THE COLLEGE OF EARTH AND MINERAL SCIENCES

THE IGNITIBILITY OF BITUMINOUS COAL

by

Clement Seymour Finney
and
T.S. Spicer

SPECIAL RESEARCH REPORT NUMBER SR-18

June 15, 1960

ANNEX PENNSYLVANIA STATE UNIVERSITY

UNIVERSITY PARK, PENNSYLVANIA

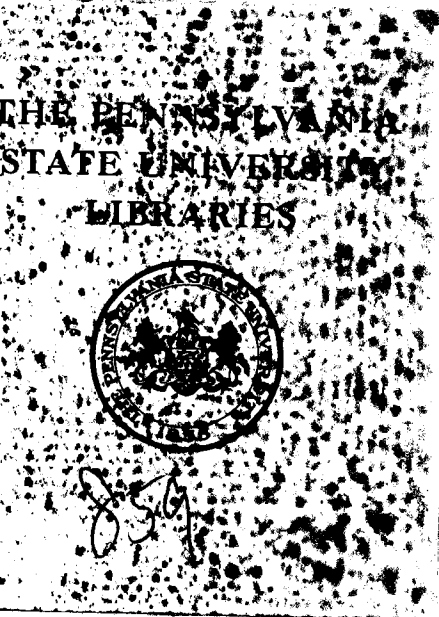# THE IGNITIBILITY OF BITUMINOUS COAL

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CLEMENT SEYMOUR FINNEY

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T. S. SPICER

An Investigation
conducted Under the Auspices
of the

COAL RESEARCH BOARD

of the

COMMONWEALTH OF PENNSYLVANIA

Special Report SR-18 transmitted herewith has been prepared by the Coal Research Section of the Mineral Industries Experiment Station. Each of the Special Reports presents the results of a phase of one of the research projects supported by the Pennsylvania Coal Research Board or a technical discussion of related research. It is intended to present all of the important results of the Coal Board research in Special Reports, although some of the results may already have been presented in progress reports. The following is a list of Special Research Reports issued previously.

SR-1	The Crushing of Anthracite	May 31, 1958
SR-2	Petrographic Composition and Sulfur Content of a Column of Pittsburgh Seam Coal	August 1, 1958
SR-3	The Thermal Decrepitation of Anthracite	September 15, 1958
SR-4	The Crushing of Anthracite with a Jaw Crusher	November 1, 1958
SR-5	Reactions of a Bituminous Coal with Sulfuric Acid	February 1, 1959
SR-6	Laboratory Studies on the Grindability of Anthracite ond Other Coals	April 1, 1959
SR-7	Coal Characteristics and Their Relationship to Combustion Techniques	April 15, 1959
SR-8	The Crushing of Anthracite with an Impactor-Type Crusher	April 25, 1959
SR-9	The Ignitibility of Bituminous Coal (A Resume' of a Literature Survey	May 4, 1959
SR-10	Effect of Gamma Radiation and Oxygen at Ambient Temperatures on the Subsequent Plasticity of Bituminous Coals	May 6, 1959
SR-11	Properties and Reactions Exhibited by Anthracite Lithotypes Under Thermal Stress	May 11, 1959

M. E. Bell, Director
M. I. Experiment Station

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SUMMARY

The ignitibility behaviour of eleven coals ranging in rank from low volatile bituminous to high volatile C bituminous has been examined by means of two laboratory tests. The ignition temperatures of dusts ranging in size from -60+200 to -325 mesh (U. S. Sieve Series) were determined in oxygen and in air using the Godbert inflammability apparatus, in which 0.2 gram of coal was blown downwards through a heated, vertical ignition tube using 2000 cc. of gas at a pressure of 12" mercury. The crossing-point temperatures in oxygen of 3.0 gram samples of the -60+200 mesh coals were obtained with a Setchkin Ignition Apparatus for solids. In this test the temperature/time history of a coal was compared with that of the preheated oxygen with which it reacted under the standard conditions of the test. The crossing-point temperature was that at which the temperature/time curves of coal and oxygen intersected.

No correlation between the volatile content of the coals and either their ignition point temperatures in air or oxygen, or their crossing point temperatures in oxygen, was found. Results with the inflammability apparatus showed, however, a definite decrease in ignition temperature with decrease in particle size.

The following conclusions were drawn from the study:

(1) The ignitibility of a bituminous coal is determined not by its total volatile content, but rather by the surface properties of both the original and partially charred or carbonised particles.

(2) Differences in the ignitibility of the bituminous class of coals are less marked than has sometimes been supposed; provided that sufficient oxygen is available, bituminous coals over a wide range of volatile contents will ignite at much the same ambient temperature when projected into a suitable hot environment in the size consist used for pulverised fuel firing.

(3) The ignitibility of a cloud of coal dust particles increases as the particle size decreases. Particle size is more important in the ignition process than is the influence of volatile content.

(4) In a dust suspension consisting of particles of different sizes, ignition commences with the finer particles and spreads throughout the whole mixture. As long as an adequate proportion of superfines is present, quite a percentage of coarse material can be tolerated.

(5) The experimental evidence supports the "thermal" or "direct oxidation" theory of ignition, which maintains that ignition occurs directly, without the distillation of volatile matter.

I   Introduction

General Statement of the Problem

Despite the large amount of fundamental research which has been carried out into the combustion of solid, liquid and gaseous fuels, the control of combustion processes in industry and the design of the equipment necessary for efficient burning to take place have always been very much branches of an industrial art rather than of an exact science. This has been especially true of the utilization of coal, a substance so heterogeneous and complex in character that all too little is known about its chemical and physical composition.

As a rough generalization it can be said that the tests used to evaluate coal fall into two main groups. On the one hand there are those which attempt to ask basic questions about the nature of the material; on the other hand there are those empirical determinations which try to predict how it will behave in use. Needless to say, if there existed a complete understanding of what coal is, then its behavior under any given conditions of industrial use could be forecast with some certainty. The fact is, however, that even with such modern techniques as electron microscopy, x-ray diffraction, absorption spectroscopy and many other powerful analytical methods employed by the physical and organic chemist, a great deal remains to be discovered about the constitution of coal. Thus, the supplier, the user, and the designer of combustion equipment have had to rely to a great extent upon information gained from a variety of empirical and hence carefully standardized tests. Over the years such information has been allied with actual plant operating results to provide a wealth of experience from which the present efficient methods of burning a wide range of coals have emerged. So far, however, industry has waited in vain for comparatively simple and speedy laboratory tests which will accurately predict combustion behavior and thus eliminate lengthy and expensive full-scale plant trials.

It is usual to regard the combustion of a solid fuel as occurring in two main stages, the ignition phase and the burning out phase.

During the ignition of bituminous coal decomposition takes place by
which a series of gases and vapors is evolved, a more or less reactive,
solid, carbonaceous residue being left. Despite the fact that the
changes which take place during ignition must greatly affect the
following combustion process, much more is known about the burning
out of the carbon residue than about the phenomena of ignition. Thus,
although there is widespread agreement that a great need exists for
a method by which industry could forecast the relative tendency of
its coals to ignite, no completely satisfactory test capable of being
correlated with industrial operation has yet been developed.

The Definition of Ignitibility

To the industrial user of bituminous coal the term "ignitibility"
is normally taken to mean the ease with which the fuel may be brought
to a state of visible, sustained combustion, and he is interested in
this property only to the extent that its evaluation will enable him
to predict just how a given coal will behave in storage or in the
furnace. Now, to the fuel engineer, the process of "visible, sus-
tained combustion" is accompanied by flame or glow. However, cases
have been quoted in the literature where visible, self-supporting
combustion without flame or glow has occurred. Jenkins and Sinnatt[1],
for instance, describe a type of slow "partial" combustion which
occurred when a small gas flame was applied to the apex of a conical
heap of finely powdered coal in the laboratory. Neither glow nor
flame appeared, but small amounts of smoke were emitted and the
travel of a combustion zone from apex to base could be followed by
observing the color change from brown, powdered coal to the black,
oxidation product.

It will be obvious in the light of such phenomena that any broad,
general definition of ignitibility cannot be based on the appearance
of flame or glow, since these are not necessarily concomitants of
either ignition or even combustion. Thus the formal definition agreed
upon by Subcommittee XVI on Ignitibility of Coal and Coke, of ASTM
Committee D-5 on Coal and Coke (now inactive), states that: "The
ignitibility of a fuel is that characteristic which determines the

ease with which the fuel may be brought to a condition of self-supporting, active oxidation. The ignitibility is governed not only by the inherent chemical characteristics of the fuel that determine its rate of oxidation at various temperatures, but also by the physical characteristics of the fuel and its surroundings that determine the rate at which it can be heated. Among these physical characteristics are (1) the size of the pieces of fuel, (2) the specific heat of the fuel, (3) the thermal conductivity of the pieces and of the aggragate, (4) the rate at which the oxygen or air is brought into contact with the fuel, and (5) the rate of heat loss to the surroundings. Chemical and physical changes, such as the melting and decomposition of bituminous coal, may occur as the fuel is heated."

This definition recognizes several important and fundamental features of ignitibility which have not always been appreciated in the past. However, by using as its criterion "the ease with which the fuel may be brought to a condition of self-supporting, active oxidation" it restricts consideration to the early stages of an oxidation process, as pointed out by Nelson and Pilcher. (3) This limitation is in accord with the views expressed by C.R. Brown (4) who in a detailed review of the phenomena of ignition states that, although ignition must proceed continuously until active or visible combustion occurs to complete the process, ignition cannot be considered as sunonymous with the appearance of flame or flow since these occur at the end rather than the beginning of the process. Rosin and Fehling, (7) on the other hand, in their report upon the ignition of coal on grates, state that whilst at low temperatures ignition is initiated by the exothermic reactions of oxygen adsorption and auto-oxidation, these reactions do not occur with sufficient velocity to result in combustion except under such conditions as those of unsatisfactory coal storage where heat dissipation may be poor. The process of ignition of a bed of particles in their apparatus is described as occuring in the following invariable sequence for all ranks of coal: (a) thermal decomposition; (b) development of glowing nuclei at the surface of

the particles; (c) sudden ignition of the volatile matter, leading to
the formation of a well developed gas flame. They consider that the
slow oxidation reactions do not accelerate until gaseous constituents
are evolved, and that the glowing nuclei are the result of surface
activation caused by the formation of semi-coke. They picture ignition
as a process in which thermal decomposition is of importance as the
agency by which coal is split up into "a spontaneously igniting solid
residue and an easily igniting volatile fraction". And they go on
to state that: "The ignition reaction begins with the nascent semi-
coke and ends with the inflammation of the volatiles."

The divergence between the concepts of Rosin and Fehling and
those of Brown is typical of the literature on ignition, and can be
explained by the different purpose of each investigation. The two
former workers were concerned with the promotion of combustion, whilst
Brown looked at ignition from the viewpoint of fire hazard. In
studies where the main interest is in fire prevention the greatest
emphasis must necessarily be upon phenomena occuring early in the
process---in the slow reactions which give rise to spontaneous heat-
ing. Such emphasis may be greatly misplaced, however, if applied to
the rapid, high temperature processes which go on in industrial
furnaces.

In the light of previous paragraphs, the conclusion must be
reached that, admirable as the formal A.S.T.M. definition may be for
broad general purposes, it is too restrictive to be applied in the
present investigation. The definition which will be adopted, there-
fore, is as given by the A.S.T.M. with the exception that "combustion"
will be substituted for "oxidation" as the last word of the first
sentence. The latter will now read, "The ignitibility of a fuel is
that characteristic which determines the ease with which the fuel
may be brought to a condition of self-supporting, active combustion."
Combustion is used here to define a reaction in which light as well
as heat is produced, i.e. a reaction accompanied by flame or glow.

The Concept of Ignition Temperature

There is nothing in the A.S.T.M. definition to indicate just how
the property of ignitibility should be determined, but many workers

in the field have postulated the occurrence of a critical temperature in the ignition process beyond which autogenous combustion must certainly occur. This critical temperature has been variously defined and determined(5), but whether it does in fact wholly represent the ignition or combustibility characteristics of a fuel has been a matter of considerable controversy.(6) Most workers seem now to be agreed, however, upon the following points:

(1) Coal and atmospheric oxygen combine at all temperatures, and there is thus no well defined ignition temperature below which combustion reactions do not occur.(3)(7)(8)(9)

(2) The concept of ignition temperature can best be expressed as that temperature in the fuel at which the heat produced by the reactions causing ignition is just greater than the heat dissipated to the surroundings.(4)(7)

(3) The ignition temperature thus defined is not an inherent property of the fuel, and any test by which it may be measured should be thought of as a purely empirical determination.(7),(8),(10)

(4) Provided that test conditions are carefully chosen and rigidly controlled, reproducible values for ignition temperature can be obtained which may be of value for classification purposes. (8)(10)

It has already been stated that many doubts have been raised as to whether the ignition temperature does in fact characterize the ease with which a fuel will ignite and burn. Rosin and Fehling (7) point out that what matters in the case of combustion is not the magnitude of the ignition point but rather the time required to reach it. They cite the case of hydrogen which, having a comparatively high ignition temperature (572°C), should have relatively poor ignitibility. In actual fact, however, hydrogen ignites with great rapidity because it possesses a thermal conductivity some six or eight times higher than other fuel gases.

Methods of Determining Ignition Temperature

The methods used to determine ignition temperatures have been grouped into three main classes:

Constant Temperature Methods

A series of runs is made, in each of which the furnace tempera-

ture is maintained at a set figure and the coal quickly introduced.
If, after a short period of "ignition lag" the coal does not reach
its ignition temperature - this being determined by the appearance
of glow, flame, or accelerated temperature rise - the test is repeated
with fresh specimens at progressively higher temperatures until, by
a process of trial and error, the lowest "temperature of ignition"
is obtained. Illustrative of this group are the methods used by
Phillips (11), and Moore. (13)

Rising Temperature Methods

The coal sample is placed in a furnace or apparatus the tempera-
ture of which is raised at a constant rate. Oxygen or air is passed
through the sample, or over the surface at a known rate, and the
temperature of the coal and of the heating apparatus is measured.
Various criteria of ignition have been used with this method. Brown(15)
took as the ignition temperature the point of inflection in the curve
showing the difference between specimen and furnace temperature
plotted against time. Swietoslawski, Roga and Chorazy (16) used the
intersection of the projections of the coal temperature curve before
and after the rapid increase in temperature. Wheeler (17), Parr and
Looms (18), Nelson et al (8), Sebastian and Mayers (19), Sherman et al
(10) took the point at which the coal sample and furnace temperature-
curves crossed when plotted against time. Kreulen's (20) criterion was
the intersection of the sample temperature-curve with a curve parallel
to the apparatus temperature-curve but lying 6°C above it.

Adiabatic Methods

In these methods the heat loss from sample to furnace is prevented,
and thus all the heat produced during the oxidation process goes to
raise the temperature of the reactants. The best known adiabatic
method is perhaps that developed at the Coal Research Laboratory
of the Carnegie Institute of Technology. (21) A modification of the
original Coal Research Laboratory test described by Sebastian and
Mayers (19), the latter method enabled adiabatic conditions to be main-
tained in the system whilst self-heating rates between 3 and 25°C per
minute were determined. Davis and Byrne in their work on spontaneous

heating (22) used what they termed an "adiabatic calorimeter" in which the temperature of a surrounding oil bath was automatically made to follow that of a sample, while oxygen preheated to the oil-bath temperature was passed through the coal. It was claimed that the temperature of the bath could be controlled to within 0.013°C of the coal temperature.

Critical Examination of Ignitibility Tests

No standard A.S.T.M. method for determining ignitibility exists, and it is doubtful whether any single, simple and reliable laboratory test can be developed which will allow an accurate forecast to be made of the ease with which a bituminous coal will ignite under the many conditions of industrial burning. As the A.S.T.M. definition makes clear, the property of ignitibility is not one which can be characterized solely by the chemical and physical properties of coal, different as these may well be. The physical environment in which the phenomena leading to ignition and combustion take place must necessarily have a profound influence upon any attempt to determine the property and to assign to it some precise numerical value. It seems, therefore, unrealistic to suppose that any meaningful index can be obtained which will correlate the behavior of a coal under laboratory conditions with its peformance in both stoker and pulverized fuel firing.

In considering the various tests which have been carried out to determine ignitibility, it is necessary to bear in mind that many of them were done for purposes quite different from those which motivate the present investigation. It is therefore pertinent to examine in closer detail two of the most promising and widely known of the established techniques, and to attempt an assessment of their value in the work projected.

The Coal Research Laboratory Test

As originally developed (19), the Coal Research Laboratory test gave values for the temperatures at which a coal sample in a stream of air or oxygen under adiabatic conditions began to self-heat and attain a specified rate of temperature increase. The apparatus is shown in

Figure 1. The test measures the sample temperature and the rate of temperature rise at the moment when sample and furnace temperature are equal, in other words, at the "crossing point", and it is presumed that under such conditions the rate of temperature rise is a measure of the reactivity of the coal. Reactivity indices T15 and T75 are reported, these being the crossing points or ignition temperatures when the self heating rates are 15°C and 75°C per minute respectively. The values of the reactivity indices are critically dependent upon the determination of the instant when the readings of the sample and furnace thermocouples are identical - that is, when there is zero heat flow between the coal sample and its environment.

