C.P. No. 1209

C.P. No. 1209

PROCUREMENT EXECUTIVE, MINISTRY OF DEFENCE

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Spontaneous Ignition of Avtur Vapour in Various Oxygen-Nitrogen Mixtures

by

J. T. Cansdale, B.Sc.

Engineering Physics Dept., R.A.E., Farnborough

LONDON: HER MAJESTY'S STATIONERY OFFICE

1972

PRICE 45 *p* NET

UDC 665.582 : 541.126 : 629.13.012.6 : 629.137.1 : 533.6.011.5 : 533.6.011.6

*CP No.1209
January 1971

SPONTANEOUS IGNITION OF AVTUR VAPOUR IN VARIOUS OXYGEN-NITROGEN MIXTURES

by

J. T. Cansdale, B.Sc.

SUMMARY

The spontaneous ignition of Avtur vapour in closed heated vessels was investigated to determine the maximum oxygen concentration required to limit ignition pressure rises to 6.9 kN/m^2 (1 lbf/in^2). The aim was to establish the maximum safe oxygen concentration to be permitted within the nitrogen filled heating ducts of the BAC Concorde Fuel System Test Facility.

Tests were made firstly in a uniformly heated 0.46 m (18 in) diameter sphere, over a temperature range from 260°C to 440°C. An oxygen concentration of less than 1% by volume was necessary to limit ignition pressures. The effect of oxygen concentration on ignition delay time was also studied.

Secondly, ignition in the presence of a 0.15 m (6 in) diameter hot pipe in a temperature controlled 0.46 m (18 in) sphere was investigated at sphere temperatures up to 180°C and pipe temperatures up to 440°C. An oxygen concentration of less than 2.5% by volume was found to limit ignition pressures as required at all conditions considered.

It was concluded that in the BAC Test Rig, a 2.5% oxygen concentration would be low enough to prevent any undesirable ignitions.

---

* Replaces RAE Technical Report 71012 - ARC 32962

CONTENTS

1 INTRODUCTION

The British Aircraft Corporation have constructed a test rig to investigate the various problems likely to be encountered in the fuel systems of supersonic transport aircraft, particularly of Concorde. The rig includes a full scale model of the Concorde fuel tanks, beneath which, in order to simulate the kinetic heating effects of supersonic flight, ducts have been built for passing heated nitrogen. The nitrogen is heated by a group of electrical elements within one section of the duct. Ideally the ducts should contain 100% nitrogen, with neither fuel nor oxygen being present, but in practice it is almost inevitable that firstly some fuel will leak from the tanks into the ducts and secondly the circulating nitrogen will contain a small concentration of oxygen. It was realised that in these circumstances there was a risk of explosion, the greatest hazard arising if the nitrogen circulating system failed and allowed a static mixture of nitrogen, oxygen and fuel to exist within the duct.

A typical heating section comprises a 0.46 m (18 in) length of duct, 0.91 m (36 in) square, containing a matrix of electrical elements. These are 9.5 mm (0.375 in) in diameter by 0.86 m (34 in) long and are mounted vertically across the duct, with a spacing of 31.8 mm (1.25 in) between element centres. The main nitrogen stream is to be maintained at a maximum temperature of 180°C, for which the elements are required to run at 440°C, and it is in the region of these hot elements that ignition is most likely to occur. The normal nitrogen pressure within the duct is 105.5 kN/m^2 absolute (15.3 psia) and it is estimated that the duct can sustain ignition pressures up to 6.9 kN/m^2 (1 lbf/in^2).

It was decided that experiments should be carried out using the spontaneous ignition apparatuses available at RAE in order to assess the maximum oxygen concentration which could be safely tolerated. The work is reported here.

2 APPARATUS AND TECHNIQUES

Two spontaneous ignition test rigs were used for the experiments, the first being for the investigation of ignition of fuel in a uniformly heated vessel and the second representing the non-uniform temperature situation of a relatively cold enclosure having a hot pipe passing through it. Unfortunately no rig is available for the investigation of ignition of fuels in a hot flowing stream of controlled mixtures of oxygen and nitrogen, other than normal atmospheric air. However, as mentioned previously, the most hazardous condition likely to arise in the BAC Test Facility will occur if the nitrogen circulating system fails, allowing the flow to stop, when the temperature conditions in the heating section will tend to those in a heated enclosure.

2.1 Uniformly heated sphere

The apparatus is shown diagrammatically in Fig.1, and was substantially that used by Macdonald and White[1]. The explosion vessel was 0.46 m (18 in) in diameter, made from 10 swg stainless steel to BS Specification S521, and was heated by an electrical heating jacket having individually controlled sections, enabling the sphere temperature to be kept uniform to within $2^{o}C$ overall. The surface temperature of the vessel was measured by eight chrome-alumel thermocouples welded to the outside of the vessel, distributed so as to survey adequately the whole surface. The gas temperature was measured by a 42 swg chrome-alumel thermocouple placed centrally inside the vessel.

2.2 Sphere with heated pipe

This rig is shown in Fig.2 and was devised by Macdonald[2] for the investigation of ignition by hot pipes. It comprises a 0.46 m (18 in) sphere similar to that described above, having a heated stainless steel pipe mounted diametrically. The sphere was immersed in an electrically heated oil bath, its temperature being monitored by five themocouples distributed over its surface. The oil could be circulated to maintain a uniform sphere temperature. The hot pipe was 0.33 m (13 in) long by 0.15 m (6 in) diameter and was made from an outer skin of 20 swg stainless steel and a thick inner lining of copper to minimise temperature variations over its surface. The 6 in pipe, although much greater in diameter than the rig heating elements, was used to represent a cluster of the BAC rig elements. Heating was by an internal electrical element, and the pipe temperature was measured by two thermocouples, these being found sufficient to give an accurate mean temperature.

2.3 Instrumentation

In both rigs the ignition pressure rise within the vessel was measured by a high frequency response pressure transducer covering the range 0 to 170 kN/m^2 (0 to 25 psi) absolute coupled to an NEP ultra-violet galvonometer recorder. A mercury manometer was used for visual observation of pressure and for metering fuel into the vessel. Ignition delay time, from initiation of fuel injection to pressure rise, was taken either from the time base of the recorder for short delays or measured by stopwatch for long delays.

2.4 Fuel injection

Avtur (D Eng RD 2494) fuel vapour was used for all tests, injected in the form of whole vapour (i.e. all fractions) from the pressurised fuel boiler. The fuel injection was controlled by a solenoid operated valve actuated by an electronic timer; variation of the injection time allowed the fuel concentration in the vessel to be varied over a wide range.

2.5 Oxygen-nitrogen mixtures

The required mixture of nitrogen and oxygen was premixed in a gas cylinder, from which it was supplied to the test vessel both for purging between tests and for the tests. Since the preparation of the gas mixtures was a somewhat lengthy procedure, and since the oxygen concentrations being used were low, the first purging after each test was made with commercial nitrogen, followed by two purges with the required mixture. No attempt was made to heat the gas before it entered the vessel, but adequate time was allowed for it to warm up before fuel injection.

The oxygen concentration in the mixture was measured at the time of mixing by a Servomex Portable Oxygen Analyser having a resolution of better than 0.1%. This instrument was calibrated before use on air and 'white spot' nitrogen.

3 TEST PROGRAMME

In all the tests, the pressure within the vessel after injection of the fuel vapour and prior to ignition was arranged to be 105.5 kN/m^2 absolute (15.3 psia), this being the absolute pressure to be used in the BAC heating ducts.

3.1 Uniformly heated sphere

Tests were initially made at a sphere temperature of 440°C using various mixtures of oxygen (4 to 7% by volume) and nitrogen, and various fuel vapour concentrations (up to 6% by volume). This temperature was chosen since it was the highest likely to be reached by the heating elements in the BAC Test Facility. However, it was thought wise to investigate ignitions at lower sphere temperatures, and tests were therefore carried out using a 4% oxygen mixture at temperature from 260°C to 400°C. In the light of the results of these tests, ignitions in mixtures having oxygen concentrations of 1% and 3% by volume at a temperature of 300°C were also investigated. Finally, a 1% oxygen mixture was tested at 350°C and 400°C. Table 1 summarises the range of temperatures and oxygen concentrations used in this test series.

