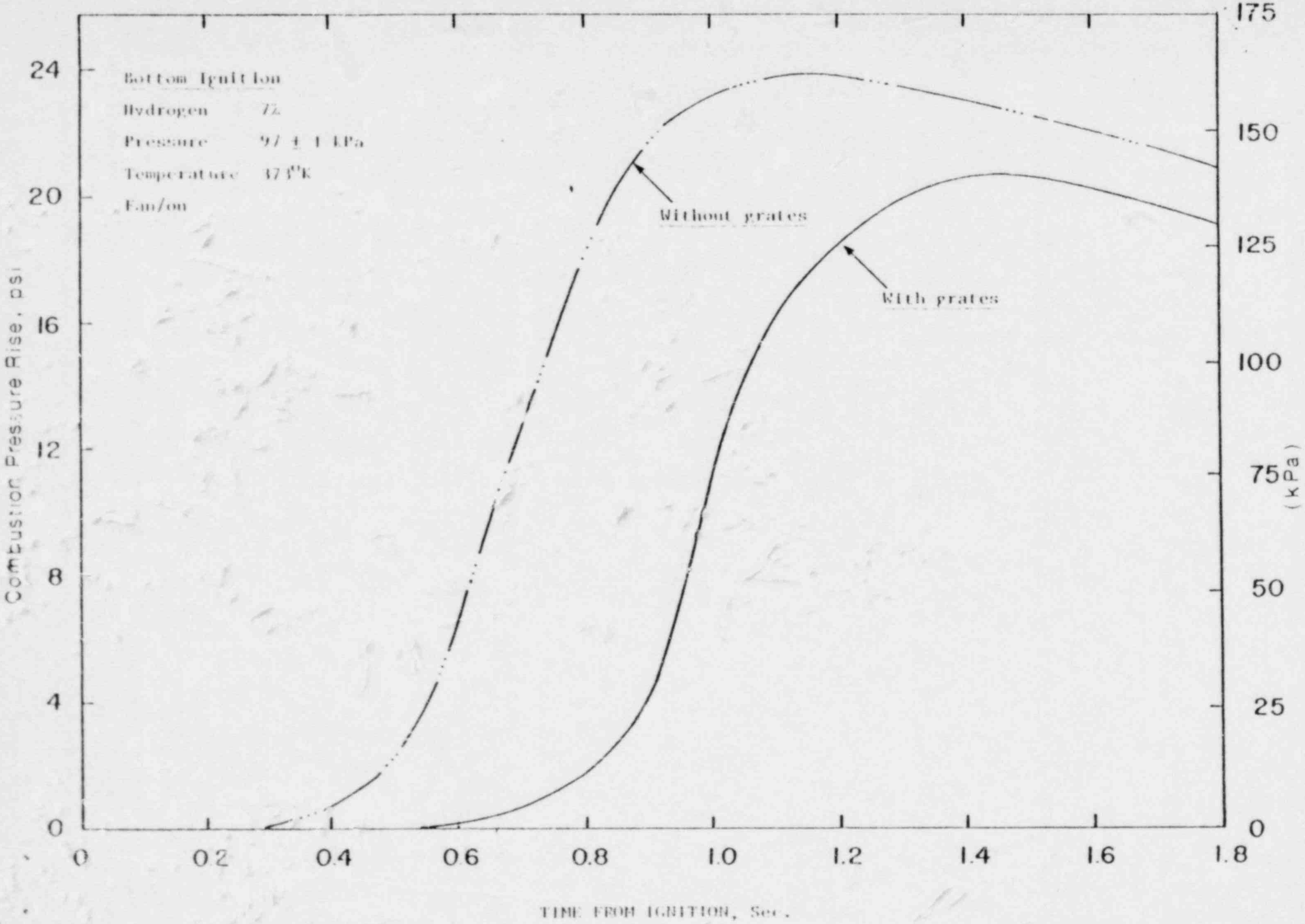

Combustion Pressure Rise, psi
0
4
8
12
16
20
24
(kPa)
0
25
50
75
100
125
150
175
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Bottom Ignition
Hydrogen 7%
Pressure 97 ± 1 kPa
Temperature 373°K
Fan/on
Without grates
With grates
TIME FROM IGNITION, Sec.

FIGURE - 20