In the original procedure it was necessary to use both air and oxygen because information could only be obtained over a restricted range of temperature when working with a single oxygen partial pressure. Furthermore, the effect of this partial pressure on the self heating rates required a simplifying assumption in calculating the reactivity indices. A modified apparatus was therefore developed (21) whereby adiabatic conditions could be maintained in the system and self-heating rates from 3° to 25°C per minute determined at any oxygen partial pressure from 0 to 1 atmosphere. This made it possible to obtain reactivity indices without any assumptions regarding the effect of the partial pressure of oxygen.

It was found (24) that the Coal Research Laboratory test yielded indices which correlated well with the dry, ash-free (d.a.f.) volatile content of the coal. Figure 2 shows T15 and T75 plotted against the percentage of volatile matter (d.a.f. basis) for 68 coals ranging in volatile content from 3.5% to 48.2%. The equations for the curves are:

$$T15 \pm 8.0°C = 229.7 - 0.01041 (V -27.5)^3$$
$$T75 \pm 11.4°C = 272.1 - 0.01338 (V -27.5)^3$$

The adiabatic method gave equations as below:

$$T15 \pm 8.1°C = 229.7 - 0.01022 (V -27.5)^3$$
$$T75 \pm 11.2°C = 285.9 - 0.01282 (V -27.5)^3$$

It can be seen that, over the range of volatile contents

INDICATING FLOW-METER

GLASS REACTION TUBE

WATT METER

220 V.

VARIABLE TRANSFORMER

FURNACE THERMO-COUPLE

INSULATION INSULATION

TAP WATER

NEEDLE VALVE

COAL SAMPLE 1" HIGH

COPPER FURNACE

POTENTIO-METER

AIR

INSULATION INSULATION

FLOWMETER

MANOMETER

THERMO-COUPLE SWITCH

SAMPLE THERMOCOUPLE

GLASS TEE

DRIERITE
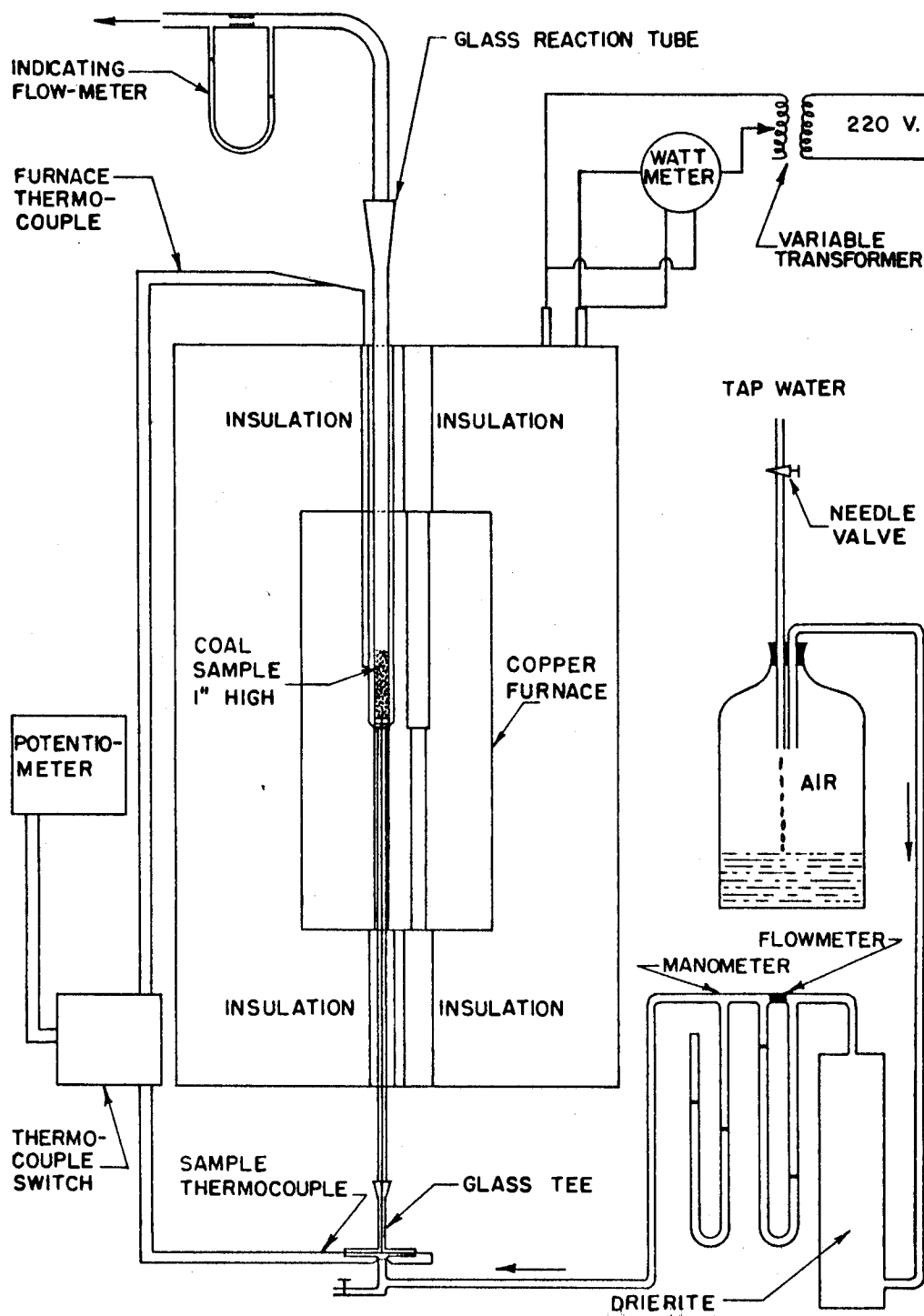
DIAGRAM OF C. R. L. IGNITION APPARATUS

(SHERMAN, PILCHER AND OSTBORG[10])

Figure 1
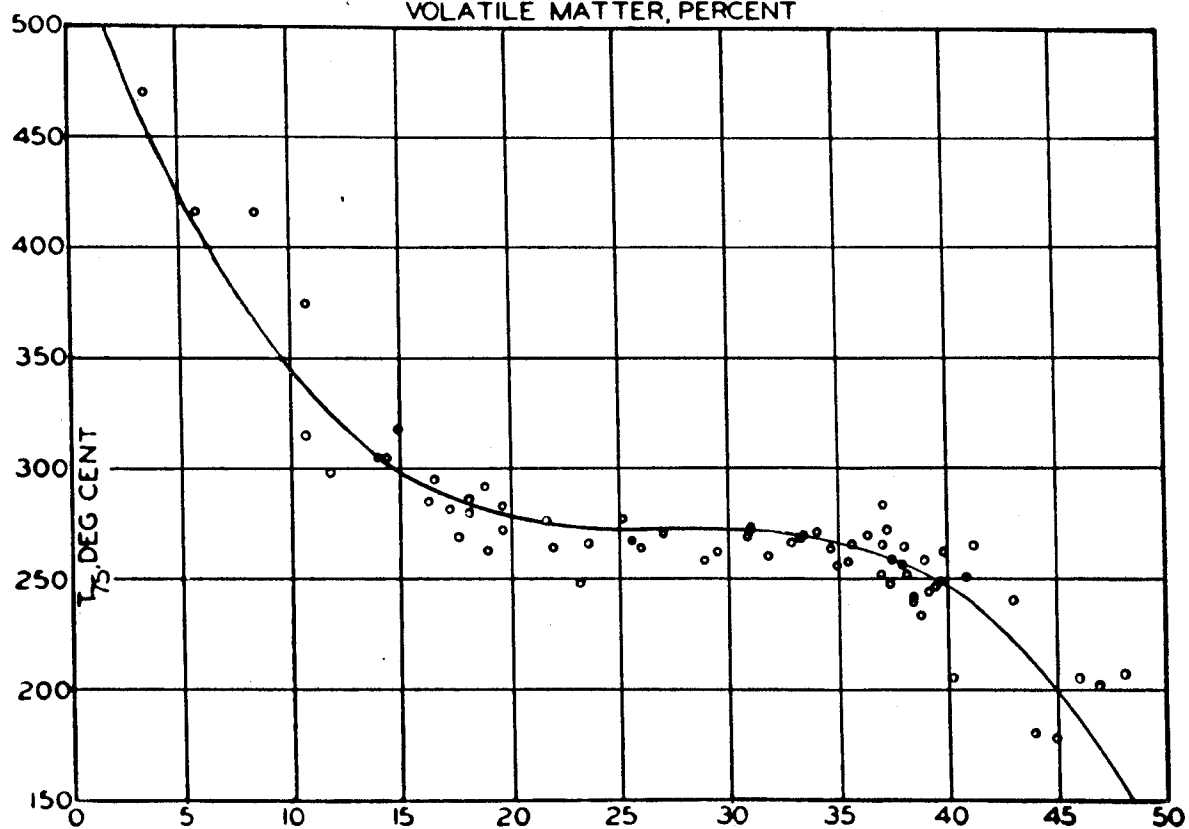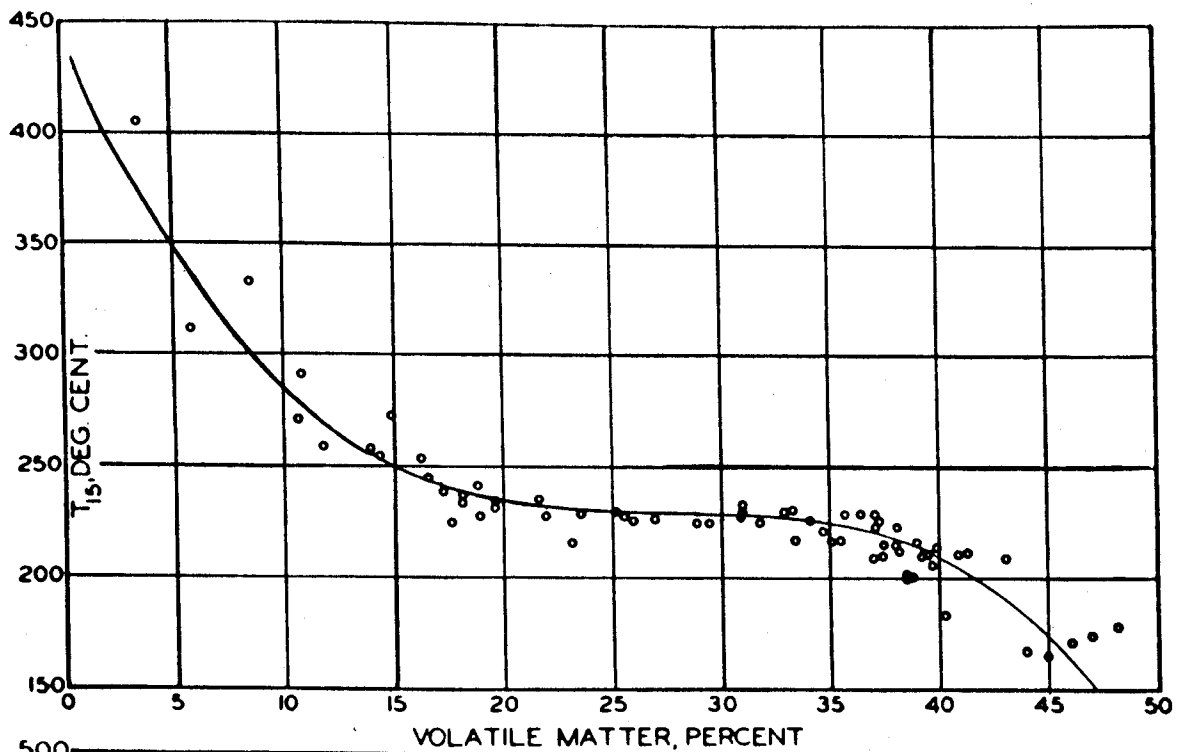
REACTIVITY INDICES T_{15} AND T_{75} FOR COALS AS A FUNCTION
OF VOLATILE MATTER CONTENTS ON DRY ASH-FREE BASIS (ORNING[24])

Figure 2

associated with bituminous coals, e.g. 17-37%(d.a.f.), there is little variation of reactivity with volatile content. Furthermore, the fact that the equations for T15 and T75 give the reactivities to within about ±8°C and ±11°C respectively, while the accuracy of the test itself is ±2°C, indicates that factors other than volatile content are responsible for the variation in the reactivity indices.

Inflammability Tests

The term "inflammability" has been used because here the criterion of ignitibility is the appearance of flame. The method belongs to the constant temperature class and is exemplified by the tests described by Phillips (11) and Lambie (14). In the case of the former, approximately 0.2 gm of -325 mesh coal is blown through a heated, vertical electrical furnace and past a hot, copper coil by a puff of 2 psig air. The furnace temperature is progressively increased until a flame results, when the ignition temperature is reported to the nearest 10°C.

In the work by Lambie, a vertical ignition tube is heated by an electric furnace to a temperature of 700°C. Varying proportions of -200 B.S. mesh coal and calcined Fuller's earth are then used to form mixtures, 1 gram samples from which are blown by oxygen at a pressure of 12" Hg through the ignition tube. The minimum amount of Fuller's earth necessary to prevent good ignition is determined, and the inflammability of the fuel is reported as the ratio by weight of the Fuller's earth to fuel in this limiting mixture. The ratio is termed the Godbert number. The criterion which best defined "good ignition" was the appearance of a white flame which just reached the open end of the ignition tube.

Discussion

Although it has been stated (3),(12) that the Coal Research Laboratory reactivity indices express a basic and inherent property of the fuel, the fact remains that the behavior of a sample in this test has not yet yielded information of much value to the user of coal or the designer of combustion equipment. On the other hand the much more empirical "inflammability" tests seem to have been of more use.

Lambie (14) discusses work by the Fuel Research Station in Britain
which showed a general relationship between the performance of pulver-
ized fuels in a Lancashire boiler and their inflammability in the God-
bert type apparatus. He also states: "It would appear that the com-
bustibility of pulverized peat in a given combustion chamber can be
roughly correlated with the combustibility as indicated by the Godbert
apparatus." Of the ignition temperatures obtained by the test which
Phillips describes, he writes that they have been found to agree
reasonably well with actual results in operation.

Despite its excellent theoretical basis, the C.R.L. test yields
indices which have not yet been correlated with industrial practice.
The test is, of course, carried out under conditions far remote from
those to which lump or pulverized coal is subjected during burning.
Consider the behavior of coal dust which is shock-heated to the extent
that the periods of pre-ignition, volatiles expulsion and combustion,
and combustion of solid carbonized residue are all compressed into
an interval of time which can be measured in fractions of a second.
How is this behavior to be assessed in terms of a test in which the
coal temperature rises for instance to 325°C over a period of say, 25
minutes? The rate of volatile release from a cloud of airborne
particles, the ignition properties of this volatile matter and of
the partially carbonized coal surface must surely be of real importance
in pulverized fuel firing. Yet they are phenomena of which the C.R.L.
test takes no account. The inflammability tests on the other hand
do attempt to simulate practical conditions, and at the present stage
of knowledge must be preferred as a measure of the propensity of
powdered fuel to ignite.

The Importance of Thermal Decomposition in the Ignition Process

It is somewhat surprising that more attention has not been paid
to the important aspects of thermal decomposition in connection with
ignitibility. It has long been known that high volatile coals ignite
and burn in lump and powdered form more easily than do low volatile
materials. Indeed the C.R.L. ignitibility test has probably not been
more widely used because the reactivity indices can be calculated with

reasonable accuracy from the easily determined volatile contents. However, Ceely and Wheater (12) concluded that the composition of the volatile matter was important and that the ignition and combustion characteristics of coal could not be closely correlated with the quantity of volatile matter alone. They also stated that the C.R.L. reactivity index, T15, does not of itself accurately predict the ignition characteristics of all solid fuels, and came to the tentative conclusion that it will adequately forecast the ignition behavior of only those fuels which do not evolve appreciable combustible volatile matter at low temperatures. The fact that T15 does not adequately predict the ignition characteristics of all fuels can be deduced from the graphs published by Orning (24) (see Fig. 2), which show little variation of either T15 or T75 within the range 17 - 37% V.M. (d.a.f.). Orning himself pointed out that, since the precision of the test was much higher than the accuracy of the equations correlating reactivity indices with simple volatile content, there must be other factors responsible for variations in the indexes. From laboratory observations made when igniting lump coal on small grates by means of radiation from above, it would seem that the reactivity of the partially coked or charred surfaces must be important. Carman, Graf and Corey (25) state that under such conditions the exposed surfaces of bituminous coals are devolatilized and coked or charred, and that the surfaces of the coke or char begin to glow before ignition of the volatile matter occurs. Ignition and flaming of the volatile matter usually follow quickly and result in rapid spread of ignition and burning across the entire bed top. It may be noted that the sequence described by Carman et al, viz. thermal decomposition, appearance of glowing nuclei on the particle surfaces, and sudden ignition of the volatile matter, is identical with the order of events described by Rosin and Fehling (7) and discussed previously. Carman et al also state, in discussing the mode of ignition of a solid fuel particle, that although the temperature range of thermal decomposition of bituminous coals overlaps that of ignition of the coke formed, immediate ignition of the volatiles at the surface does not necessarily follow even at that point on the surface where

ignition of the solid particle has occurred, since the ignition temperatures of the decomposition products are, in general, higher than those of the highly reactive coke surface. The evolved gases will be quickly ignited, however, by the rapid temperature increase at the coal surface after the onset of initial glowing. In discussing the influence of the ignition of volatile matter on the ignition of bituminous coal, Seyler and Jenkins (26) noted that their tests showed no indication of breaks when the rate of heat evolution was plotted against the reciprocal of the absolute temperature. They point out that if ignition of the coal were caused by inflammation of the volatile matter, a change of slope of the Arrhenius Line would occur. However, they warn that their particular tests may not have been taken to sufficiently high temperatures, since in the case of anthracite a distinct break in the Arrhenius Line occurred at a temperature near to the ignition point.