3.2 Hot pipe ignition

The first tests used a 5% oxygen mixture at various combinations of sphere and rod temperature, the sphere varying from 120°C to 180°C and the pipe from 350°C to 440°C. Ignition of fuel in a 4% oxygen mixture was then studied with the pipe at 440°C while the sphere was varied from 120°C to 180°C, with additional tests with sphere at 180°C and pipe at 400°C. Finally, a 2.5% oxygen mixture was tested with the sphere at 180°C and the pipe at 440°C, these having been found to be the most severe conditions at a 4% oxygen concentration. These test conditions are summarised in Table 2 and were chosen as being representative of those likely to exist in the BAC rig.

4 RESULTS

Figs.3 to 6 plot the ignition pressure rise as a function of fuel concentration for various oxygen concentrations in the uniformly heated sphere at different temperatures. Fig.7 summarises these results as the ratio of the maximum pressure rise to the initial pressure at optimum fuel concentration, plotted against the initial oxygen concentration. Full curves are drawn for temperatures of 300 and 440°C and broken lines are shown for temperatures of 350 and 400°C at which there are insufficient results to draw accurate curves. Some results by Kurtovich and Hays[3] are also reproduced, and although their tests were made at normal atmospheric pressure, i.e. 101.4 kN/m^2 (14.7 lbf/in^2) absolute, rather than 105.5 kN/m^2 absolute as used by RAE, the results are comparable as they are expressed as a ratio to initial pressure. These results are for ignition at optimum fuel concentration and temperature.

Figs.8 and 9 give the ignition delay times plotted against sphere temperature and initial oxygen concentration respectively.

Figs.10 to 12 refer to the heated pipe in a sphere, and give the pressure rise versus the fuel concentration at various oxygen concentrations and temperature conditions.

5 DISCUSSION OF RESULTS

(a) The fuel concentration required for maximum pressure rise was very much greater in the hot pipe rig than in the uniformly heated sphere; the former was around 15% while the latter was about 3% by volume. This is in agreement with Macdonald's work[1,2]. The reason for this difference is not easily explained, although condensation of fuel vapour on the relatively cool walls of the sphere of the hot pipe rig and the non-uniform fuel distribution throughout the convection currents within this vessel may be responsible.

(b) The maximum pressure rise increases with oxygen concentration as shown by the isothermal curves in Fig.7. At 300°C there seems to be a logarithmic relationship, but further points are required to confirm this.

(c) The optimum temperature to give maximum pressure rise varies with oxygen concentration, from about 300°C at both 21.8% and 4% oxygen to about 350°C at 1% oxygen. Although it is to be expected that in the range from 4 to 21.8% oxygen the maximum pressure rise would occur at approximately 300°C insufficient results were obtained either to confirm this or to predict with certainty the value of the maximum pressure rise in this range.

The results by Kurtovich and Hays included in Fig.7 are for optimum fuel concentration and temperature and show that the curve of maximum ignition pressure at optimum conditions versus oxygen concentration is concave upwards at low concentrations; this agrees with the trend of the present experimental results. It should be pointed out that the curve must shortly reverse this trend for the line to pass through a pressure ratio of between 4 and 7 at 21.8% O_2.

(d) It was noted during calibrations of the fuel injection timer when the uniformly heated sphere was filled with commercial nitrogen that some reaction was taking place between the fuel vapour and the extremely small quantity of oxygen (about 0.3% by volume) present in the nitrogen. While the pressure rise was small, and only perceptable using a water manometer, it does illustrate that unlike spark and flame ignition, the reaction can only be limited, and not necessarily eliminated, by reduction of oxygen concentration unless this is reduced to zero.

(e) Fig.8 shows that the region of negative temperature coefficient between 400 and 460°C, where the ignition delay time increases with increase in temperature, is independent of the oxygen concentration.

(f) The curves of ignition delay against oxygen concentration given in Fig.9, although drawn on a rather limited number of experimental points, are consistent enough to suggest that they are tolerably accurate and useful as general reference data.

6 CONCLUSIONS

(a) It was shown that in the uniformly heated closed vessel it was necessary to reduce the oxygen concentration to somewhat less than 1% by volume in order to limit ignition pressure rises to 6.9 kN/m^2 (1 lbf/in^2) (see Figs.6 and 7).

(b) Tests in the hot pipe rig showed that a 2.5% oxygen concentration was sufficiently low to limit ignition pressures to less than 6.9 kN/m^2 (1 lbf/in^2), the maximum pressure rise actually measured in this concentration being 5.5 kN/m^2 (0.8 lbf/in^2), as shown in Fig.12.

(c) It was concluded from the test results that an oxygen concentration of 2.5% by volume would be low enough to prevent ignition pressures of more than 6.9 kN/m^2 in the BAC rig, it being considered that firstly the configuration was nearer to that of the RAE hot pipe rig and secondly some relief would be gained by venting of local ignition pressures along the long duct, giving an additional margin of safety.

Table 1

RANGE OF CONDITIONS STUDIED IN UNIFORMLY HEATED SPHERE

Sphere temperature °C	O_2 concentration % by volume
260	4
300	1
300	3
300	4
350	1
350	4
400	1
400	4
440	4
440	5
440	6
440	7

Table 2

RANGE OF CONDITIONS STUDIED IN HOT PIPE RIG

Sphere temperature °C	Pipe temperature °C	O_2 concentration % by volume
120	440	4
120	440	5
150	440	4
150	440	5
180	350	5
180	400	4
180	400	5
180	440	2.5
180	440	4
180	440	5

REFERENCES

No.	Author(s)	Title, etc.
1	J. A. Macdonald R. G. White	Spontaneous ignition of kerosene (Avtur) fuel vapour: the effect of vessel size. RAE Technical Report 65138 (ARC 27371) (1965)
2	J. A. Macdonald	Ignition of aviation kerosine by hot pipes. RAE Technical Report 67162 (ARC 30326) (1967)
3	D. D. Kurtovich G. E. Hays	Spontaneous ignition and supersonic flight. Society of Automotive Engineers - National Aeronautics and Space Engineering and Manufacturing Meeting Los Angeles, California, Paper 431 C 9-13 October 1961