It should be noted that the results of the three investigations discussed in the previous paragraph were obtained on small scale equipment, or with laboratory apparatus, where conditions of ignition are very different from those of industrial furnaces. In the case of chain grate or spreader stoker firing, for example, flames from the actively burning bed would doubtless ignite the gases from the freshly charged, decomposing coal. It is therefore likely in practice that general ignition of the bed results not only from ignition of volatile matter by the glowing surface of the charred or coked particles, but also from ignition of these volatiles by established flames. In the case of pulverized fuel firing it is probable that the phases of pre-ignition, volatiles expulsion, ignition and combustion of volatile matter and of solid residue occur simultaneously at different points in the furnace according to the size of the coal particles and the environmental conditions.

It has been seen that whilst the d.a.f. volatile content of a coal may provide a valuable index of its ignitibility behavior, the total volatile content is not of itself an infallible criterion. As already suggested, therefore, the ignition properties of the sur-

face of the decomposing coal and of the decomposition products must
be important, as must the temperature at which volatile evolution
commences. A search of the literature, however, indicates that
extremely little appears to be known about the combustibility of
volatile matter, for example. Obviously there are difficulties in
studying the release and ignition of volatiles, especially in the
case of pulverized coal where the time periods involved are exception-
ally small. Such difficulties may account for the fact that, although
the changes which occur during the ignition and combustion of volatile
matter considerably influence the succeeding stages of pulverized
fuel combustion (27),much more is known about the combustion of the
residual coke particles than about the phenomena associated with the
primary ignition process. In connection with the latter, an apparatus
has been described by Finch (28) which gives a controllable supply of
volatile matter for more than one hour. The volatiles were ignited
by an electrically heated spiral to give a diffusion flame in air,
and the ignition temperatures of the volatile matter from both coal
and char were measured. Differing results were obtained according to
the material from which the igniting spiral was made. Platinum gave
ignition temperatures considerably lower than tungsten and nichrome,
for example. Results with nichrome were reproducible to within $10^{\circ}C$,
and the ignition temperatures of volatiles from two chars were lower
than those of the volatile matter from the parent coals.

Specific Statement of the Problem

No fully satisfactory test for ignitibility yet exists and it
is doubtful whether a single, simple laboratory test can be developed
which will be of value in predicting the ignitibility of coal when
fired in both pulverized and lump form. Of the techniques used in
the past, the "crossing point" methods and the "inflammability"
methods appear to have been most widely favoured, the latter having
so far seemed to offer the better possiblilty of correlating igni-
tibility behavior in the laboratory with that of pulverized fuel
in practice. The purpose of this research is to apply both methods
of investigation to coals of widely differing properties in an effort

to obtain consistent values for the ignitibility of pulverized coal;
to determine whether, as has been reported by other workers, the values
thus obtained can be correlated with the total volatile content of the
coal, and to discover whether the results obtained by one technique
can be correlated with those of the other.

II   Procedure of the Investigation

Coal Samples

Eleven different samples of -60 mesh coal were obtained from Bituminous Coal Research, Inc. of Pittsburgh. Four of these coals were from Pennsylvania seams, three from West Virginia, two from Illinois, and one each from Ohio and Indiana. In terms of A.S.T.M. rank, the coals range from the low volatile material of the Upper Kittanning and Pocahontas No. 3 seams to the high volatile C of the Indiana No. 5 seam. The coals are identified in Table I, and characterised in Tables II, III, and IV. All the information contained in Tables I to IV was supplied by Bituminous Coal Research, Inc., with the exception of the ultimate analyses of coals 5, 8, 12, 13, 15, 16 and 18. Because this data was not available, representative values published by the Bureau of Mines have been given.

A Ro-tap sieve shaker was used to obtain the various size fractions, and U.S. Standard Sieves were used throughout.

Apparatus

Inflammability Apparatus

The type of apparatus used was originally developed by Godbert (29) at the Sheffield Laboratories of the British Safety in Mines Research Board. Similar apparatus has since been utilised to investigate the inflammabilities of American and Indian coal dusts (23) (30) (31), pulverised pitches (32), metal powders (33), and powdered plastics (34).

A schematic drawing of the apparatus is shown in Figure 3 and a photograph of the experimental set-up in Figure 4. The storage reservoir for oxygen or air was constructed from a two liter flask and was connected by means of 5/16" glass tubing to a suitable mercury manometer. To the outlet of the reservoir was attached a short length of 3/8" rubber tubing to which were fitted an electro-hosecock and a smaller manually operated hosecock.

The function of the electro-hosecock was to allow rapid and uniform release of air or oxygen from the reservoir, through the rubber tubing, and on through the glass connecting piece at the end

ANTI-SPLASH DEVICE

MERCURY RESERVOIR

AIR OR O_2 SUPPLY

2 LITER STORAGE RESERVOIR (O_2 & air)

ELECTRO HOSECOCK

HOSECOCK

24/40 S.T. GROUND JOINT

CONNECTING PIECE

VYCOR IGNITION TUBE

STAINLESS STEEL LINER

ELECTRIC FURNACE

THERMOCOUPLE BEAD

TO TEMP. CONTROLLER

POWER SOURCE
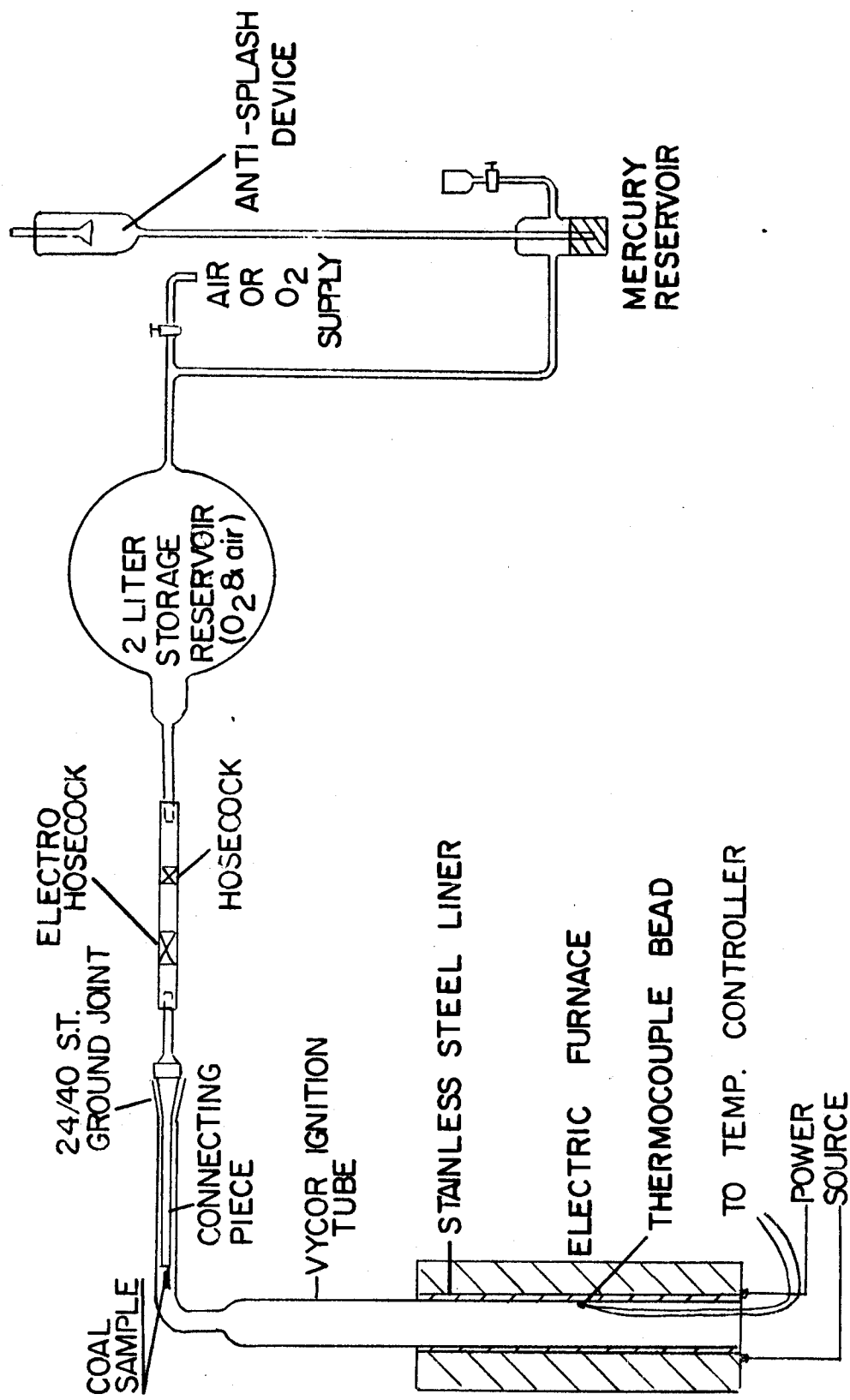
COAL SAMPLE

FIGURE 3   Inflammability apparatus (schematic).
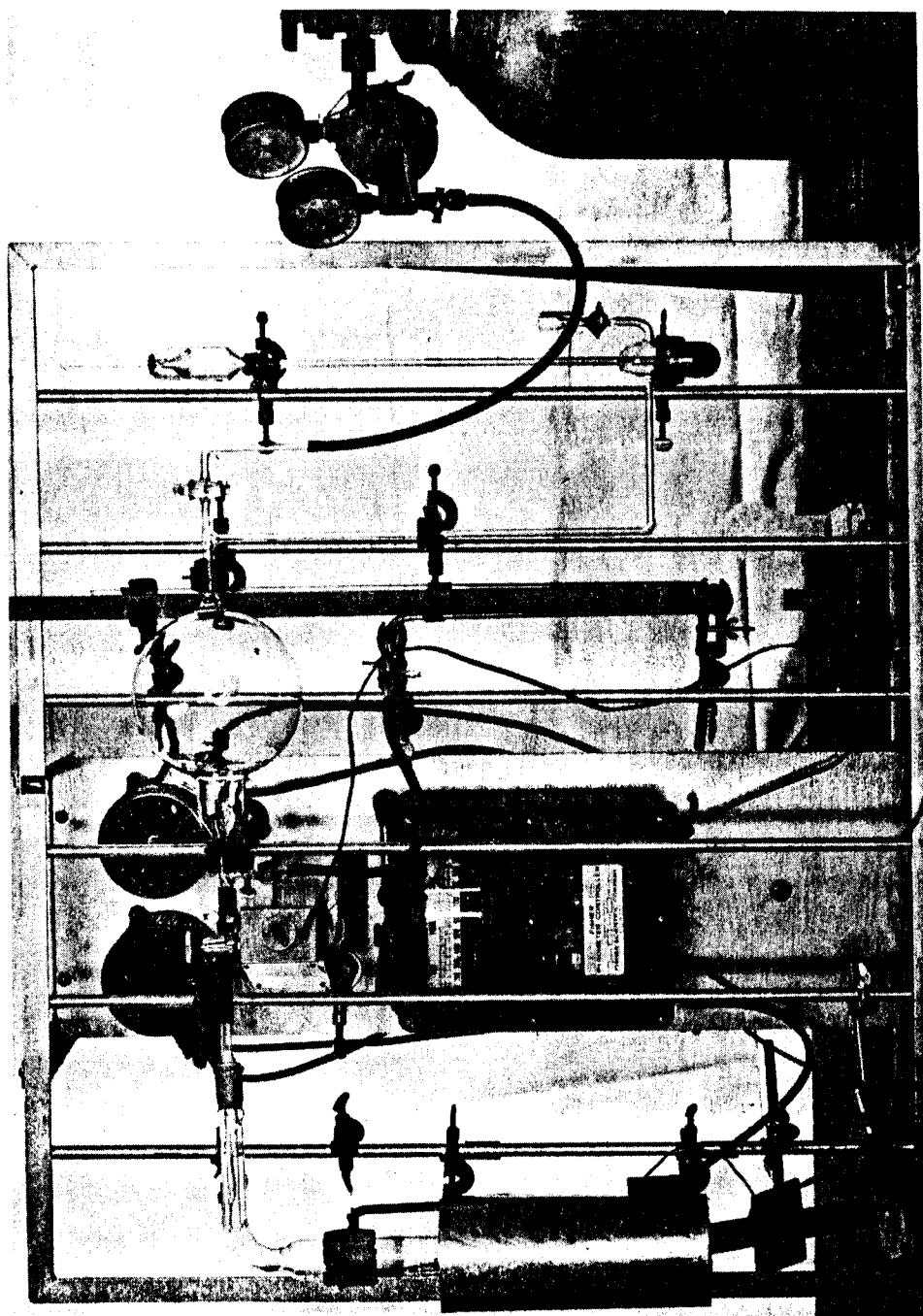
FIGURE   4   Photograph   of   inflammability   apparatus .

TABLE I – SOURCE OF COALS

Coal No	B.C.R. Lot No	State	County	Bed	Nominal Screen Size Sampled	Tons of Coal Represented by Sample	Gross Sample Lbs.
1	C-166-1502A	Pennsylvania	Cambria	Upper Kittanning	3/4 x 0"	300	1274
2	C-167-1502A	Pennsylvania	Indiana	Lower Kittaning	3/4 x 0"	250	1224
3	C-168-1502A	Pennsylvania	Indiana	Upper Freeport	1-1/4 x 3/8"	500	1105
4	C-169-1502A	Pennsylvania	Washington	Pittsburgh	1-1/4 x 1/2"	600	1151
5	C-114-1502	Ohio	Jefferson	Ohio No 8	1-1/2 x 3/8"	750	1045
8	C-117-1502	West Virginia	McDowell	Pocahontas No 3	1 x 3/8"	225	1017
12	C-121-1502	Illinois	Saline	Illinois No 5	1" x 10 mesh	250	1130
13	C-297-1502	Illinois	Franklin	Illinois No 6	1" x 48 mesh	12	250
15	C-193-1502	Indiana	Gibson	Indiana No 5	1-1/2" x 28 mesh	8	250
16	C-293-1502	West Virginia	Gilmer	Pittsburgh	1-1/8" x 5/8"	5	250
18	C-304-1502	West Virginia	Marion	Pittsburgh	1-1/4" x 3/4"	10	250

TABLE II - PROXIMATE ANALYSES

Coal No	Bed	Air Dried Basis %				Dry Basis %			D.A.F. Basis %	
		Moisture	V.M.	Ash	F.C.	V.M.	Ash	F.C.	V.M.	F.C.
1	Upper Kittanning	0.9	16.2	9.4	73.5	16.3	9.5	74.2	18.0	82.0
2	Lower Kittanning	1.0	26.9	10.0	62.1	27.2	10.1	62.7	30.2	69.8
3	Upper Freeport	0.6	28.9	9.2	61.3	29.1	9.3	61.6	32.0	68.0
4	Pittsburgh	1.9	38.4	7.9	51.8	39.1	8.0	52.9	42.5	57.5
5	Ohio No 8	2.6	39.2	6.8	51.4	40.2	7.0	52.8	43.2	56.8
8	Pocahontas No 3	0.6	20.4	8.5	70.5	20.5	8.5	71.0	22.4	77.6
12	Illinois No 5	4.9	34.2	7.6	53.3	36.0	8.0	56.0	39.1	60.9
13	Illinois No 6	4.6	45.0	5.7	44.7	47.2	6.0	46.8	50.2	49.8
15	Indiana No 5	7.2	45.4	7.2	40.2	48.9	7.8	43.3	53.0	47.0
16	Pittsburgh	1.1	40.8	6.8	51.3	41.3	6.9	51.8	44.4	55.6
18	Pittsburgh	1.1	43.4	5.7	49.8	43.9	5.8	50.3	46.6	53.4

TABLE III – GIESELER DATA AND FREE SWELLING INDICES

Coal No	Bed	Maximum Fluidity		Free Swelling Index	
		D.D.P.M.	°C	No	m.m.^{2}
1	Upper Kittanning	1.6	473	9 1/2	586
2	Lower Kittanning	960	425	10	600
3	Upper Freeport	2710	433	8 1/2	520
4	Pittsburgh	1290	431	6 1/2	375
5	Ohio No 8	33	428	4	221
8	Pocahontas No 3	180	465	9 1/2	581
12	Illinois No 5	3.6	418	3 1/2	215
13	Illinois No 6	39.5	420	3 1/2	208
15	Indiana No 5	4.0	402	2 1/2	142
16	Pittsburgh	4000	409	7 1/2	456
18	Pittsburgh	6370	409	8	472

TABLE IV. — ULTIMATE ANALYSES, CALORIFIC VALUES, AND RANK

Coal No	Bed	Ultimate Analysis Dry, Ash-Free %					B.T.U./Lb. M.M.F. Basis	A.S.T.M. Rank
		C	H	N	S	O		
1	Upper Kittanning	87.6	4.1	1.2	1.4	5.7	15752	Low Volatile
2	Lower Kittanning	85.9	5.2	1.0	1.9	6.0	15161	Medium Volatile
3	Upper Freeport	86.8	5.3	1.0	1.8	5.1	15472	High Volatile A
4	Pittsburgh	82.8	5.5	1.6	2.5	7.6	15307	High Volatile A
5	Ohio No 8	79.1-81.6	5.0-5.7	1.4-1.6	1.7-5.2	7.1-12.8	14087	High Volatile A
8	Pocahontas No 3	89.8-91.6	4.4-5.0	1.0-1.7	0.5-1.1	1.2-3.5	15490	Low Volatile
12	Illinois No 5	79.8-83.2	5.2-5.7	1.6-1.9	2.4-4.8	7.2-8.7	13591	High Volatile B
13	Illinois No 6	80.2-82.2	5.1-5.7	1.6-1.9	0.9-4.1	8.8-10.8	13267	High Volatile B
15	Indiana No 5	79.2-80.0	5.5-5.6	1.5-1.8	4.2-5.2	8.2-10.2	13042	High Volatile C
16	Pittsburgh	83.2-85.2	5.4-5.9	1.6-1.7	0.8-3.2	5.7-7.0	15402	High Volatile A
18	Pittsburgh						14775	High Volatile A

of which the coal sample was entrained and blown vertically down through the heated ignition tube. Release of the electro-hosecock was accomplished by the excitation of a solenoid supplied with 90 volts of direct current through a hand operated snap switch. Although the electro-hosecock was designed to operate on 115 volt alternating current, it was found that annoying hum occurred and that excessive chattering interfered with its efficient operation. A small half-wave filtered power supply was therefore constructed to obviate these troubles. It was also found that if the electro-hosecock was left in the closed position for any extended period the solenoid would over-heat. A smaller manual hosecock was therefore used to seal the rubber tubing during all but the short time taken to run a test.

After the electro-hosecock, the rubber tubing was connected to the end of a glass connecting piece, details of which are given in Figure 5. This 220 mm. long connecting piece was made from the inner part of a 24/40 standard taper ground joint. To the drip tip of this inner part was joined a piece of 10 mm. bore glass tubing, a "tear-drop" shaped hole (approx 7 mm. in length by 5 mm. at its widest) being made in the bottom of the latter, 20 mm. away from the smaller diameter of the ground zone. The purpose of the hole will be explained in the section on experimental procedure. The other end of the 10 mm. tubing was cut so that its upper half was removed over a length of 25 mm., the lower half thus forming a semi-cylindrical "boat" into which the coal could easily and conveniently be weighed for insertion into the apparatus. The connecting piece fitted into the horizontal arm of the ignition tube as shown in Figure 3. The ignition tube was constructed wholly of Vycor glass, the 19 mm. bore horizontal arm leading by means of a 90° bend into a vertical tube of 32 mm. bore and 38 mm. external diameter. Details are shown in Figure 5. The vertical portion of the ignition tube fitted snugly into the stain-less steel liner (1 9/16" bore, 1 3/4" external diameter) of the 10" high electrically heated furnace.

This furnace was constructed as follows. A 10 inch length of stainless steel tube (internal diameter 1 9/16", wall thickness 3/32")

190

40

43

24/40 S.T. GROUND
JOINT

22 O/D
19 BORE

12 O/D
10 BORE

11 O/D
9 BORE

25

"TEAR-DROP" SHAPED
HOLE

120

220

32

445

38

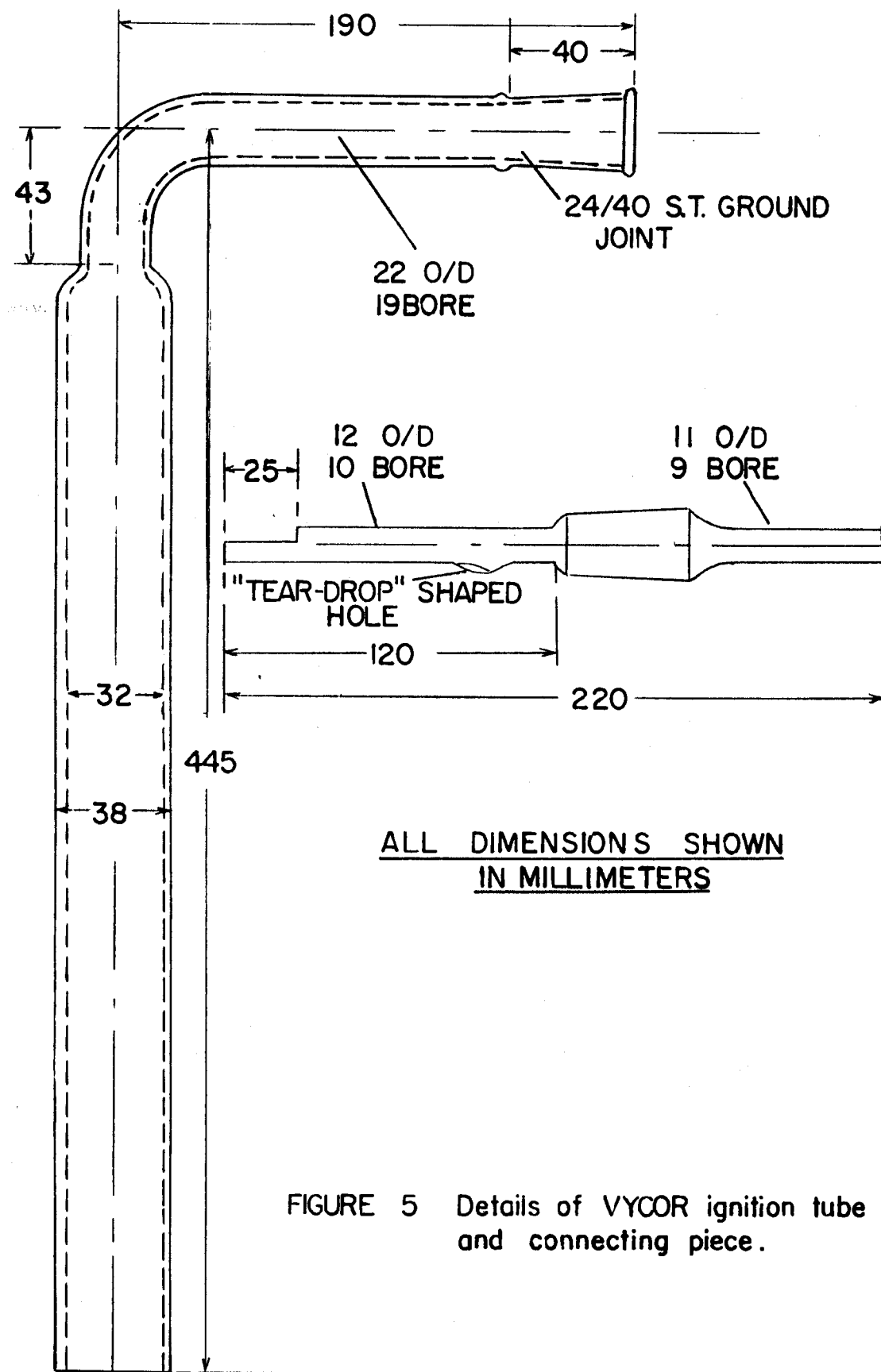ALL DIMENSIONS SHOWN
IN MILLIMETERS

FIGURE 5   Details of VYCOR ignition tube
and connecting piece.

was given an exterior coating of alundum cement 1/16" thick. The tube was then wound with Kanthal electric resistance ribbon, the winding being covered by a 1/8" later of alundum cement to keep it in place. The furnace was insulated by a 1 1/2" layer of high temperature insulations and clad by means of 20 gauge sheet steel.

Temperature control was obtained by sensing the inner wall temperature of the Vycor ignition tube by means of a number 20 A.W.G. chromel-alumel thermocouple the junction of which was kept in contact with the wall at a position half way along its heated length. The thermocouple was connected to a pyrometer controller of the dynamic type. Visual temperature indication was continuous, and any temperature between ambient and 1150°C could be selected by means of a manual set point. At the set point, the temperature indicating needle triggered a mechanical system connected to a single pole, single throw, tilting mercury switch. This in turn was so connected as to excite the coil of a double pole, double throw, 110 volt relay during periods of heat demand. The latter relay selected the output of either of two manually adjustable, tapped, variable auto-transformers connected to 110 volt a.c. current by means of a hand operated master switch, and carried the selected pre-set output to the resistance winding of the furnace. Temperature control to within ±5°C could be obtained as follows. The variac supplying current to the furnace during periods of heat demand was set at a value slightly in excess of that required to maintain the desired temperature at the ignition tube wall. The second variac, which supplied current during periods of no heat demand, was set to a value slightly below that necessary to maintain temperature. Readjustment of both auto-transformers had to be made according to the temperature range in which a particular determination was being carried out.

Experimental Procedure with Inflammability Apparatus

With the electro-hosecock open and the hand-operated hose cock shut, the glass connecting piece was removed from the apparatus and replaced by a suitably sized rubber bung. The required temperature was then set on the controller, and the current to the furnace switched

on at the master switch. The ignition tube was allowed to come up to the selected temperature, and a period of thirty minutes allowed for temperature stabilization. 0.2 gram of the coal sample to be tested was weighed out into the semi-cylindrical end of the connecting piece which, after removal of the rubber bung, was carefully placed in position in the horizontal arm of the ignition tube. The free ends of the connecting piece and the 3/8" rubber tubing were connected, and oxygen or air admitted to the storage reservoir until a pressure of rather more than 12" mercury was indicated on the manometer. [The oxygen was taken from cylinders supplied by the Air Reduction Company, and the air from the compressed air system of the University.] The gas pressure in the storage reservoir was reduced to exactly 12" mercury, the electro-hosecock switched to the shut position and the manual hosecock opened fully. As soon as the indicating needle of the pyrometer controller coincided with the pre-set temperature, the electro-hosecock was switched open to allow the coal sample to be blown rapidly and completely through the hot ignition tube.

In preliminary tests made when testing out the apparatus, it was found that, without the "tear-drop" shaped hole in the bottom of the connecting piece, some coal dust was always left lying on the bottom of the horizontal arm of the ignition tube. It seemed that enough resistance was being set up by the 90 degree bend to cause a portion of the dust to collect under the end of the connecting piece. With a suitable hole in the bottom of the latter, enough scavenging was obtained to give complete transport of the whole sample down through the ignition tube.

The criterion of ignition was the appearance of flame extending just beyond the bottom of the ignition tube. According to whether the sample did or did not ignite, the pre-set temperature at the controller was either decreased or increased stepwise, 10°C at a time, and further determinations carried out exactly as above. Eventually two temperatures differing by 10°C could be reached, at the higher of which definite ignition occurred, whilst at the lower no ignition took place. A minimum of three ignitions at the higher

temperature and three failures to ignite at a temperature 10°C lower, were considered to define the ignition point satisfactorily. The ignition temperature was then reported as the mean of the two values.

Since the criterion of ignition in the above method depends wholly upon visual observation, it was at first thought that the reproducibility of the test might be poor because of the subjective errors to which any observer is liable. It was soon found, however, that no great perception on the part of the operator was needed to obtain a reproducibility of ±5°C, except perhaps in the case of the coarsest samples tested. With oxygen, a temperature much in excess of that needed to cause ignition gave a brilliant, white, almost gaseous flame for all but the very coarse sized samples such as -60+100 or -60+200 mesh (U.S.Sieve Series). Under such conditions the flame would extend six or eight inches past the bottom of the ignition tube and the distinct report of a pressure wave would be heard. With reduction of temperature the flame length and the production of noise would decrease. At the ignition temperature, that is with a flame extending just beyond the ignition tube, only the faint sound of a report was audible. Naturally, at a temperature much below ignition no flame appeared. As the temperature was raised, it was always possible to tell when ignition was being closely approached, for at some 10° or 20°C below ignition, bluish-white smoke would appear and the distinctive acrid odour typical of incomplete combustion would become evident. For the coarse samples such indications were less emphatic. Even at temperatures considerably higher than the ignition point, for example, the flame tended to be short and very sparky. Some judgement on the observer's part was thus necessary in deciding just what constituted ignition with such material. When using air, the flames produced were, unlike the bright, intense, oxygen flames, much more red in colour and pressure reports were uncommon. The volume and odour of the smoke produced just below the ignition point were much more pronounced than when using oxygen.

To a moderately experienced and acute observer the decision as to precisely what constituted ignition presented no difficulties.

The test method could, of course, be refined by the use of such de-
vices as photo-electric cells and associated measuring or recording
equipment. It is considered, however, that the technique employed
resulted in no appreciable experimental error. The "ignition tempera-
tures" reported for this test are, of course, the lowest temperatures
to which the inner wall of the Vycor ignition tube had to be raised in
order that flame might be produced when the coal dust was blown down
through it. The test provides no information about temperatures with-
in the dust cloud itself.

Crossing Point Apparatus

The crossing point apparatus was obtained from Custom Scientific
Instruments, Inc. of New York. Sold under the name of the "Setchkin
Ignition Apparatus for Solids", it was developed by N. P. Setchkin
(35)(36) from an original design by the British Standards Institution
(37). The apparatus, which is shown in Figures 6 and 7, consists of a
vertical, refractory furnace-tube of 4 inch bore and 8 3/4 inches in
length. The furnace tube is electrically heated, 50 turns of No. 16
B. & S. gauge nichrome wire in an asbestos sleeve being wound around
the tube and embedded in alundum cement. The inner refractory tube,
of 3 inch bore, 8 3/4 inches in length, and with a wall thickness of
approximately 1/8 of an inch, is placed inside the furnace tube and
rests on three small blocks in the bottom of the furnace. The annular
space between the two tubes is used to preheat air or oxygen, which is
admitted tangentially through a copper tube. The preheated air or
oxygen enters the inner tube at the bottom. The top of this tube is
covered with a split refractory disk containing a 1 square inch hole
for observation and for the exit of smoke and gases.

The coal sample is contained in a Parr volatile matter crucible
made of a nickel chromium alloy. Crucibles of this type have a capa-
city of 13 ml, a top diameter of 26 mm. and a height of 34 mm. A wire
loop of 25 mm. diameter holds the crucible centrally in the inner
tube at a height such that surface of the coal sample is approximately
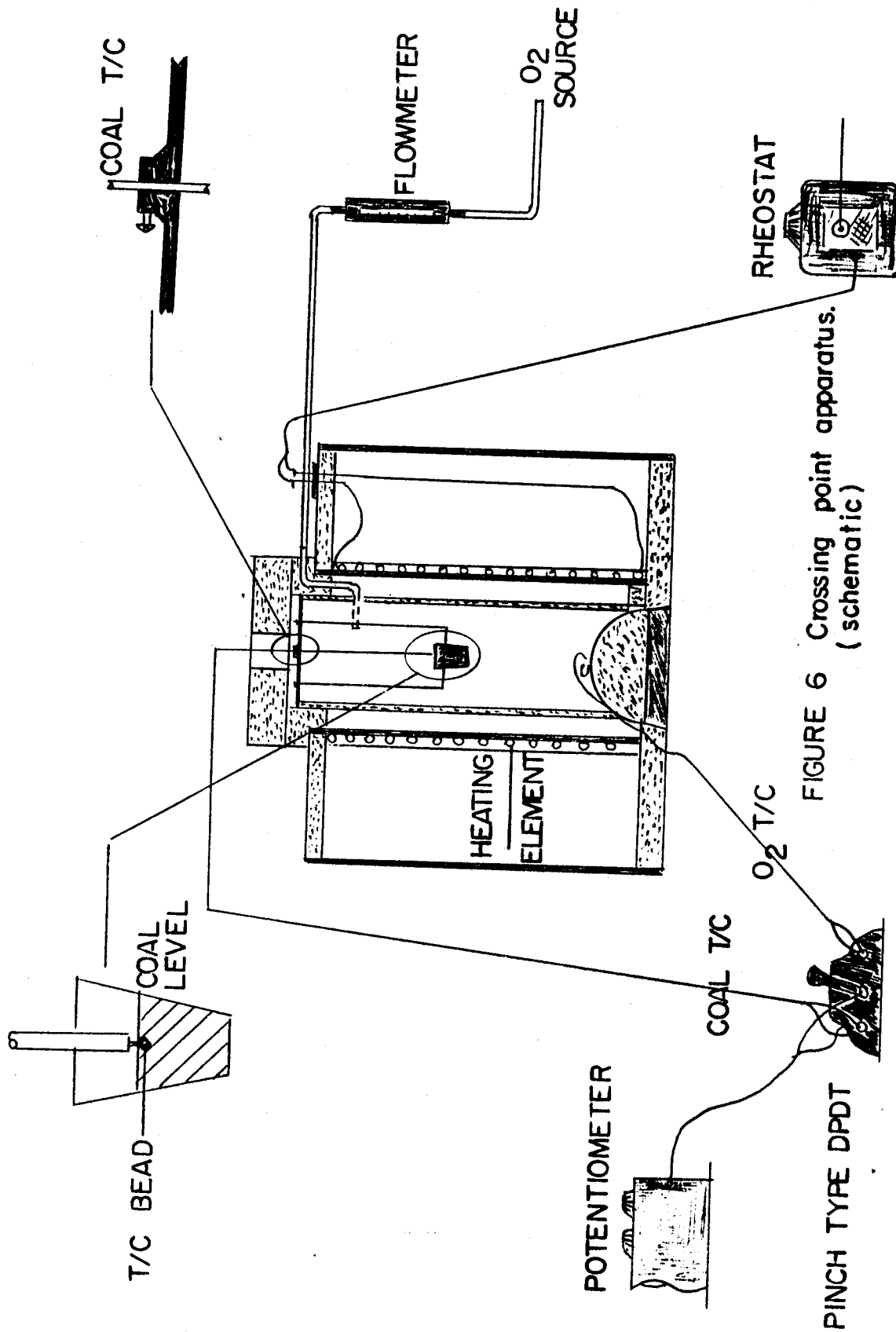4 5/8 inches from the top of the tube.