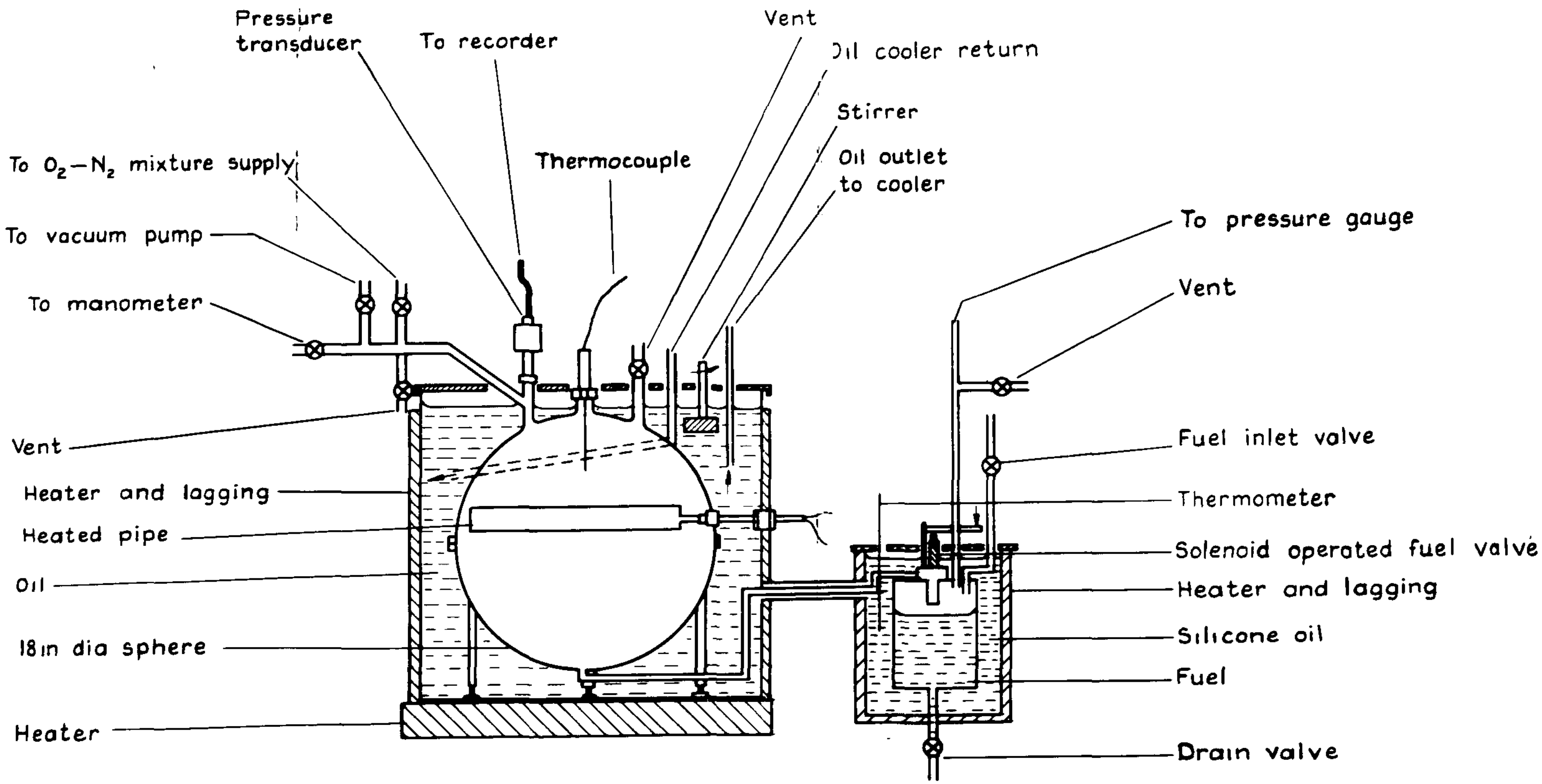

Fig. 2 Apparatus for investigating the ignition of fuel vapour by hot pipes

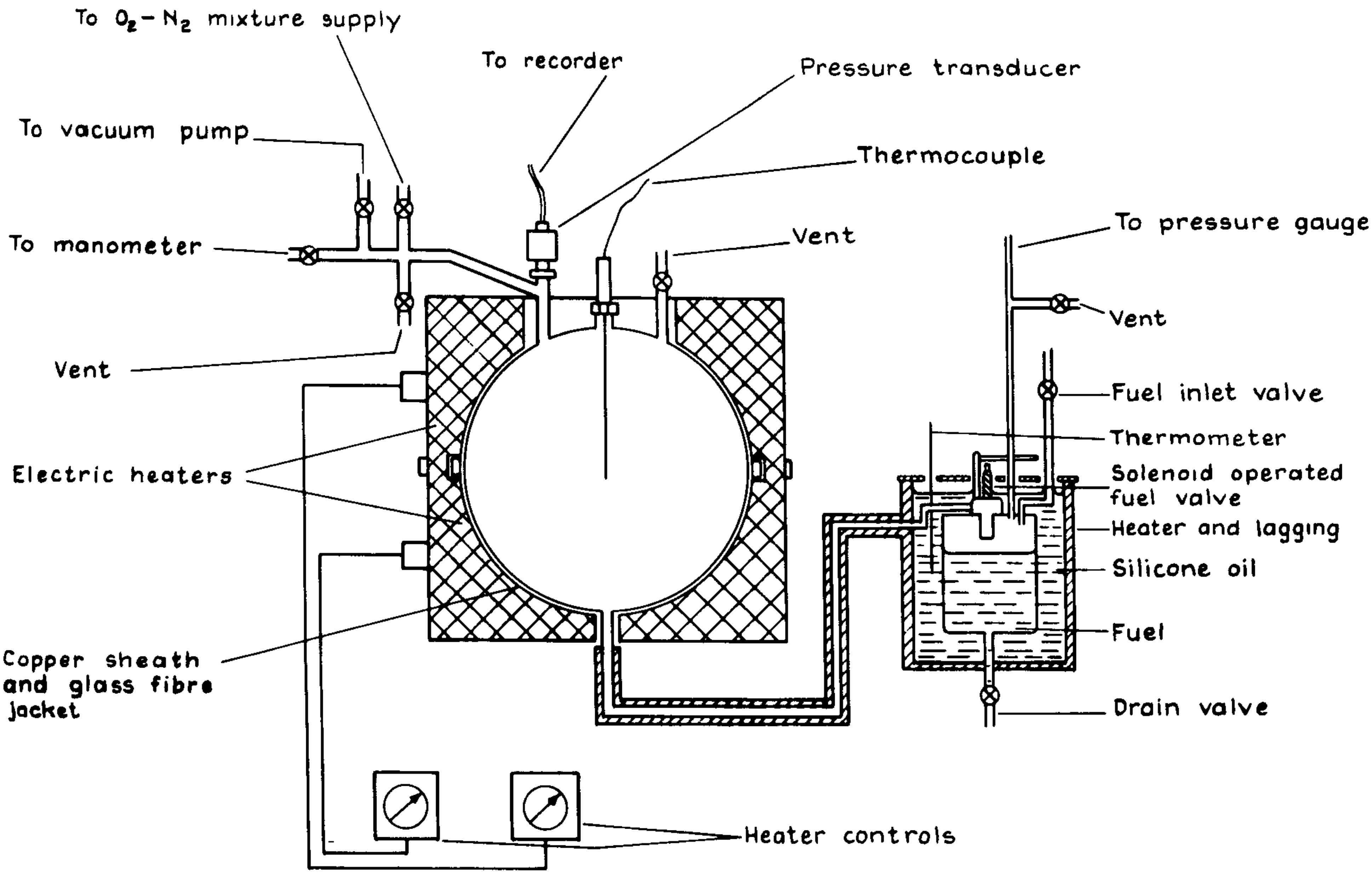

Fig. 1 Apparatus for investigating the spontaneous ignition of fuel vapour

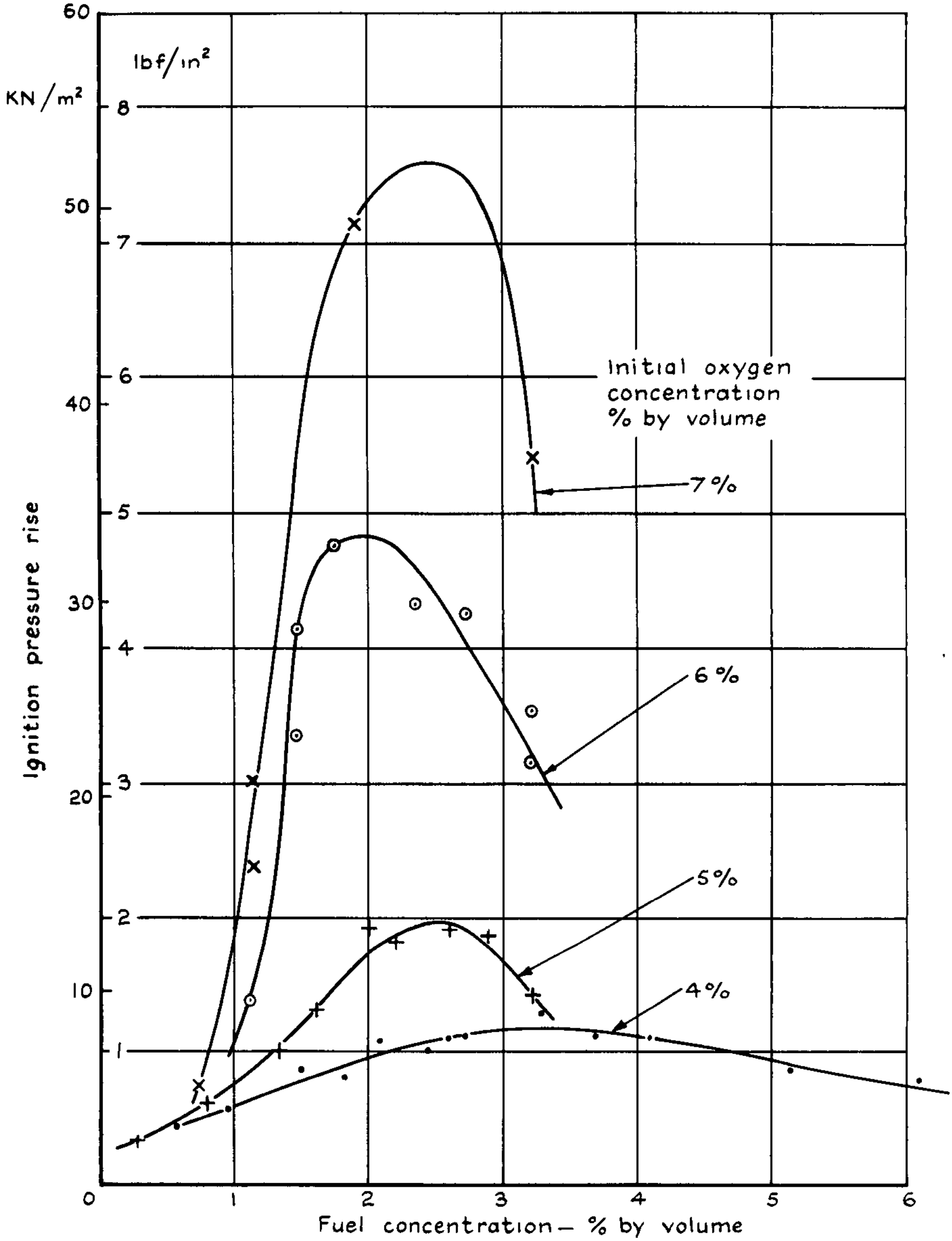

Fig. 3 Effect of fuel concentration on ignition pressure rise: uniformly heated sphere at 440°C

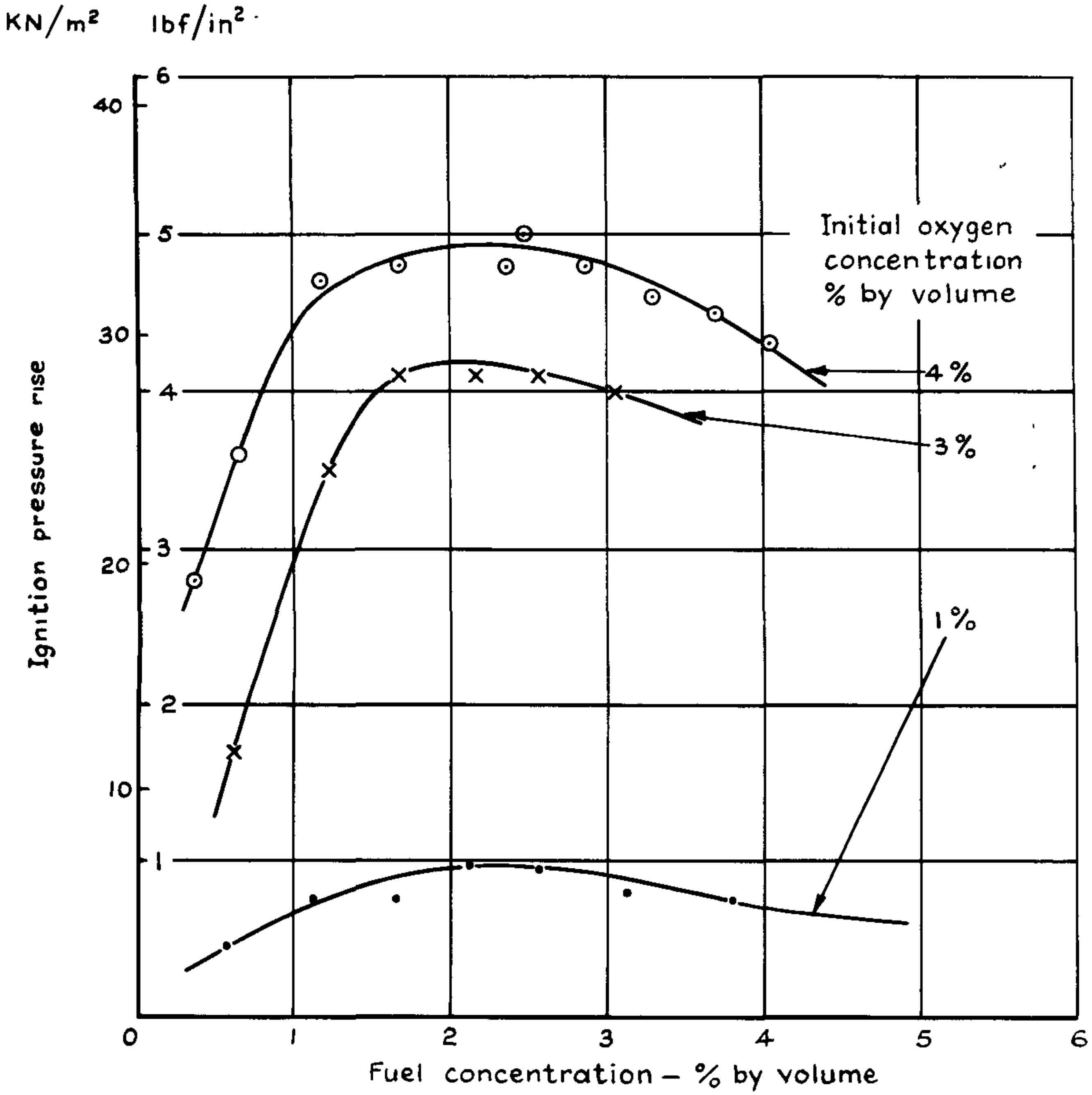

Fig. 4 Effect of fuel concentration on ignition pressure rise: uniformly heated sphere at 300 °C