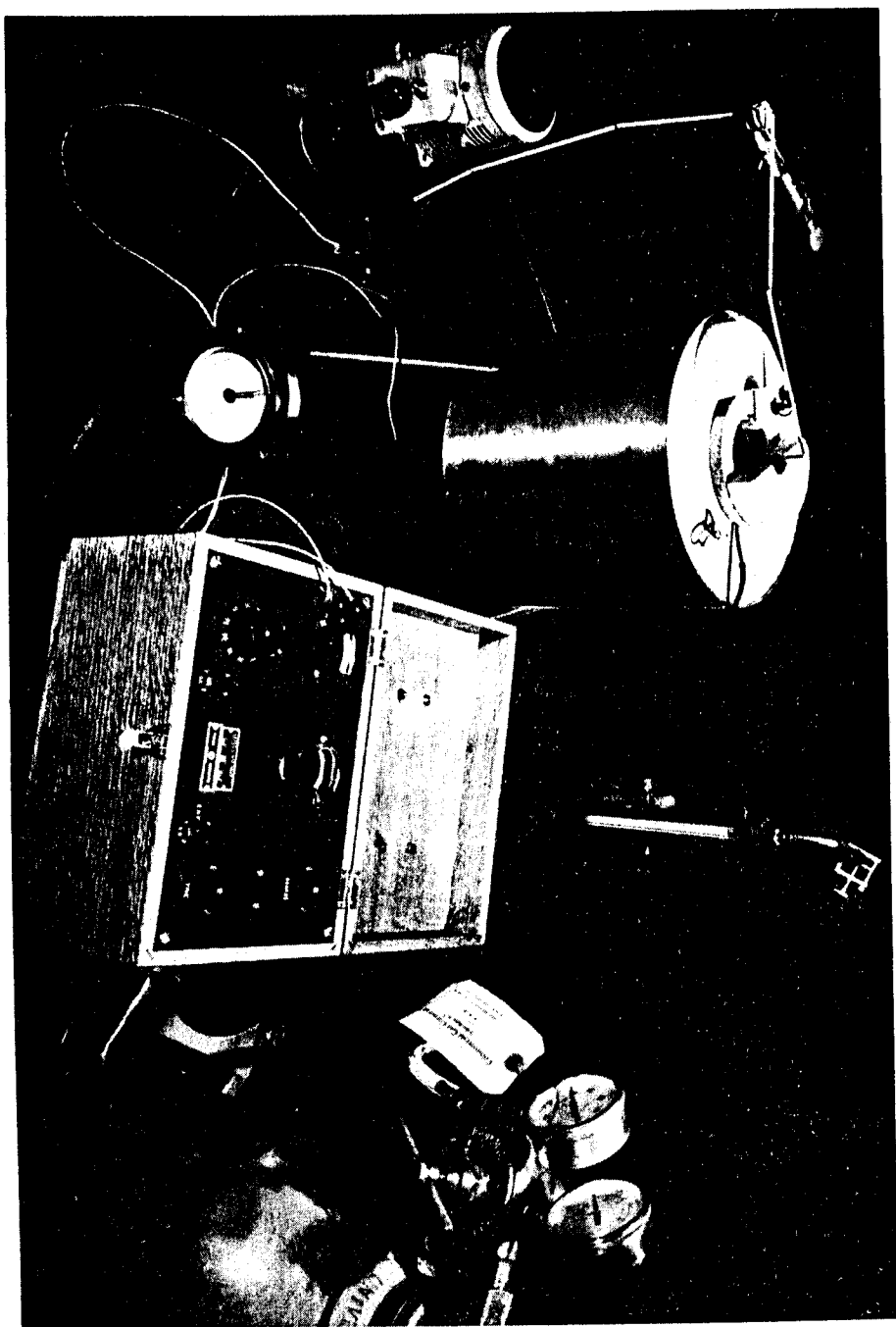FIGURE 6 Crossing point apparatus. (schematic)

FIGURE 7   Photograph of crossing point apparatus.

The temperature of the coal and of the reacting gas (oxygen in the present case) were measured by means of two chromel alumel thermocouples connected by a pinch type, double-pole, double throw switch to a Leeds and Northrup potentiometer. The thermocouple measuring the temperature of the oxygen was located beneath the crucible as shown in Figure 6. The bead of the thermocouple used to determine the coal temperature was positioned centrally just below the surface of the sample in the crucible. Temperature control was obtained by means of a variac connected in series with the heating coils. The rate of gas flow through the apparatus was measured by a Fischer and Porter Flowrator using tube number 01-N-15 in conjunction with a 5/32 inch stainless steel ball float.

Determination of Crossing Point Temperature

Three grams of -60+200 mesh coal were weighed out into the crucible, which was then gently tapped fifteen times on the bench top, being rotated slightly between taps. The crucible was fitted into the wire loop, the coal thermocouple carefully fixed in position with its bead just under the surface of the sample, and the whole assembly positioned in the inner refractory tube. The rate of oxygen flow was adjusted to give a velocity through the inner refractory tube of 5 feet per minute, and the variac set to give an average gas temperature increase of 9°C per minute throughout the latter period of the test. Current to the furnace winding was then switched on and a timing clock started at the same instant. Readings of the potentiometer for coal and oxygen were made every five minutes for the first fifteen minutes, and at intervals of one minute thereafter. Time/temperature plots were made for the coal and oxygen, and the crossing point temperature obtained from the position at which the two plots intersected.

Although some initial runs were made with air instead of oxygen, the use of air was discontinued. It was found that the time/temperature plot for air either failed to intersect that for the coal, or approached it so gradually as to make the crossing temperature difficult to determine. When using oxygen, on the other hand, a sharp intersection of the two lines could always be expected. As may

be seen from Figures 8, 9, 10, and 11, rates of temperature increase
could be repeated quite closely in duplicate tests, and the crossing
point temperatures of all coals were reproducible to within 5°C

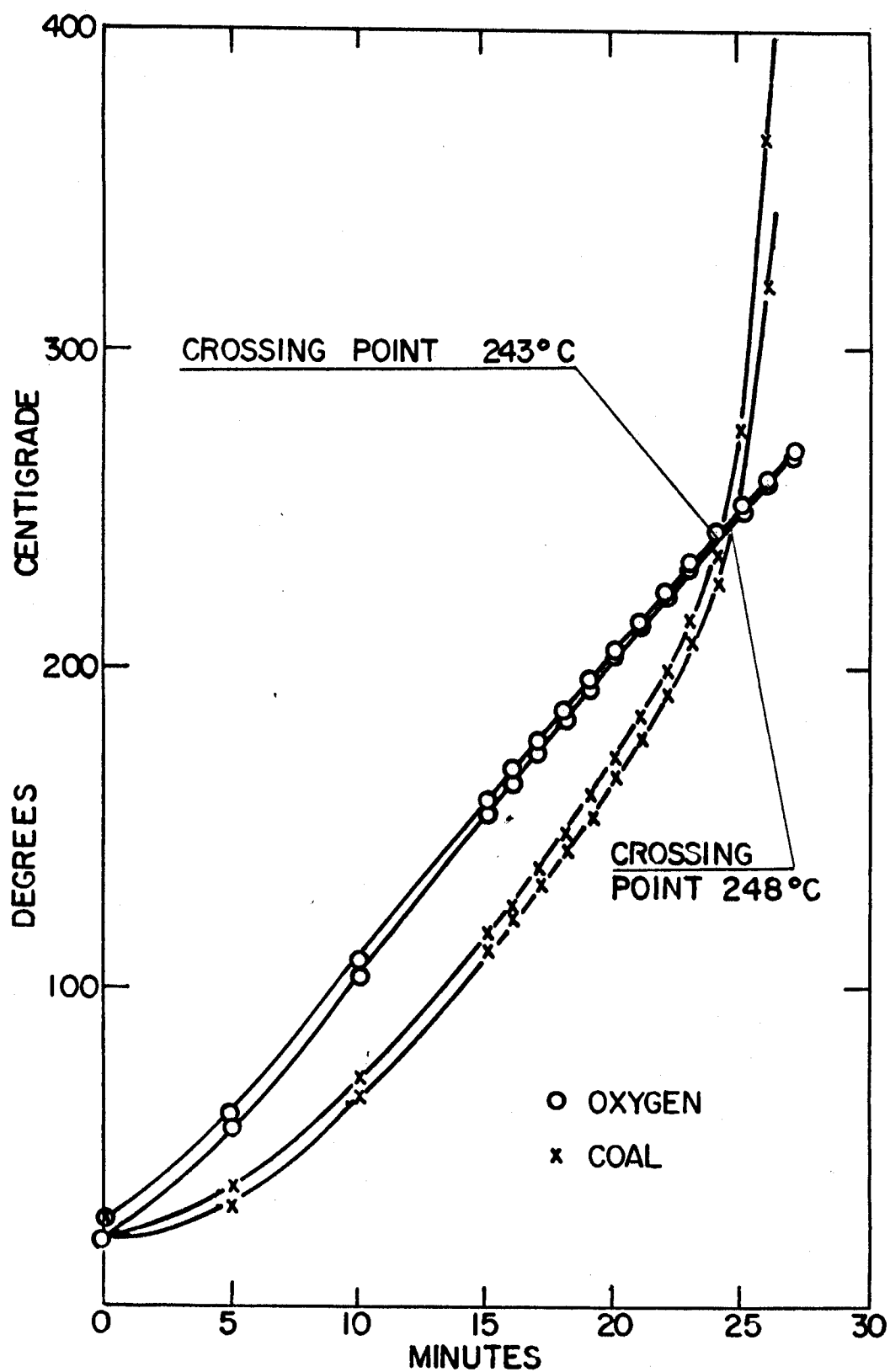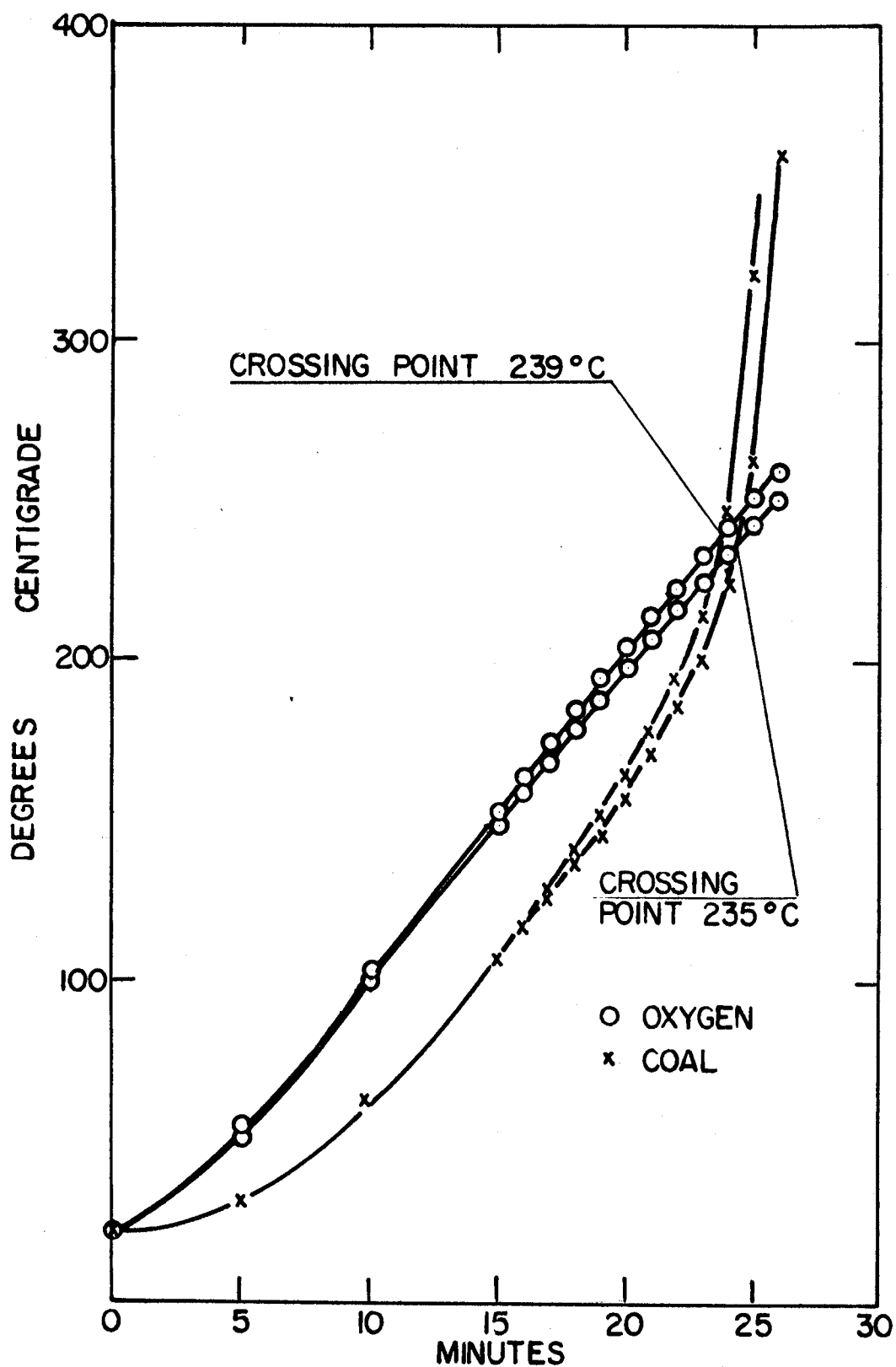FIGURE 8   Time/temperature curves for coal no. 1.
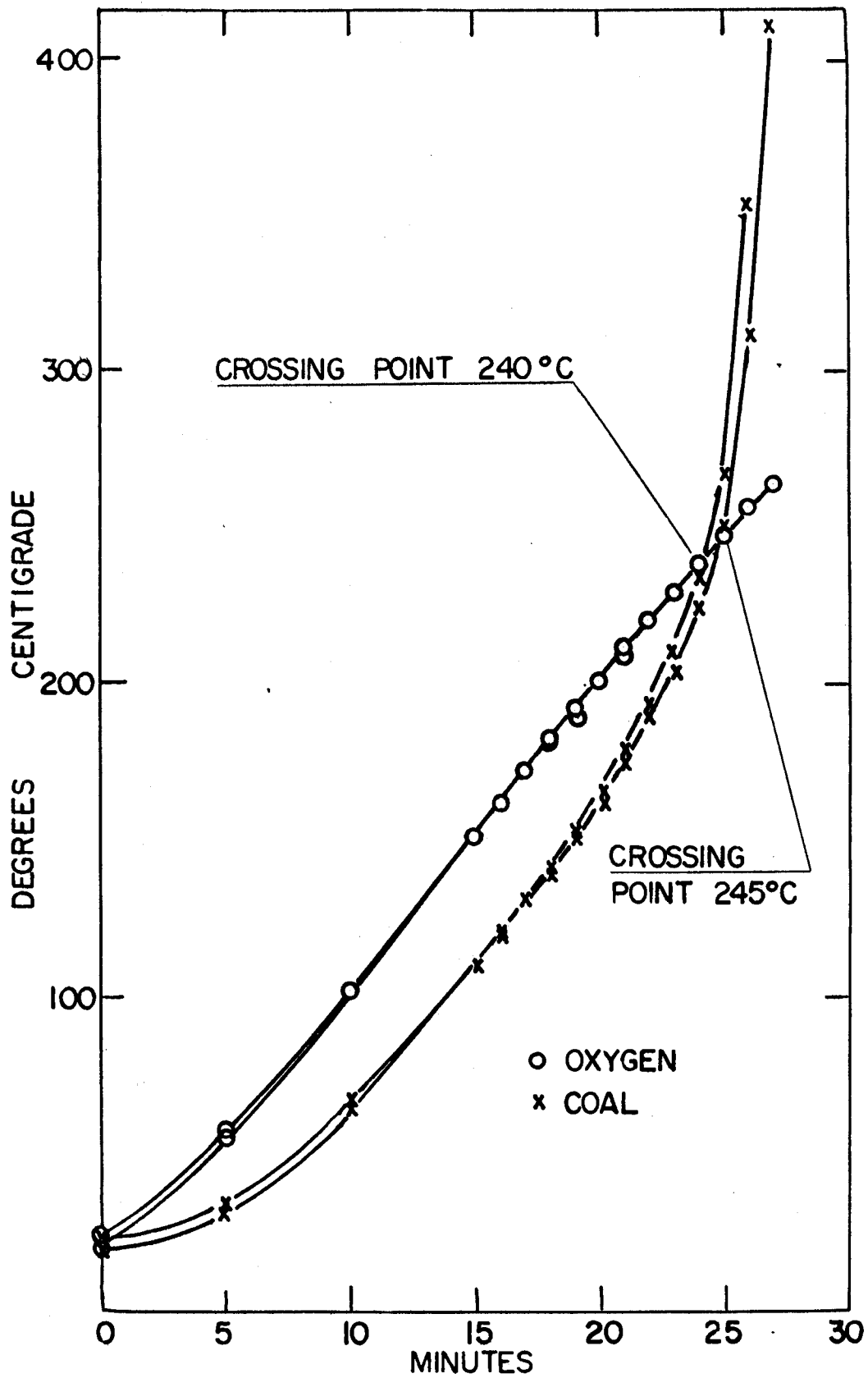
FIGURE 9 Time/temperature curves for coal no. 2.