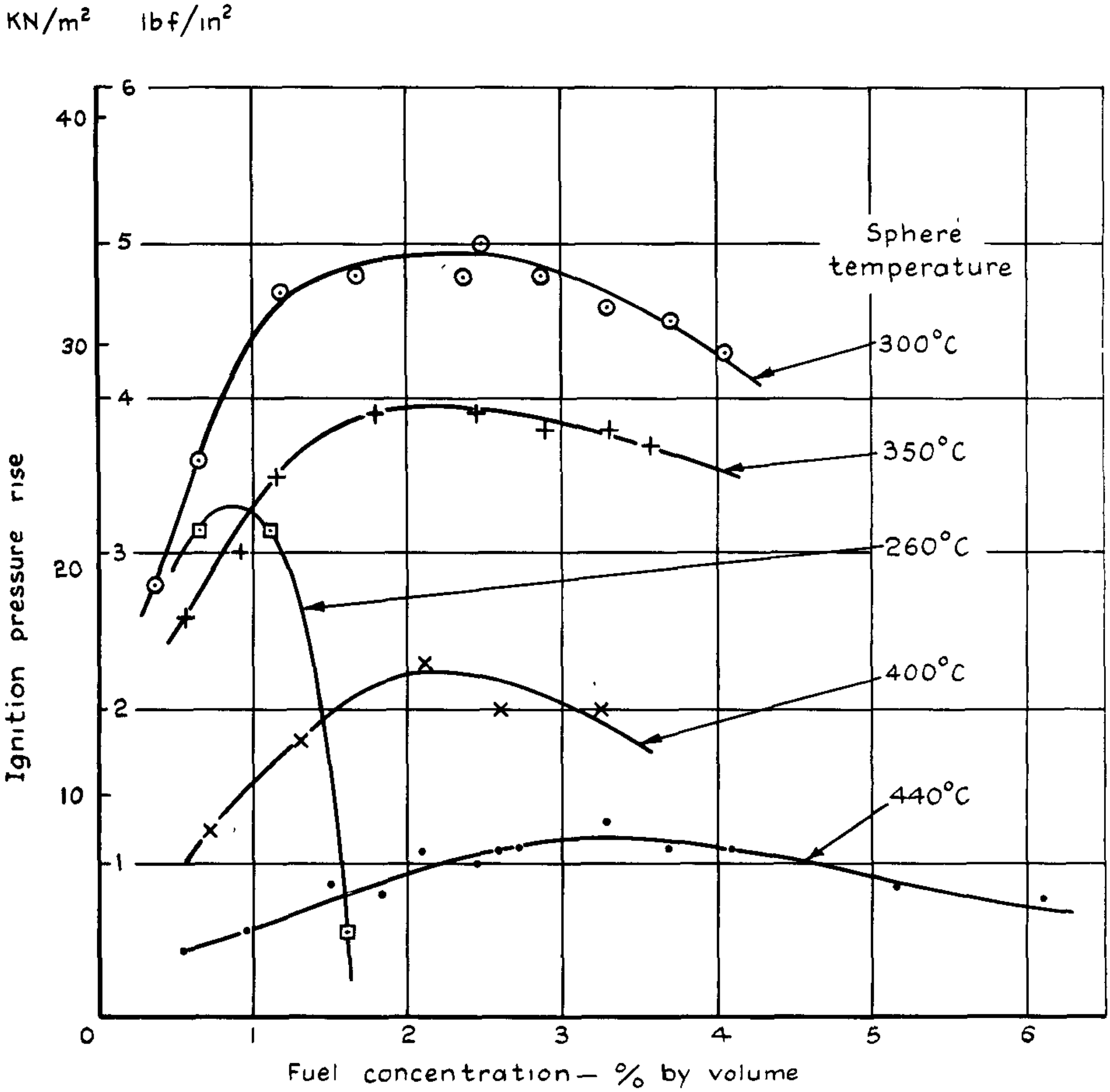

Fig. 5 Effect of fuel concentration on ignition pressure rise in uniformly heated sphere

Initial oxygen concentration of 4 % by volume

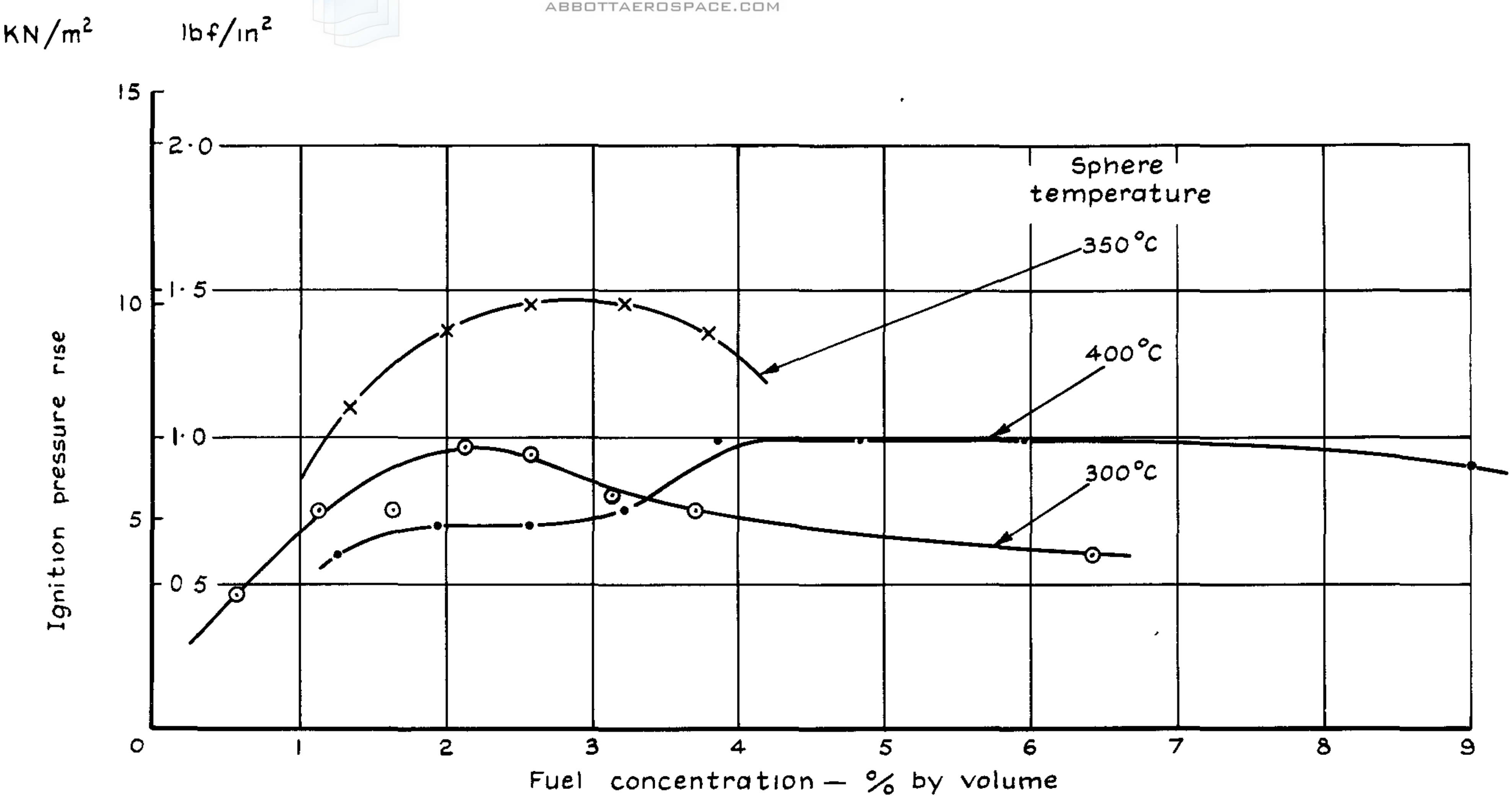

Fig. 6 Effect of fuel concentration on ignition pressure rise in uniformly heated sphere