CROSSING POINT 240°C

CROSSING POINT 245°C

o OXYGEN
x COAL

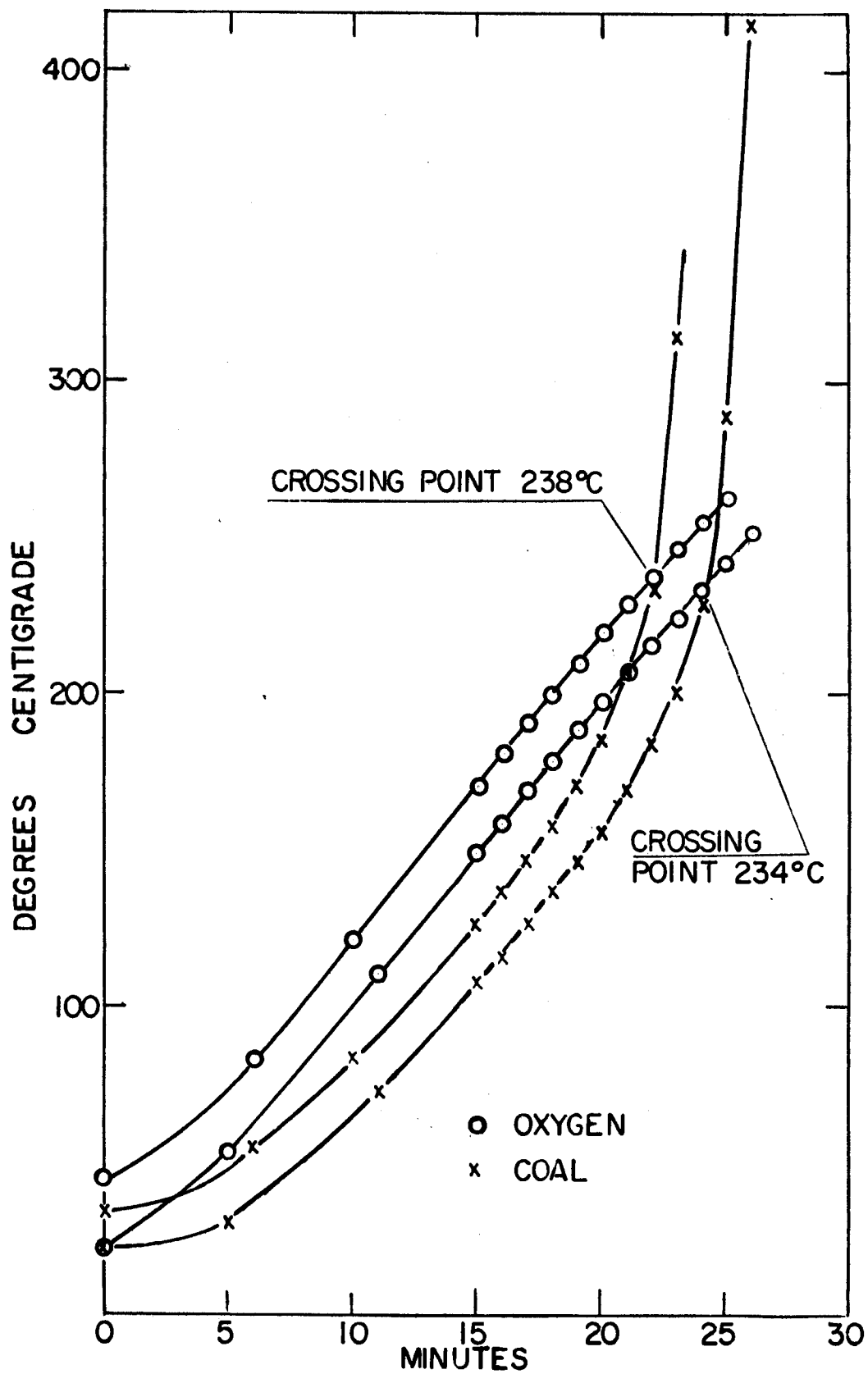FIGURE 10   Time/temperature curves for coal no. 3.

FIGURE II Time/temperature curves for coal no. 4.

III Experimental Results

Ignition Temperatures obtained with the Inflammability Apparatus

The ignition temperatures in oxygen of the -60, -60+200, -200, -200+325, and -325 mesh coals are given in Table V. The ignition temperatures in air of the -200 and -325 mesh size fractions are shown in Table VI. There seems to be little or no relationship between ignition temperature as determined by the inflammability test and the composition or characteristics of a coal, for no significant correlation can be found between ignition temperature and any of the values listed in Tables II, III, or IV. No matter whether tested in air or in oxygen, the volatile content of a coal seems to provide no guide at all to its tendency to ignite in the inflammability apparatus. Inspection of Figure 12, where the ignition temperatures in oxygen of the -200, -200+325, and -325 mesh fractions of the eleven coals have been plotted against the d.a.f. volatile contents, shows no trend towards decrease in ignition temperature with increase in volatile content. From Figure 13, where the ignition temperatures in air have been plotted against d.a.f. volatile content, it can be seen that there is a slight tendency for the higher volatile coals to have somewhat lower ignition temperatures. Even in air, however, the difference in ignition temperature between the highest volatile coal (No 15 with 53.0% V.M.) and the lowest (No 1 with 18.0% V.M.) is only 90°C for the -200 mesh material and 85°C for the -325 mesh. If coal No 15 be excluded, these differences become considerably less. Thus, as between coal No 1 and coal No 13, that is over the range of volatile content 18.0% to 50.2% (d.a.f.), only a 50°C difference in ignition temperature exists for the -200 mesh coal, and only 30°C for the -325 mesh. Differences such as these are scarcely likely to be of importance in pulverized fuel firing.

As would be expected, the ignition temperatures determined when using air were considerably higher than those obtained with oxygen. The actual difference varies somewhat with each coal, and also to a lesser extent with the particular size range considered. In general,

TABLE V - IGNITION TEMPERATURES IN OXYGEN
DEGREES CENTIGRADE

Size Range U.S. Standard Sieve	Coal No 1 (18.0)	Coal No 8 (22.4)	Coal No 2 (30.2)	Coal No 3 (32.0)	Coal No 12 (39.1)	Coal No 4 (42.5)	Coal No 5 (43.2)	Coal No 16 (44.4)	Coal No 18 (46.6)	Coal No 13 (50.2)	Coal No 15 (53.0)*
-60 +200	865	855	780	835	855	730	865	815	825	900	735
-60	640	635	615	625	615	615	595	560	565	650	555
-200 +325	605	655	585	585	615	590	585	600	570	655	570
-200	575	615	560	555	595	585	565	560	575	570	535
-325	535	605	525	515	565	575	565	560	545	545	535

TABLE VI - IGNITION TEMPERATURES IN AIR
DEGREES CENTIGRADE

Size Range U.S. Standard Sieve	Coal No 1 (18.0)	Coal No 8 (22.4)	Coal No 2 (30.2)	Coal No 3 (32.0)	Coal No 12 (39.1)	Coal No 4 (42.5)	Coal No 5 (43.2)	Coal No 16 (44.4)	Coal No 18 (46.6)	Coal No 13 (50.2)	Coal No 15 (53.0)*
-200	870	855	845	845	835	835	830	835	825	820	780
-325	845	835	825	820	815	825	820	810	810	815	760

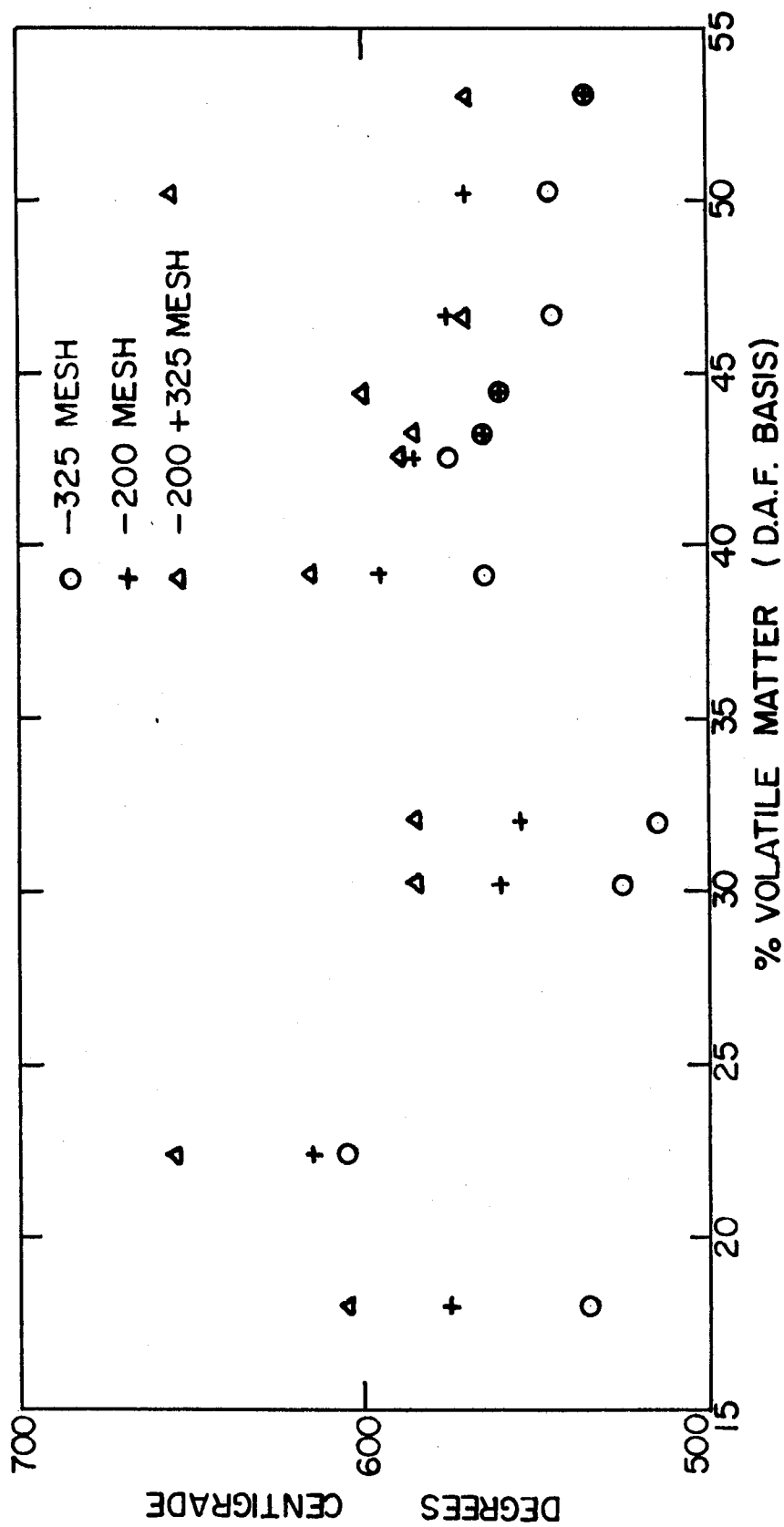* Values in parentheses are percentage volatile contents on dry, ash-free basis.

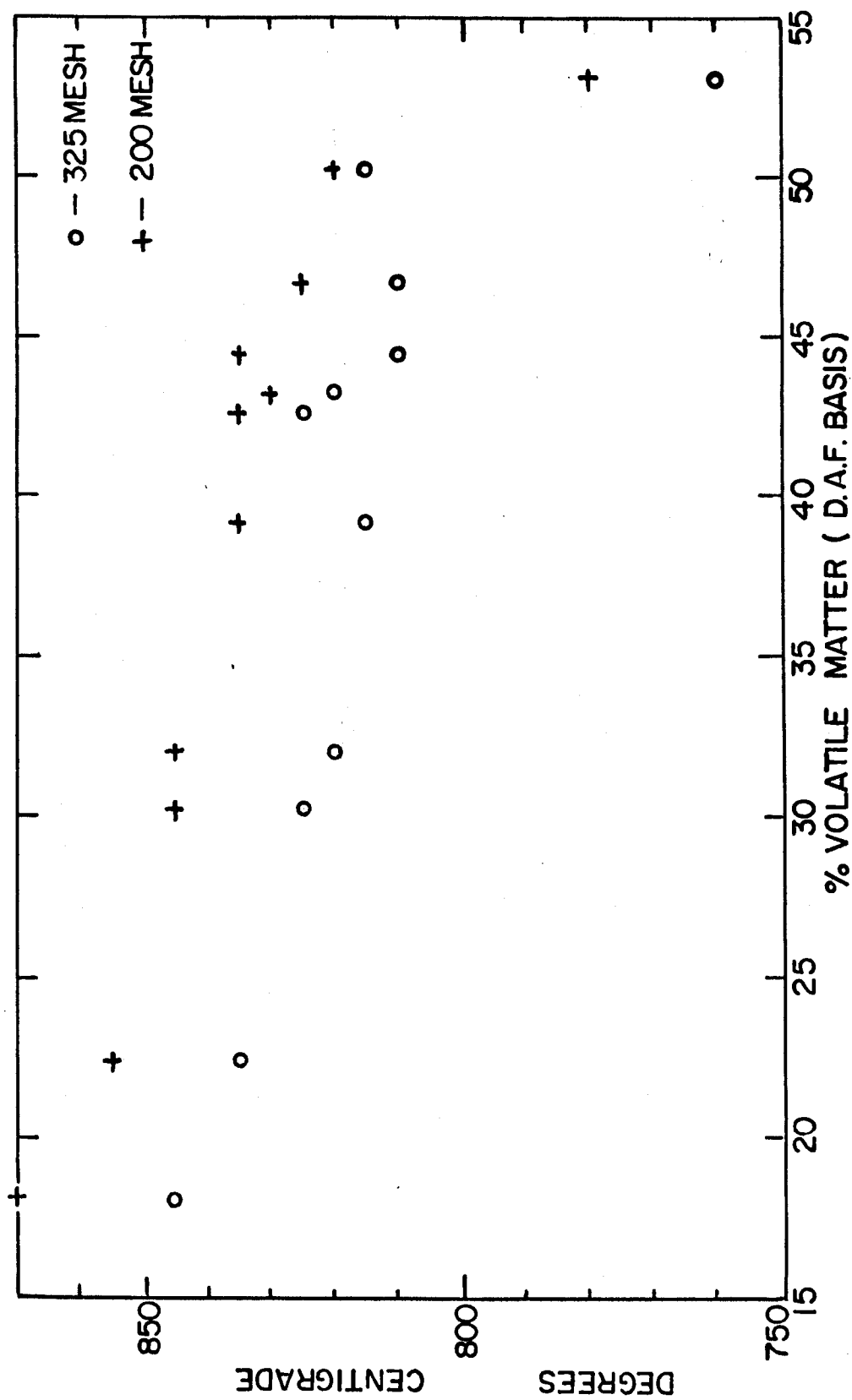FIGURE 12 Relationship between ignition temperature in oxygen and volatile content.

FIGURE. 13   Relationship between ignition temperature in air and volatile content.

however, ignition temperatures in air were found to be between 225°C and 310°C higher than when oxygen was used.

The influence of particle size on ignition temperature is considerable. Almost without exception previous investigators of the combustibility, ignitibility, or explosibility of dust clouds have found that the smaller the particle size the easier it is for combustion, ignition, or explosion to occur. [Hartmann (38), however, states that there does seem to be a limit to the effect of fineness, and points out that very fine particles tend to agglomerate, are subject to rapid oxidation on exposure to air, and in the case of some coals may contain the less reactive constituents.] Godbert (39) quotes the results of the French worker, Vidal, who measured the inflammability of coal dusts by the effects produced in a bunsen flame of coal gas and air, or coal gas and air with coal dust in suspension. The lengthening of the flame, the extent to which paper wrapped around lead pellets was charred by the flame, and the violence of the throw imparted to a pith-ball pendulum after ignition, were all taken as an indication of the relative inflammability. In every case the inflammability of the finest dust (-120 mesh) was more pronounced than that of the coarser material (-60 mesh and -1mm.). Godbert and Greenwald (23), after an exhaustive study of the effect of the fineness of coal dust on the relative inflammability as determined in the Godbert-type apparatus, concluded that "the inflammability of the coal dusts varied directly with the fineness". Brown (4) has stated that, "practically all writers agree that the ignition temperature is decreased with increased fineness, particularly as the mean diameter of the individual grains (for coals, etc.) becomes very small." The ignition temperatures reported in Table V and VI confirm the findings of other workers. As the particle size increases, so does the ignition temperature increase. Indeed, for all the coals tested, the effect of going from -325 mesh size to -60+200 mesh when using oxygen is very comparable with the effect of going from -325 mesh in oxygen to -325 mesh in air. For instance the ignition temperatures of the -325 and -60+200 mesh samples of coal No 1 in oxygen

are 535°C and 865°C respectively; the ignition temperature of a -325 mesh sample of the same coal in air is 845°C.

In some cases, notably coals 5, 8, 15, 16, and 18, the ignition temperatures of the -60 mesh material in oxygen are within 30°C of the -325 mesh samples. This is doubtless due to the fact that the percentages of superfines (i.e. -325 mesh coal) in these particular samples are comparatively high. Table VII shows the sieve analyses of the eleven coals. These were carried out on representative portions of the -60 mesh coal as received from Bituminous Coal Research, Inc. Coals 5, 8, 15, 16 and 18 all contain more than 35% superfines. The ignition temperatures of the -60 and -325 mesh fractions of coal No 12, however, are not as close as might be expected in view of the 54.4% of superfines which the -60 mesh sample contained. No satisfactory explanation for this apparent anomaly can be given.

The importance of fine coal in ignition is further emphasised by considering those samples in which the -60+200 fraction predominates, viz Nos 1, 2, 3, 4, and 13. Table VIII shows the ignition temperatures in oxygen of the -60 mesh, -60+200, and -325 mesh fractions of these five coals. As may be seen, although in all five coals the -60 mesh sample contained more than 50% of -60+200 mesh material, the ignition temperatures of the -60 mesh material are much closer to those of the -325 mesh than to those of the -60+200 mesh coal. Coal No 13 is especially interesting in this respect. Although the -60 mesh sample contained no less than 61% of -60+200 mesh coal, and although the ignition temperature of the latter in oxygen was found to be 900°C, the ignition temperature of the -60 mesh material itself was, at 650°C, only 105°C higher than the value of 545°C obtained for the -325 mesh fraction. Evidence of this sort would seem to indicate that in the case of dust clouds ignition commences with the fine particles, flame propagation then spreading rapidly through the mixture. It also points to the fact that quite a proportion of relatively coarse coal particles can probably be tolerated in the feed to a pulverised fuel burner provided that an adequate quantity of superfines is also present.

TABLE VII - SIEVE ANALYSES OF COALS

Size Range	Coal No 1 %	Coal No 2 %	Coal No 3 %	Coal No 4 %	Coal No 5 %	Coal No 8 %	Coal No 12 %	Coal No 13 %	Coal No 15 %	Coal No 16 %	Coal No 18 %
-60+200	50.9	55.4	56.2	61.9	14.3	6.1	12.7	61.2	13.9	13.6	14.3
-200+325	26.8	18.0	26.8	8.7	50.4	16.9	32.9	14.5	23.0	33.3	47.4
-325	22.3	26.6	17.0	29.4	35.3	77.0	54.4	24.3	63.1	53.1	38.3

TABLE VIII - IGNITION TEMPERATURES IN OXYGEN OF -60, -60+200, and -325 MESH FRACTIONS OF COAL No 1, 2, 3, 4, and 13.

Size Range	Coal No 1 °C	Coal No 2 °C	Coal No 3 °C	Coal No 4 °C	Coal No 13 °C
-60+200	865	780	835	730	900
-60	640	615	625	615	650
-325	535	525	515	575	545

The influence of particle size on ignition temperature makes it essential to control this variable when attempting ot compare the values for different coals. Consider, for instance, coals No 2 and 15, with volatile contents of 30.2% and 53.0% (d.a.f.) respectively. The ignition temperatures in oxygen of the -60 mesh samples are 615°C for the lower and 555°C for the higher volatile coal. This is not evidence of any relationship between ignition temperature and volatile content, however, for it can be seen that the ignition temperatures in oxygen of the -325 fractions of the two coals differ by only 10°C. The reason why the -60 mesh sample of coal No 15 has a much lower ignition temperature in oxygen than that of coal No 2 is that the former contains 63% of -325 mesh material campared with only 26.6% for the latter.

It is plain that meaningful comparisons of ignition temperatures can only be made when any variations due to differences in size consist between samples have been eliminated. This may conveniently be done in any of three ways. Firstly, only sufficiently fine samples may be used. Obviously, there will be much less variation in size consist with -200 mesh (74 micron) coal than with -60 mesh (250 micron) coal. With -325 mesh (44 micron) coal any iffects due to particle size differences should be small indeed. In the second method only closely sized fractions may be used. Thus a comparison of the ignition temperatures of the -200+325 mesh fractions will be more valuable than any comparison between the -60 mesh or even the -60+200 mesh samples. Thirdly, artificial mixtures of fixed proportions may be made up. This last procedure was, in fact, used during this investigation. Mixtures containing an equal proportion of the -60+200, -200+325, and μ325 mesh fractions were made up for a selected seven of the eleven coals, and the ignition temperatures in air determined. The results are given in Table IX.

TABLE IX - IGNITION TEMPERATURES IN AIR OF MIXTURES CONTAINING EQUAL
PROPORTIONS OF -60+200, -200+325, AND -325 MESH COAL

Coal No 1 18.0% V.M.	Coal No 8 22.4% V.M.	Coal No 2 30.2% V.M.	Coal No 3 32.0% V.M.	Coal No 12 39.1% V.M.	Coal No 13 50.2% V.M.	Coal No 15 53.0% V.M.
920 C	875 C	880 C	870 C	885 C	855 C	810 C

It can be seen that the trend is very similar to that shown in Table VI. As between the highest and the lowest volatile coals there is certainly a distinct difference in ignition temperature. On the other hand, between the remaining five coals, which span a range of volatile content from 22.4% to 50.2% (d.a.f.), the greatest difference in ignition temperature is a mere 25 C. Here is additional evidence of the importance of particle size rather than volatile content.

Although it had been assumed that the difference in ingition temperature between coarse and fine coal was due only to size and hence surface area effects, it was necessary to check whether any element of selective breakage in the sample preparation could, by leading to petrographic differences between the various fractions have been partially responsible. It is well known that many of the medium volatile coals are rather friable, and that frequently the vitrain and fusain will tend to concentrate in the finer sizes of such coals whilst the clarain and durain, being more difficult to break, will remain in the coarser fractions. In Table X the ignition temperature in oxygen of three coarse fractions of coals No 2 and 3, and of the -200 mesh fractions, are compared with the ignition temperatures of -200 mesh samples obtained by hand crushing the coarse material.

TABLE X - IGNITION TEMPERATURES IN OXYGEN--COMPARISON OF +200 MESH AND -200 MESH FRACTIONS WITH -200 MESH COAL OBTAINED BY RE-CRUSHING COARSE MATERIAL

Size	Coal No 2	Coal No 3
-60 + 100 Mesh	880°C	875°C
-60 + 200 Mesh	780°C	835°C
-100 + 200 Mesh	700°C	735°C
-200 Mesh	560°C	555°C
-60 + 100 Re-Crushed To -200 Mesh	515°C	495°C
-60 + 200 Re-Crushed To -200 Mesh	565°C	490°C
-100 + 200 Re-Crushed To -200 Mesh	565°C	535°C

In every case the value obtained for the coarse coal re-crushed to -200 mesh was equal to or less than the value originally obtained for a -200 mesh sample. Thus the decrease in ignition temperature with size is predominantly a surface area effect rather than the result of any petrographic distinction between the various size ranges. It is difficult to say just why the re-crushed samples should, in certain cases, have ignition temperatures between 45°C and 65°C lower than the original -200 mesh coal. No sieve analyses of the small quantities of coal re-crushed to -200 mesh were made, and it is possible that in some instances the hand grinding process in the mortar and pestle was carried out somewhat vigorously and resulted in the production of a large proportion of easily ignited super-fines. Another possibility is that, although the decrease in ignition temperature with size is primarily a surface area effect, some of the coarse fractions were sufficiently different petrographically to give different ignition temperatures when re-crushed. A third reason why some of the re-crushed samples could have given lower test results than the original -200 mesh coal was sought in possible oxidation effects. The original -200 mesh coal had certainly had time to oxidise before being tested. The re-crushed samples, on the other hand, were all tested within one or two days of grinding. Oxidised coal might be expected to have a higher ignition temperature than coal which had not long been exposed

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to atmospheric oxygen. This line of thought had to be abandoned, however, after the results reported in the following paragraph had been obtained.

In order to examine whether oxidation effects had any influence on the ignition temperatures given by the inflammability apparatus, -4 mesh samples of coals 1 and 4 were obtained. From these samples, fractions of the following sizes were sieved.

-4+10 mesh, -200+325 mesh, -200 mesh, -325 mesh.

The -4+10 mesh fraction was further crushed to give -200+325, -200, and -325 mesh sub-fractions. In this way there were obtained for both a high and low volatile coal, oxidised and unoxidised samples of -200, -200+325, and -325 mesh material. The ignition temperatures of these samples are given in Table XI.

TABLE XI - IGNITION TEMPERATURES OF OXIDISED AND UNOXIDISED COALS.

	Coal No 1		Coal No 2	
	Unoxidised	Oxidised	Unoxidised	Oxidised
325 Mesh	550°C	555°C	535°C	545°C
-200 Mesh	575°C	585°C	550°C	560°C
-200+325 Mesh	600°C	610°C	585°C	590°C

It can be seen that the effect of atmospheric oxygen on the ignitibility properties of fine coal as determined in this test is negligible.

Crossing Point Temperatures

Duplicate crossing point temperatures in oxygen of the eleven coals are given in Table XII.

TABLE XII - CROSSING POINT TEMPERATURES IN OXYGEN

Coal No	%Volatile Content (D.A.F.)	Crossing Point Temperatures °C	
1	18.0	243	248
8	22.4	243	246
2	30.2	235	239
3	32.0	240	245
12	39.1	232	***
4	42.5	234	238
5	43.2	233	235

16	44.4	236	239
18	46.6	236	239
13	50.2	231	234
15	53.0	235	236

*** Insufficient -60+200 mesh coal available.

All that can be said of these results is that the crossing point temperatures of the two coals containing the least quantity of volatile matter are very slightly higher than those of the high volatile materials.

IV DISCUSSION

Comparison with other studies

Correlation between Ignitibility and Total Volatile Content.

The fact that neither the ignition temperature as determined in the inflammability apparatus, nor the crossing point temperature as given by the Setchkin apparatus, vary very greatly with total volatile content, confirms the doubts of some previous workers that volatile matter alone can provide a satisfactory index of the ignitibility behaviour of a bituminous coal, or of its combustibility or explosibility. It is pertinent at this stage to examine the claims by former investigators that a relationship between such properties does, or does not, exist.

Godbert (39) in an excellent historical survey of laboratory methods of determining inflammability discusses Taffanel's work of 1911 in which a dust cloud was blown by air through a heated tube and the volume of flame produced at the mouth of the tube measured photographically. According to the volume of flame produced, a dust could be placed in one of a number of classes which were designated A, B, C, D, E, F, G, and H, the ignitibility increasing in this same order. Taffanel found that the least inflammable dusts of class A (which gave no flame under the experimental conditions) had volatile contents of less than 10%, whilst those of class B had about 10%. Those of class C had 10-14%, class E 16-24%, class F 24-28%, and those of class G more than 28%. As Godbert points out, however, when the Explosion in Mines Committee

in Britain repeated Taffanel's work, they found ho correlation at all
between volatile content and ignitibility. Of four coals testes, all
had very different inflammabilities despite the fact that their vola-
tile contents were almost the same. According to Godbert, the exper-
iments of Bedson and Widdas (1906-1910), who determined both the ig-
nition temperature and pressure rise upon inflammation of coal dusts,
substantiated to a limited extent the ignitibility - volatile content
relationship found by Taffanel, as did the work of Allison (1925).
The method chosen by Allison consisted of firing an explosive charge
into a coal dust cloud, inflammability being measured by the extent
to which the coal lengthened tha flame produced by a charge of black
powder. In contrast to the results put forward by Taffanel, Bedson
and Widdas, and Allison, Godbert quotes experiments carried out by
Mallard and Le Chatelier (1882) and by the U.S. Bureau of Mines
(1913-1917) which indicated that only an ill-defined relationship
exists between inflammability and volatile content. The Bureau of
Mines' workers only went so far as to state that a coal dust of high
volatile content (e.g. a lignite) was more inflammable than a coal of
average volatile content (e.g. a bituminous coal), and that the lat-
ter was more inflammable than a low volatile material such as anthra-
cite. Using a wooden gallery 4 metres long, 0.15 metres wide and 0.4
metres in depth, in which coal dust was ignited by a lamp introduced
through a window, and also a cubical wooden box of 50 cm sides in
which dust was ignited by a naked flame placed at the centre, Mallard
and Le Chatelier found that the most inflammable dusts contained
more than 30% volatile matter. They did not inflame under any condi-
tions in either apparatus if the volatile contents were less than 25%.
The apparatus used at the U. S. Bureau of Mines consisted of a 1400'
c.c. glass explosion vessel in which coal dust was ignited by an elec-
trically heated platinum spiral. The criterion of inflammability
was the pressure developed by the inflammation. The results indicated
little connection between volatile content and inflammability, and
the relationship suggested by Taffanel could not be substantiated.'
Two further series of tests which also failed to confirm this rela-

tionship are noted by Godbert (ref. 39). In 1891, Holtzwart and Von Neyer tested the explosibility of brown coal dusts by blowing the material with air past a series of electric sparks produced in a glass ignition tube by means of two platinum wires arranged to form a spark gap of 3 to 4 mm. Proximate and ultimate analyses failed to show any correlation between the chemical composition and inflammability of the dusts. Finally, Morgan (1913-1915) showed that no relationship between the proximate analyses of eleven coals (ten bituminous and one lignite) and their inflammabilities could be found. Morgan used a steel explosion bomb in which a dust blown into suspension by an air current was ignited by a hot platinum spiral. The pressure developed was recorded, and the maximum pressure developed taken as a criterion of inflammability. There was absolutely no relationship between volatile content and inflammability.

Mason and Wheeler (40) have reported on a series of tests carried out during 1923-1925 by the British Safety in Mines Research Board in which the inflammability of coal dust was determined by igniting mixtures of dust and incombustible in an explosion gallery by means of a small cannon. Inflammability was assessed by the amount of incombustible (Fuller's earth) that had to be mixed with the coal in order to prevent continuous flame propagation. The results were compared with those obtained inder similar conditions by Taffanel at the Experimental Station of Le Comite' Central des Houillères de France, at Liévin, and by the Bureau of Mines at their Experimental Mine, Bruceton, Pennsylvania. Of their own results, Mason and Wheeler state that, "A rough relationship can be traced between the chemical properties of the bituminous colas tested and the inflammabilities of their dusts, as judged by the amount of incombustible dust that had to be mixed with them to prevent continued propagation of flame under the conditions of the test". They go on to say that "there is a relationship between the content of 'volatile matter' (calculated on an ash-free dry basis) and the amount of incombustible matter which must be present in the mixed coal dust and incombustible dust in order that continued propagation of flame shall not take place (under

standard conditions of ignition), there being a tendency for the
fine dusts from coals containing the higher percentages of volatile
matter to be the more readily inflammable". That the relationship
is a rough one can be seen by the results which Mason and Wheeler
quote. For example, of the twelve bituminous coals tested, coals A
and B contained 40.9% and 40.48% (d.a.f.) volatile matter; the total
incombustible needed to suppress inflammation was 70% and 57% re-
spectively. Coal F contained 36.13% and coal K 28.55% volatile
matter. The total incombustible required for these two coals was
almost identical, being 42% and 41% respectively. Coal E, the vol-
atile content of which at 36.25% was almost the same as that of coal
F, required must more inert to prevent inflammation--58% in fact.
Such results lend emphasis to the statement by Mason and Wheeler that,
"All the investigations, whether carried out on a large or a small
scale, clearly show that the degree of fineness of a coal dust mainly
determines the ease with which it can be ignited and can propagate
flame when raised as a cloud in air." The data which Mason and
Wheeler quote for the experiments at Liévin and Bruceton are shown
in Tables XIII and XIV respectively.

TABLE XIII - INFLAMMABILITY DATA BY TAFFANEL, (REF. 40)

| Coal | % Volatile Matter (D.A.F.) | % Incombustible in Mixtures incapable of flame propagation | |
		Igniting Source A	Igniting Source B
A	40	60	70
I	36	58	72
B	32	60	70
C	23	60	70
D	18	46	55
E	15	50	60
F	13	8	42
H	10	0	Not Tested

TABLE XIV - INFLAMMABILITY DATA BY U.S. BUREAU OF MINES, (REF.40)

| Coal | % Volatile Matter (D.A.F.) | Amount of Incombustible in Mixture incapable of Propagation of Flame | |
		Ignition Source A	Ignition Source B
A - Anthracite	6.0	X	X
B - Anthracite	6.6	X	X
C - Semi - Anthracite	9.9	X	20
D - Semi - Anthracite	10.2	X	X
E - Semi - Bituminous	17.5	37	48
F - Semi - Bituminous	20.0	45	55
G - Semi - Bituminous	20.8	53	65
H - Semi - Bituminous	22.1	52	60
I - Semi - Bituminous	25.4	60	70
J - Semi - Bituminous	27.0	55	65
K - Semi - Bituminous	27.1	61	70
L - Bituminous Coking	32.5	63	73
M - Bituminous Coking	39.6	62	76
N - Bituminous Coking	40.0	63	77
O - Bituminous Coking	40.8	--	82
P - Bituminous Non-Coking	41.7	63	73
Q - Bituminous Non-Coking	42.0	--	74
R - Bituminous Non-Coking	44.9	--	79
S - Bituminous Non-Coking	46.8	67	78
T - Bituminous Non-Coking	49.7	67	78

X   Propagation of flame did not occur with the pure dust.

Of his results, Taffanel is quoted as stating: "Assuming the contents of volatile matter of a coal to afford a rough measure of its quality, it would appear that the proportion influences the inflammability of the dusts to the greatest extent when the volatile matter contents of the coals are comparatively low. In general one can say that a coal dust is more inflammable the more volatile matter it contains, but the differences are not great if the proportion exceeds 25%; whereas, when the coal contains less than 25%, the decrease

in inflammability of the dust with decreasing volatile matter content is very marked." The same remarks apply almost equally well to the data obtained by the Bureau of Mines at Bruceton.

In a later series of tests carried out by Mason and Wheeler (41) in 1928, the relative inflammability, as measured by the mean flame speed over a given distance, and the relative explosibility, as measured by the maximum pressure developed, were measured, and compared with the relative inflammability as determined for the same coals from the quantity of inert dust needed to suppress inflammation. The tests were carried out in a larger diameter explosion gallery than that used in the work of 1923-1925. The results are shown in Table XV.