Initial oxygen concentration of 1% by volume

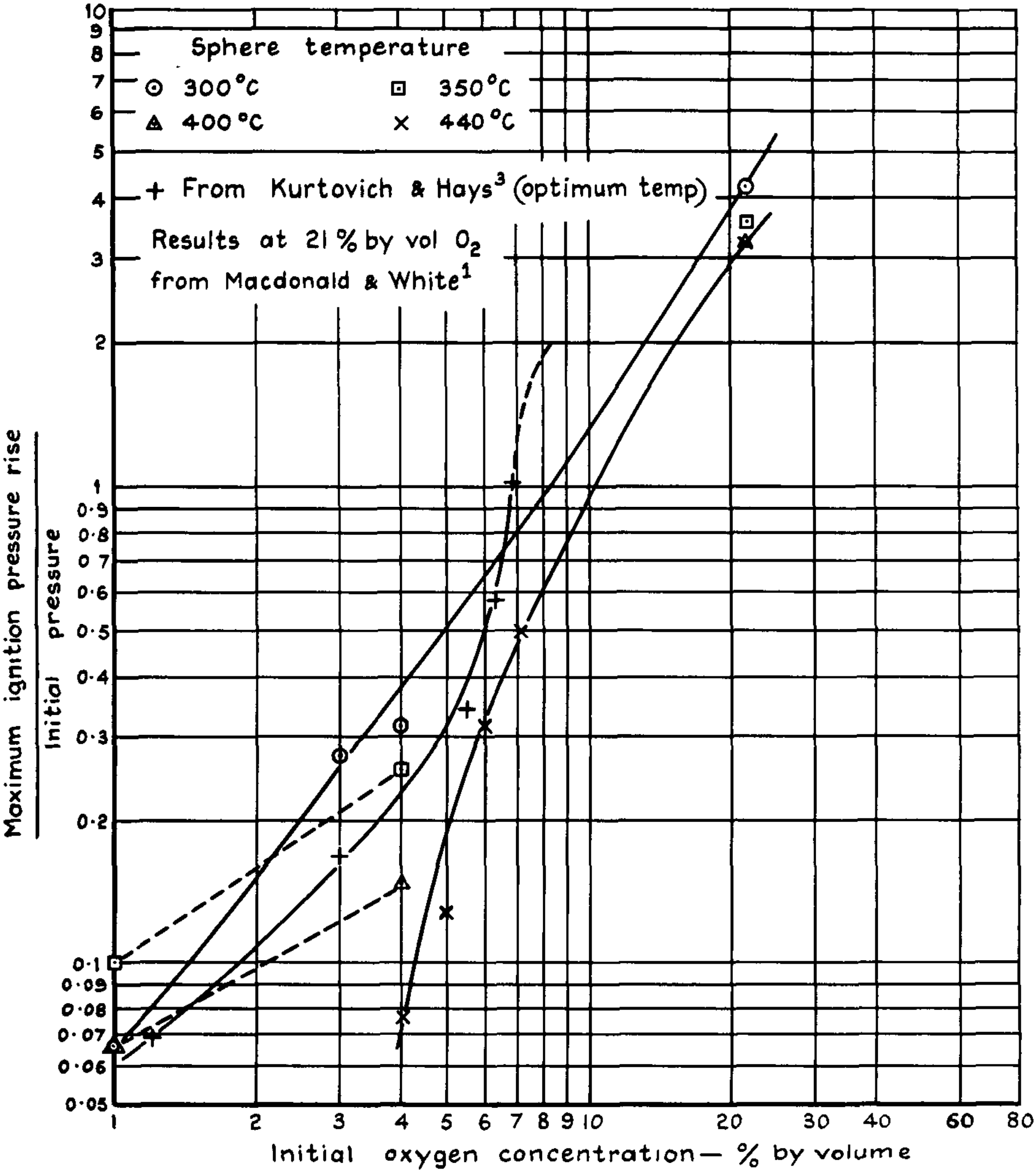

Fig.7 Variation of maximum ignition pressure rise with initial oxygen concentration; Optimum fuel concentration in uniformly heated sphere

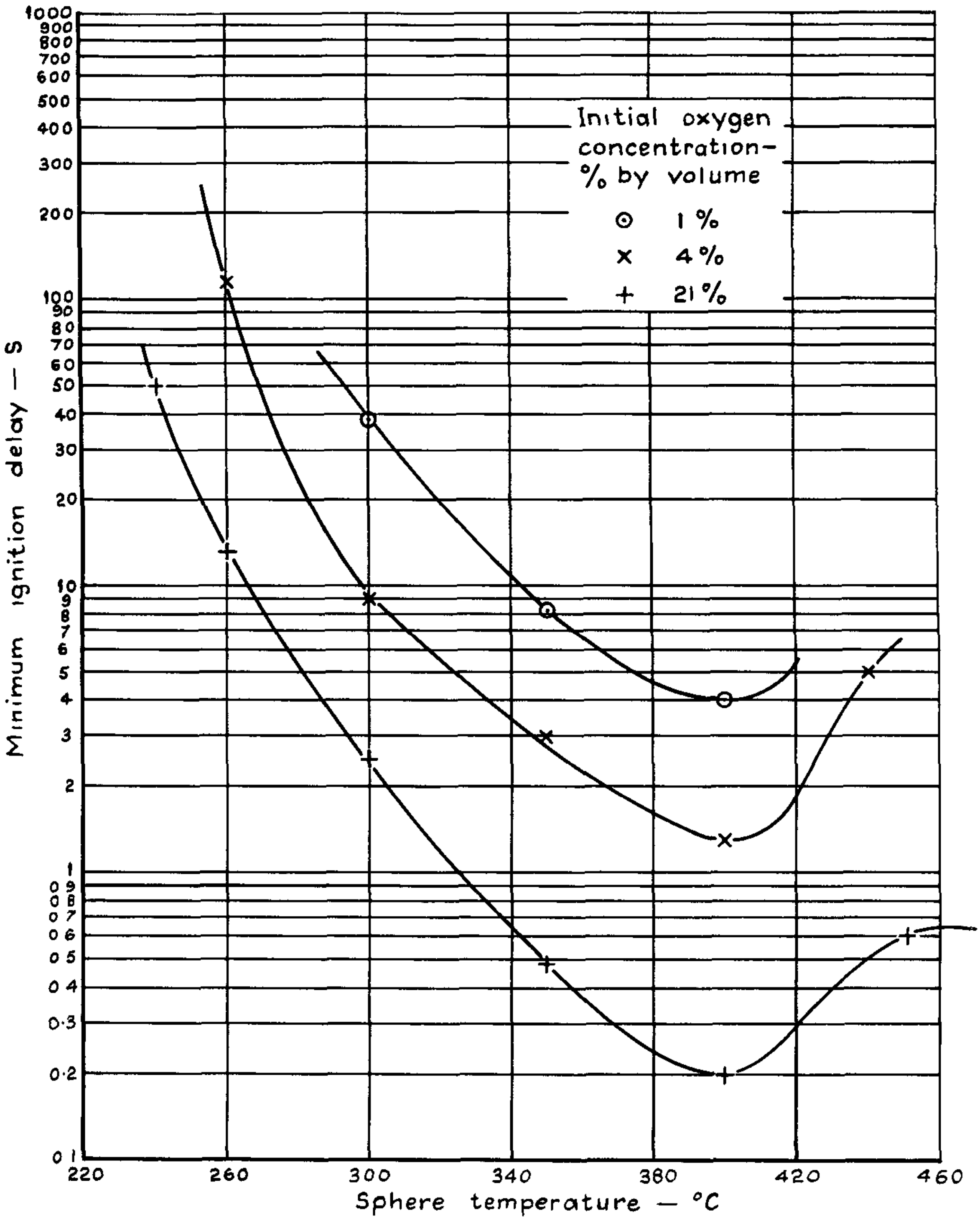

Fig. 8 Variation of minimum ignition delay time with sphere temperature and oxygen concentration in uniformly heated sphere