TABLE XV - RELATIVE INFLAMMABILITY AND EXPLOSIBILITY
(Mason and Wheeler), Ref. 41

Coal	% Volatile Content Dry Ash-Free Basis	Relative Inflammability Incombustible Dust Required to Suppress Inflammation Percentage	Mean Flame Speed F.P.S.	Relative Explosibility Max. Pressure Lbs. per Square Inch
A	40.97	65	380	37
B	40.48	50	340	38
C	39.63	55	360	47
E	36.25	55	356	40
F	36.13	35	299	29
G	34.62	45	256	29
H	34.08	45	337	25
I	32.76	45	272	33
K	28.55	35	276	28
L	27.44	30	260	19

Mason and Wheeler considered that this data showed "the general utility of volatile matter determinations as a guide to their degree of inflammability and explosibility", and they go on to state that "the order of inflammability and the order of explosibility as thus determined are approximately the same".

Godbert and Wheeler (29) have given values for the relative

inflammability of sixty British coals varying in volatile content
from an anthracite with 5.3% (pure coal basis) to a high volatile
coal with 43.6%. The apparatus they used was identical in principle
with that employed during the present research, but the criterion of
inflammability adopted by Godbert and Wheeler was the number of parts
of inert dust per part of coal dust which were required to suppress
ignition. The inflammability as thus determined was plotted against
volatile content on a pure coal basis. Of the resulting chart,
Godbert and Wheeler have this to say: "This diagram shows clearly
the general tendency for the inflammability of the dusts to increase
with their volatile contents, but it also shows that the relationship
is far from a strict one. For example coal B18 contains 32.7% of
volatile matter and coal B19 mearly the same amount, 31.1%. Yet the
inert dust limit of B18 is 22 and that of B19 is only 13. Similar
departures from a strict relationship are noticeable throughout the
range of coals". To emphasise the extent of the variation from a
strict relationship between volatile content and inflammability
Table XVI has been prepared from selected values taken from the com-
plete data for the 60 coals.

TABLE XVI – SELECTED VALUES OF INFLAMMABILITY AND VOLATILE CONTENT
TAKEN FROM DATA BY GODBERT AND WHEELER, (ref. 29)

Coal No	Inert dust limit. Parts of Inert Per Part of Coal	% Volatile Content Pure Coal Basis
17	21	43.6
31	12	39.1
19	12	34.0
8	19	33.5
20	21	33.2
15	16	33.2
39	24	33.0
44	10	31.5
53	12	26.9
57	10	25.9
40	5	25.4
45	5	14.2

These values have been plotted in Figure 14, from which it can be seen that there is little relationship between inflammability and volatile content. Admittedly only thirteen coals which show poor correlation have been chosen out of the sixty which were tested. However, reference to the original paper will show that, over about 20% volatile content especially, (that is, for the majority of the sixty coals) serious departures from anything but a very rough relationship can be found.

If the evidence from more recent work is considered, the same lack of a satisfactory relationship between the total volatile content of a bituminous coal and its ignition, combustion or explosion behaviour is found. Ceely and Wheater's conclusion (12) that the ignition and combustion characteristics of a coal cannot be closely correlated with the quantity of volatile matter alone, has already been mentioned; and attention has also been drawn to the fact that the reactivity indices T15 and T75 determined in the test developed at the Coal Research Laboratory of the Carnegie Institute of Technology show very little variation over the range 17-37% volatile matter (d.a.f.). Lambie (14), who investigated the combustibility of coal and peat by a technique identical with that of Godbert and Wheeler (Ref. 29) found that in the case of thirteen coals ranging in volatile content from 5% to 35%, there was close correlation between inflammability and volatile content for coals having less than about 28% volatile matter; but that at higher volatile contents the correlation was poor. For peats there appeared to be no correlation, and very little relationship either between inflammability and carbon, oxygen, or hydrogen content, or calorific value. Phillips (11) who obtained the ignition temperatures of anthracites, bituminous coals, coal chars, cokes, petroleum cokes, and charcoals in a very similar way to that used in the present research, found a rough, general relationship whereby higher volatile fuels tended to have the lower ignition temperatures, but very considerable scatter can be seen in his
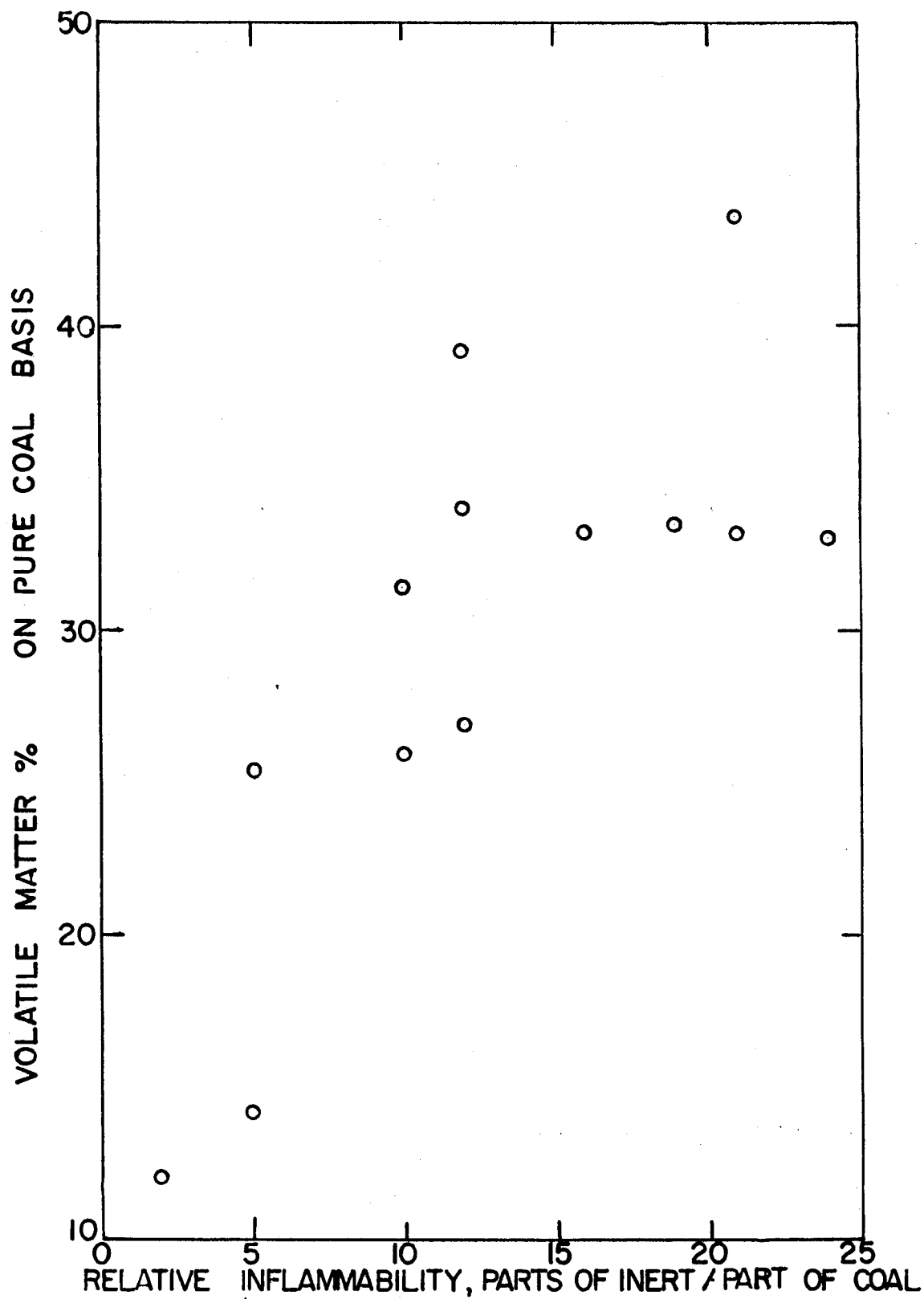
FIGURE 14 Relationship between inflammability and volatile content.
(after Godbert and Wheeler, ref. 29)

plot of ignition temperatures against volatile contents. Hartmann (42), in a report of work carried out upon coal dust explosions by the Bureau of Mines, states that, "the combustible volatile content of coal, related to its age and rank, has a most important effect on the explosibility of the dust. For low volatile coals the explosibility increases almost linearly with increase in the volatile content, but above about 25%, in the range of medium and high volatile bituminous coals, the explosibility rises only slightly with increase in volatile content."

The Mechanism of the Ignition Process

The processes which occur when a cloud of coal particles is injected into a hot environment are complicated indeed, and no universally acceptable explanation of the mechanism of ignition of coal dust has yet emerged. Two theories have been proposed, the "pre-distillation theory" and the "thermal theory". According to the former, which was the first to be put forward, the energy provided by the source of ignition raises the temperature of the dust particles, causing an evolution of volatile matter. The gases thus released then mix with air and rapidly ignite, the heat evolved being sufficient to cause ignition of the solid particles. According to the "thermal theory", which has also been termed the "direct oxidation" theory, ignition occurs directly without the distillation of volatile matter. The coal dust receives energy from the igniting source, a temperature being reached at which the production of heat by oxidation is more rapid than the rate of heat dissipation. Continous surface heating then follows and leads to visible ignition, after which the propagation of flame is assured by the conduction and radiation of heat to the neighbouring unburned layers of the mixture of dust and air. It is obvious that if the "predistillation theory" be accepted, the ignitibility of coal dust suspensions will depend to a great extent upon the characteristics of the volatile matter. If, on the other hand, the "thermal" or "direct oxidation" theory is correct, the surface properties of the original coal particles and of the partially charred or carbonised particles must be over-riding importance.

It has been made abundantly clear that the lack of any relation-
ship between total volatile content and ignitibility as discovered in
the present investigation, has been confirmed by the results obtained
by other investigators. Even had such a relationship been widely and
definitely proved, however, it would not, as has sometimes been
claimed, justify the conclusion that the pre-distillation theory is
correct. The volatile content of coal is determined in the laboratory
under carefully standardised conditions of time and temperature
which in no way correspond to those of actual ignition, in which the
particles undergo very high rates of heating. It cannot therefore
be said that the amount of volatile matter obtained from the standard
laboratory test will correspond with that actually released during
ignition. Furthermore the volatile content given by the standard
determination includes not only inflammable gases such as the hydro-
carbons, carbon monoxide and hydrogen, but also incombustibles such
as water and carbon dioxide. Thus, although the low rank coals such
as brown coal and lignite have high total volatile contents, much of
the volatile matter consists of carbon dioxide and water. The relative
proportions of combustible and incombustible gases vary from coal to
coal. If, then, a direct relationship between total volatile content
and ignitibility or inflammability exists, it seems improbable that
such a relationship will exist between the amount of combustible
volatile material and the ignitibility. Yet, the latter is certainly
what might be expected. There are further objections to the pre-
distillation theory; for instance, the fact that although the ignition
temperatures of the decomposition products of coal vary considerably,
in many cases they are higher than that of the dust itself. Perhaps
one of the most serious objections against the pre-distillation
theory, however, is the telling accumulation of evidence in support of
the fact that ignition at the coal surface occurs first and is then
followed by ignition of the volatile matter. The identical sequence
of events leading to the ignition of fuel beds, as observed by Rosin
and Fehling (7) and Carman et al (25) has already been described, viz.
development of glowing nuclei at the surface of the particles, fol-

lowed by sudden ignition of the volatile matter. Godbert (39) discusses experiments carried out by the U. S. Bureau of Mines to determine to what extent distillation of coal dust particles prior to their inflammation occurs, and states that, "these experiments conducted at the Bureau of Mines suggest that the influence of the gases distilled from coal have little influence on its ignitibility". However, in his next sentence he qualifies this statement by adding that "it is not, however, logical to generalise from experiments on a few coals, and it may be that with other coals and other conditions of ignition, the volatile constituents of a coal may play an important part in its ignition". Orning (43) studied the ignition of individual coal particles by photographing their descent through a vertical, electrically heated furnace and by observing their behaviour when placed upon a refractory pedestal in a miniature furnace (which could reach 950°C within two seconds) and viewed through a microscope. In the miniature furnace it was found that the volatile matter rarely ignited, but that ignition of the solid residue occurred at one point and then moved as an ignition wave over the surface. As far as the experiments in the larger furnace were concerned, Orning states that "Ignition of the solid residue was not conditioned upon the prior ignition of the volatile matter". The photographic records of the experiments carried out in the larger furnace at 800°C showed that volatiles ignition occurred only rarely, although occasionally a particle would show ignition of the coke residue. When ignition of the volatile matter did take place the photographs showed two or more particles igniting in positions so close together that they must have helped each other to ignite, the effect being particularly marked with finer coal.

The fact that in the present investigation no relationship between total volatile content and ignitibility could be found, together with the experimental evidence obtained by others (and discussed above) leads to the conclusion that the ignition of bituminous coal may best be described by the "thermal theory"; and that the surface characteristics of the original, and of the partially charred, coal

particles are of greater importance in the ignition process than the
properties of the volatile matter.

Limitations and Applications of the Study.

Because coals ranging from low volatile bituminous to high vola-
tile C bituminous have shown very similar ignitibility behaviour when
examined by the inflammability and crossing point tests, it should
not be assumed that coals of all rank would behave identically under
these test conditions. Still less should it be assumed that coals of
all rank are equally easy to ignite under industrial burning condi-
tions. Neither low rank coals such as those of the lignitic or sub-
bituminous class have been tested, nor has any work been done with the
anthracites. It is believed that the pronounced difference in surface
reactivity towards oxygen which exists between the low and high rank
coals would certainly make itself evident in both the tests described;
so that significantly lower ignition and crossing point temperatures
would be obtained with lignites, for instance, than with anthracites.
For the same reason (i.e. lower surface reactivity towards oxygen) it
is believed that cokes would give high ignition and crossing point
temperatures, and that some coal chars might well yield lower values
than those of the original coals from which they were made, because of
the effects of surface activation. As far as ignition in practice is
concerned, an anthracite can certainly not be ignited with the same
ease as can a high volatile bituminous coal. However, the results ob-
tained in this study seem strongly to suggest that the differences in
ignitibility behaviour between the high and low volatile bituminous
coals may not be as great as are often believed; and that, provided
ample oxygen is available, bituminous coals over a wide range of vola-
tile content will, in the size consist used for normal pulverised fuel
firing, ignite at much the same ambient temperature when projected
into a suitable hot environment. That differences in ignitibility
within the bituminous class itself are in fact found in practice may
seem inconsistent with the latter statement. It must be remembered,
however, that even in the case of the inflammability test where the
conditions do attempt to simulate to some extent those which are of

importance in industrial furnaces, the circumstances under which igni-
tion takes place are not those of an industrial burning process.
Nevertheless, if coals of such widely different volatile contents can
be brought to ignite over a comparatively small range of temperatures
in the laboratory (contrived and favourable to ignition as the in-
flammability test may be), there is little doubt that all bituminous
coals can be satisfactorily dealt with in practice. If the results
with the eleven coals examined can be taken as typical, then the dif-
ference in ignitibility found in practice between bituminous coals
of high and low volatile content is not completely determined by the
properties of the coal.

V SUMMARY AND CONCLUSIONS

The ignitibility behaviour of eleven coals ranging in rank from
low volatile bituminous to high volatile C bituminous has been
examined by means of two laboratory tests. The ignition temperatures
of dusts ranging in size from -60+200 to -325 mesh (U. S. Sieve
Series) were determined in oxygen and in air using the Godbert inflam-
mability apparatus, in which 0.2 gram of coal was blown downwards
through a heated, vertical ignition tube using 2000 cc. of gas at a
pressure of 12" mercury. The ignition temperature was taken as the
minimum required at the ignition tube wall in order that a flame
should be produced just beyond the bottom of the tube. The crossing-
point temperatures in oxygen of 3.0 gram samples of the -60+200 mesh
coals were obtained with a Setchkin Ignition Apparatus for solids.
In this test the temperature/time history of a coal was compared with
that of the preheated oxygen with which it reacted under the standard
conditions of the test. The oxygen flow through the apparatus was 5
feet per minute, its temperature being raised at the rate of 9°C per
minute. The crossing-point temperature was that at which the tempera-
ture/time curves of coal and oxygen intersected.

No correlation between the volatile content of the coals and
either their ignition point temperatures in air or oxygen, or their
crossing point temperatures in oxygen, was found. Results with the
inflammability apparatus showed, however, a definite decrease in

ignition temperature with decrease in particle size.

The following conclusions were drawn from the study:

(1)   The ignitibility of a bituminous coal is determined not by its total volatile content, but rather by the surface properties of both the original and partially charred or carbonised particles.

(2)   Differences in the ignitibility of the bituminous class of coals are less marked than has sometimes been supposed; provided that sufficient oxygen is available, bituminous coals over a wide range of volatile contents will ignite at much the same ambient temperature when projected into a suitable hot environment in the size consist used for pulverised fuel firing.

(3)   The ignitibility of a cloud of coal dust particles increases as the particle size decreases. Particle size is more important in the ignition process than is the influence of volatile content.

(4)   In a dust suspension consisting of particles of different sizes, ignition commences with the finer particles and spreads throughout the whole mixture. As long as an adequate proportion of superfines is present, quite a percentage of coarse material can be tolerated.

(5)   The experimental evidence supports the "thermal" or "direct oxidation" theory of ignition, which maintains that ignition occurs directly, without the distillation of volatile matter.

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