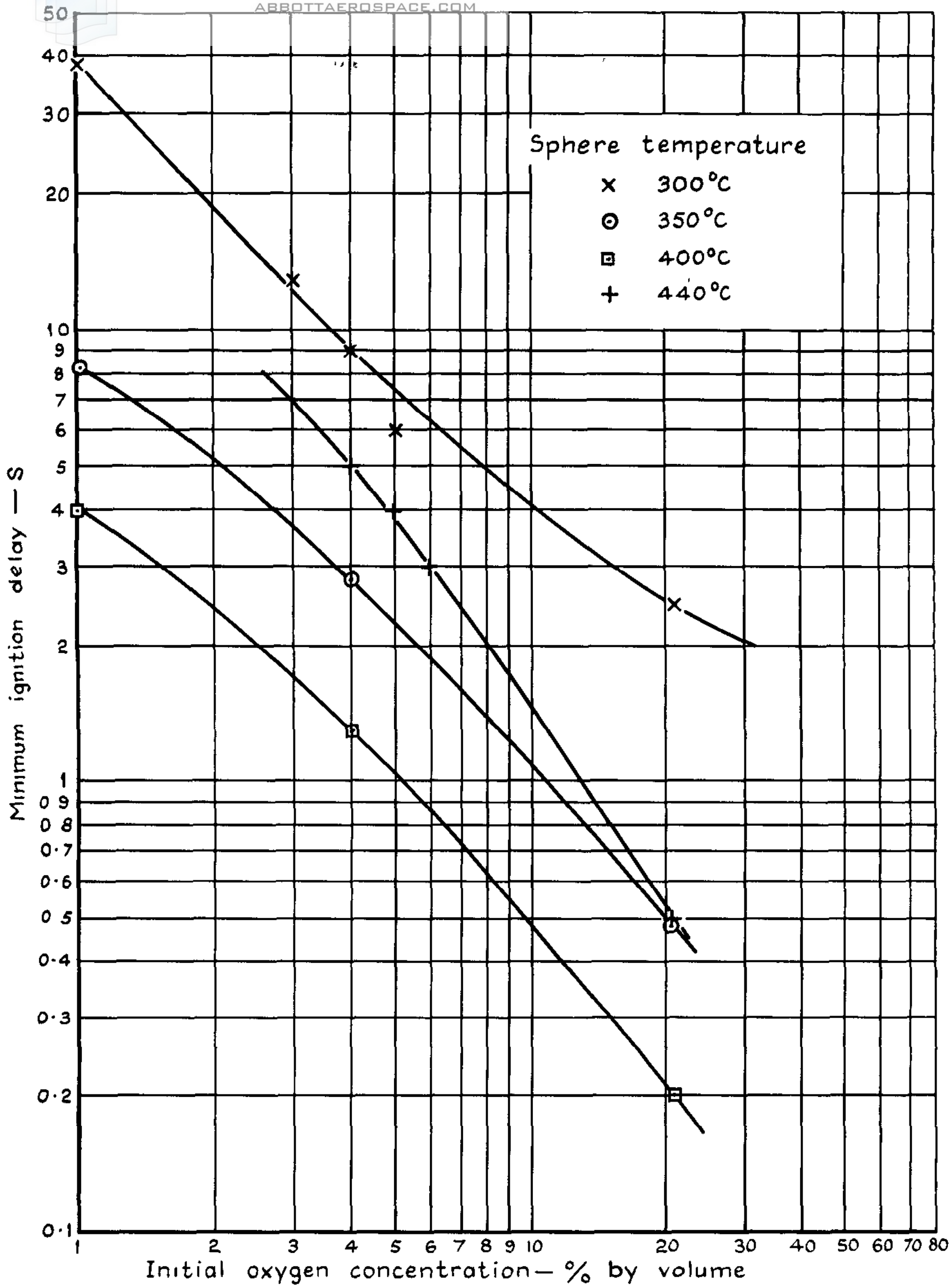

Fig. 9 Variation of minimum ignition delay with oxygen concentration in uniformly heated sphere at various temperatures. Optimum fuel concentration

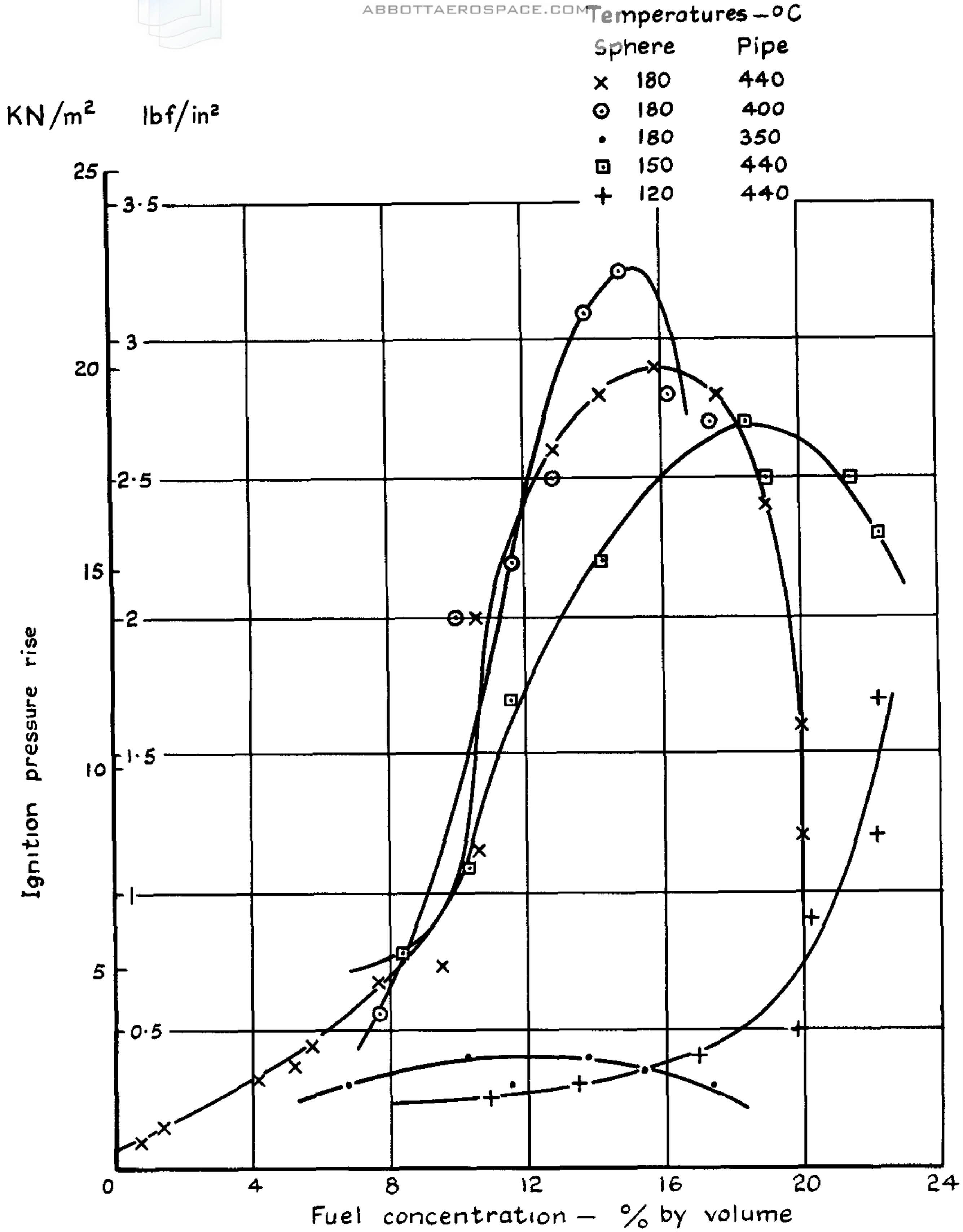

Fig. 10 Effect of fuel concentration on ignition pressure rise in sphere with heated pipe

Initial oxygen concentration of 5% by volume

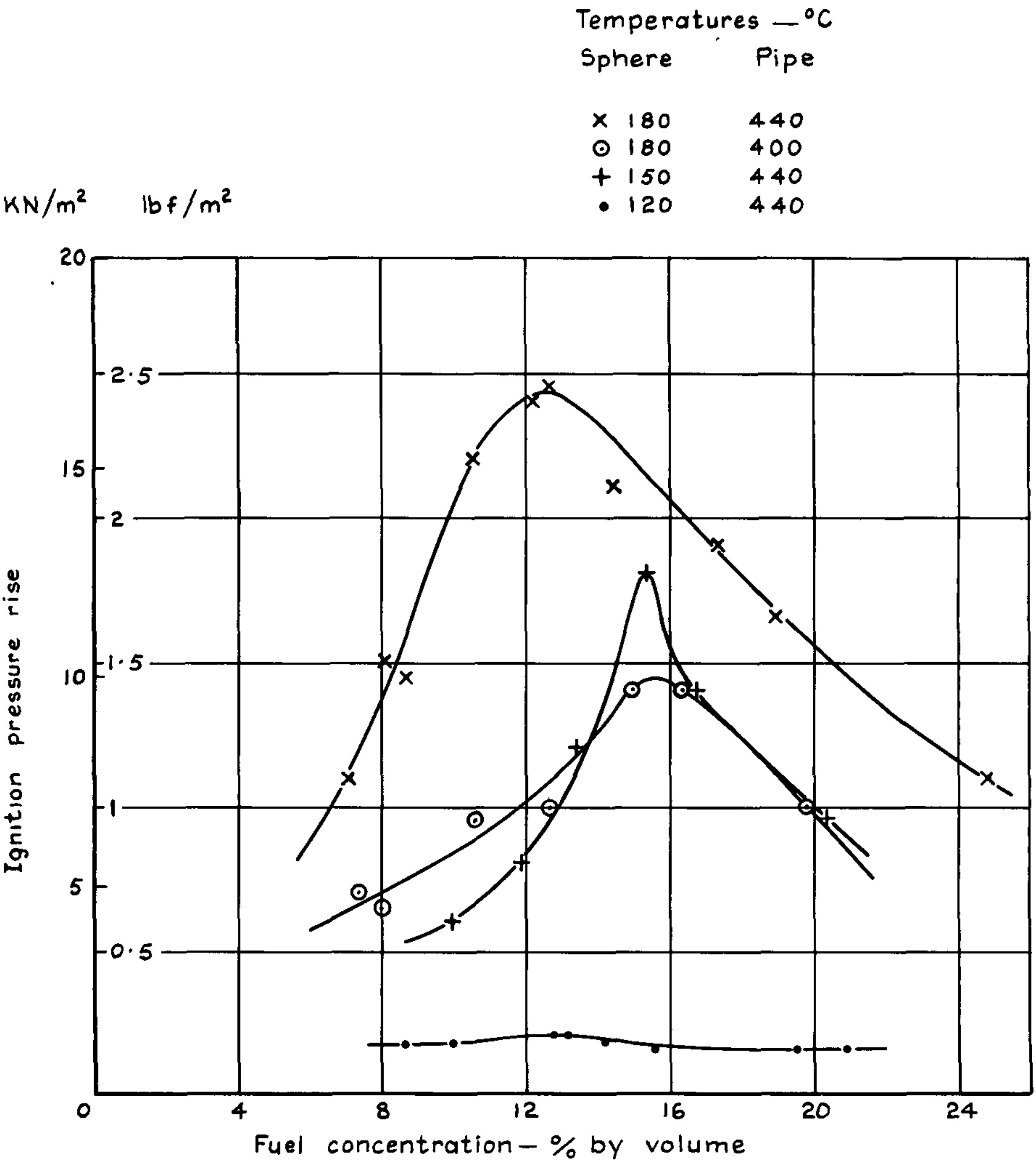

Fig. 11 Effect of fuel concentration on ignition pressure rise in sphere with heated pipe
Initial oxygen concentration of 4 % by volume

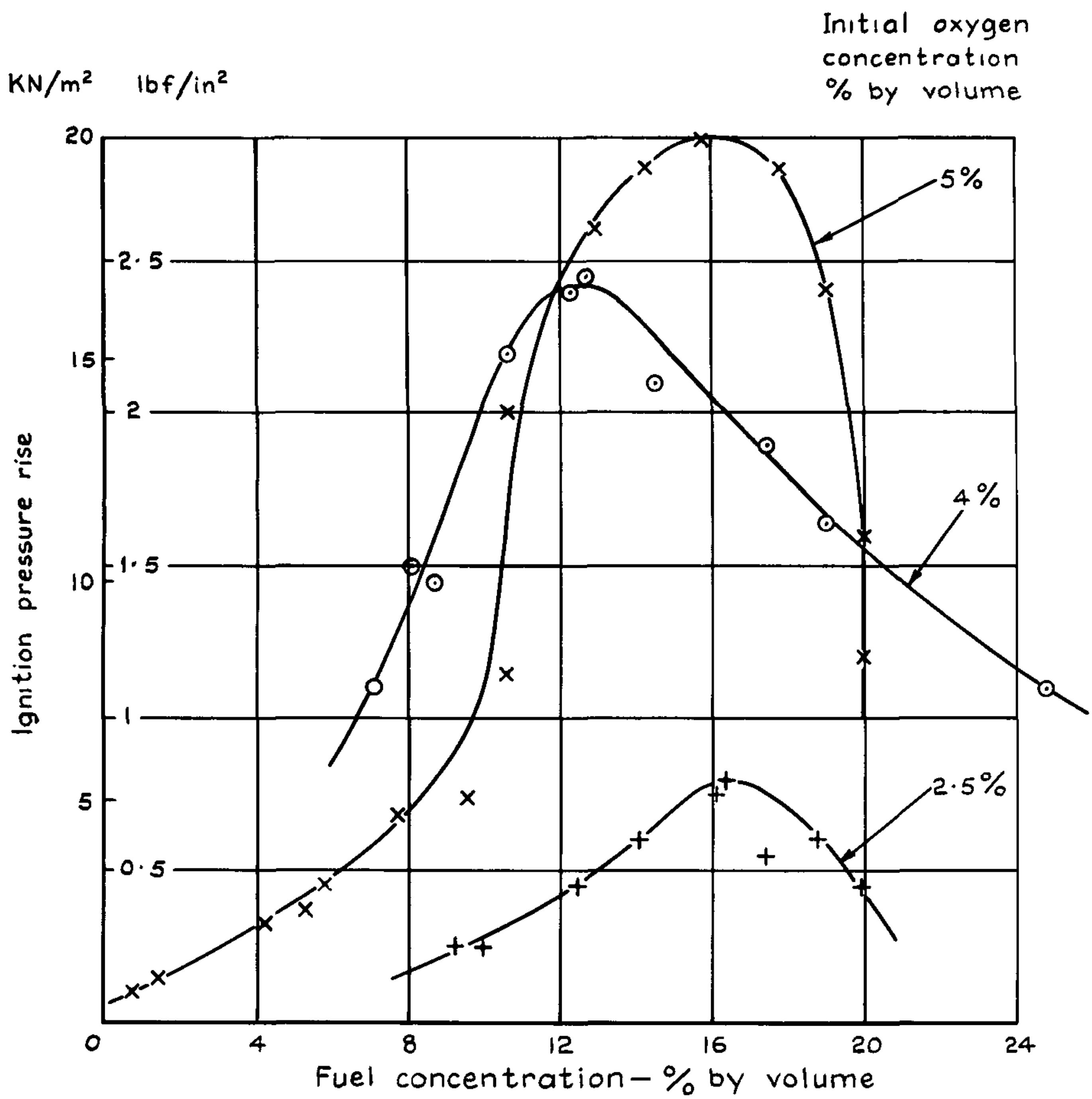

Fig. 12 Effect of fuel concentration on ignition pressure rise in sphere with heated pipe
Sphere temperature 180°C, pipe temperature 440°C

Printed in England for Her Majesty's Stationery Office by the Royal Aircraft Establishment, Farnborough Dd 502109 K 4

DETACHABLE ABSTRACT CARD

ARC CP No 1209
January 1971

Cansdale J T

SPONTANEOUS IGNITION OF AVTUR VAPOUR IN VARIOUS OXYGEN-NITROGEN MIXTURES

665 582
541 126
629 13 012 6
629 137 1
533 6 011 5
533 6 011 6

The spontaneous ignition of Avtur vapour in closed heated vessels was investigated to determine the maximum oxygen concentration required to limit ignition pressure rises to 6 9 kN/m^2 (1 lbf/in^2) The aim was to establish the maximum safe oxygen concentration to be permitted within the nitrogen filled heating ducts of the BAC Concorde Fuel System Test Facility

Tests were made firstly in a uniformly heated 0 46 m (18 in) diameter sphere, over a temperature range from 260°C to 440°C An oxygen concentration of less than 1% by volume was necessary to limit ignition pressures The effect of oxygen concentration on ignition delay time was also studied

Secondly ignition in the presence of a 0 15 m (6 in) diameter hot pipe in a temperature controlled 0 46 m (18 in) sphere was investigated at sphere temperatures up to 180°C

(Over)

ARC CP No 1209
January 1971

Cansdale J T

SPONTANEOUS IGNITION OF AVTUR VAPOUR IN VARIOUS OXYGEN-NITROGEN MIXTURES

665 582
541 126
629 13.012 6
629 137 1
533 6.011.5
533 6 011.6

The spontaneous ignition of Avtur vapour in closed heated vessels was investigated to determine the maximum oxygen concentration required to limit ignition pressure rises to 6 9 kN/m^2 (1 lbf/in^2) The aim was to establish the maximum safe oxygen concentration to be permitted within the nitrogen filled heating ducts of the BAC Concorde Fuel System Test Facility

Tests were made firstly in a uniformly heated 0 46 m (18 in) diameter sphere, over a temperature range from 260°C to 440°C An oxygen concentration of less than 1% by volume was necessary to limit ignition pressures. The effect of oxygen concentration on ignition delay time was also studied

Secondly ignition in the presence of a 0.15 m (6 in) diameter hot pipe in a temperature controlled 0 46 m (18 in) sphere was investigated at sphere temperatures up to 180°C

(Over)

and pipe temperatures up to 440°C. An oxygen concentration of less than 2.5% by volume was found to limit ignition pressures as required at all conditions considered.

It was concluded that in the BAC Test Rig, a 2.5% oxygen concentration would be low enough to prevent any undesirable ignitions.

and pipe temperatures up to 440°C. An oxygen concentration of less than 2.5% by volume was found to limit ignition pressures as required at all conditions considered.

It was concluded that in the BAC Test Rig, a 2.5% oxygen concentration would be low enough to prevent any undesirable ignitions.

C.P. No. 1209

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London WC1 V 6HB
13a Castle Street, Edinburgh EH2 3AR
109 St Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
50 Fairfax Street, Bristol BS1 3DE
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY
or through booksellers

C.P. No. 1209

SBN 11 470477 5