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Final Report

IGNITION OF GASEOUS MIXTURES WITH ELECTRICALLY HEATED WIRES

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ABSTRACT

The results of a study of the ignition process in a stagnant, gaseous mixture are presented. Electrically heated wires of various materials and diameters were employed as the source of ignition energy. The effect of variation of energy input rate upon ignition time was investigated.

High-speed motion pictures were taken of the hot-wire-ignition process in order to study the growth characteristics of the combustion region. A relatively small number of ignition tests using electrical sparks were photographed for purposes of comparing the spark-ignition and heated-wire-ignition processes. These two processes appeared similar.

A mathematical model of the hot-wire-ignition process is presented. This model correlates much of the experimental data.

OBJECTIVE

The objective of this study is to obtain a better understanding of the ignition process and to establish the parameters which are important to ignition.

INTRODUCTION

Developments in reciprocating engines have indicated a need for additional information regarding the ignition of combustible mixtures. Such information should be useful in improving existing spark-ignition system or in the development of new and different types of ignition systems.

The process of igniting a combustible mixture by a heated body shows promise of providing useful information regarding the ignition process. A research program was initiated at the University of Michigan Aircraft Propulsion Laboratory by the Chrysler Corporation for the study of the ignition process, principally by the use of a heated wire.

This is a final report of the first phases of that study.

PRELIMINARY ANALYSIS

The ignition process in an internal-combustion engine is difficult to study. It takes place in a short-time interval and in a region where the volume and pressure are changing. Because of the difficulty involved in studying the problem in the engine itself, it was necessary to design an experimental apparatus which retained the important physical aspects of the phenomenon, and yet which was flexible enough to permit changes in the test conditions as the experiments progressed. Further, it was desired that the ignition process be isolated as much as possible from extraneous effects. To this end, the following ideas were considered.

Since the time required for ignition to occur after energy is applied to the mixture is small, the piston movement and hence pressure change during this time interval are small enough to be neglected. Thus, a study of ignition in a constant pressure chamber is sufficient.

A combustible mixture and a means of putting energy into a small region in this mixture are necessary items for the study of ignition. The type of fuel or energy input may change quantities relative to one another, but the basic idea will remain the same.

Therefore, a hydrocarbon gaseous fuel, such as propane, would be a good choice and easy to use experimentally. Further, the choice of an energy supplier is not critical in that the only physically important fact is that energy be supplied in a small region at a high rate. Hence, either a spark plug, or a hot wire, for instance, could be used.

It was believed that the important parameters would be time for ignition, rate of energy addition, fuel-air ratio, fuel, pressure, and temperature. Instrumentation was considered for the accurate and rapid measurement of the necessary quantities. Moreover, since so little is understood about the actual ignition mechanism, it was believed important to provide visual representation of the whole process with Fastax movies. This necessitated the use of a glass-walled chamber.

EXPERIMENTAL APPARATUS AND PROCEDURE

The test procedure consisted of recording, during the time required for ignition, the amount of current through and voltage applied to a wire immersed in a gaseous fuel-air mixture. The time of ignition was also recorded. This procedure required the following equipment: a test chamber and fuel-air supply system, multichannel recording equipment, and motion-picture equipment. Additional equipment was required for the spark-plug tests.

TEST CHAMBER AND FUEL-AIR SUPPLY SYSTEM

A schematic diagram of the test equipment may be seen in Fig. 1. The test chamber used was a 15-inch-long section of four-inch pipe with 1-inch-thick glass ends. The relative position of the thermocouples, hot-wire assembly, spark plug, and inlets and outlets may be seen in Fig. 1.

1. Propane-Air Experiments.—The fuel-air supply system for the propane-air experiments consisted of six buried 3-cubic-foot cylinders containing premixed propane and air. The cylinders were filled, using a partial-pressure technique and the resulting mixtures were analyzed. The procedure used for charging the test chamber was as follows:

a. The test chamber was evacuated to a pressure of 6 inches of Hg absolute.

b. The propane-air mixture was added until the pressure was approximately 25 psi greater than the desired test pressure.

c. The chamber was again evacuated to 6 inches of Hg absolute and refilled to a pressure 25 psi greater than the test pressure.

d. The test-chamber pressure was reduced to the desired test pressure.

e. The recording equipment was turned on and the charge was ignited.

2. Gasoline-Air Experiments.—In order to conduct the few experiments made with gasoline, a simple procedure was used to charge the test chamber with a combustible gasoline-air mixture.

a. The test chamber was filled with air and then evacuated to 6 inches of Hg absolute.

b. A known volume of liquid gasoline was metered from a 5-ml pipette into a section of the test-chamber feed line.

c. This metered amount of liquid was then allowed to evaporate into the evacuated test chamber.

d. Additional air was then fed to the test chamber through the section of the line previously occupied by the liquid gasoline, until the desired pressure was reached.

e. The recording equipment was turned on and the charge was ignited.

The above procedure, while not permitting accurate determination of the gasoline-air ratio, resulted in a mixture containing all the components initially present in the gasoline, not just the lighter hydrocarbons.

HOT-WIRE ASSEMBLY AND POWER SUPPLY

A sketch of the hot-wire assembly chamber may be seen in Fig. 2; as indicated, the length of wire which was heated electrically was one inch. Care was taken to insure that the wire was mounted between the terminal posts in the same manner for each experiment. The motion pictures indicated that in each case the wire sagged slightly during heating, because of thermal expansion.

During these experiments, no attempt was made to prevent wire burnout. Wire burnout could have been prevented by using a different type of electrical circuit (such as a condenser discharge circuit) or incorporating additional equipment in the circuit used, but it was

believed that the technique used would result in more information being obtained in the time available.

The power supplied to the hot wire was obtained from two 12-volt storage batteries. Thus, any voltage from 2 to 24 volts, in 2-volt increments, could be applied, thereby allowing the wire-heating rate to be varied over a wide range.

MULTICHANNEL RECORDING EQUIPMENT

The voltage drop across the wire, the current through the wire, the temperature of the gas in the test chamber, and the quantity of light emitted from the test chamber were continuously recorded by a Consolidated Engineering Corporation Type 5-119 Recording Oscillograph. The thermocouples (see Fig. 1) were used to indicate gas temperature and were a delayed but positive indication that combustion had occurred.

The quantity of light emitted from the test chamber, as indicated by a photomultiplier tube located as shown in Fig. 1, was used as a means of indicating the time of ignition.

A diagram of the electrical circuit used for the hot-wire experiments is shown in Fig. 3. The galvanometers used in the oscillograph in the voltage and amperage circuit had a flat frequency range of over 2000 cps, as installed.

The galvanometers used to record the thermocouple outputs were sensitive, but because of this sensitivity they had a low-frequency response, 30 cps. This response time was not a problem, since no attempt was made to interpret the instantaneous temperature during combustion.

The voltmeter and ammeter shown in Fig. 3 were used to calibrate the recording circuits. During combustion tests these meters were left in the circuit, even though most tests were of such a short duration that the meters did not respond. This was done to insure that all connections in the electrical circuit would be identical during tests and calibration.

The oscillograph used was capable of various paper speeds up to 100 inches/sec. Practically all tests were recorded at paper speeds of 40 inches/sec. since this speed was adequate. A typical oscillograph record is shown in Fig. 4.

HIGH-SPEED MOTION-PICTURE EQUIPMENT

High-speed pictures were taken of the ignition process in order to calibrate the photomultiplier-tube system as well as to obtain additional information regarding the mechanism of ignition. A Fastax camera and related timing equipment (Wollensak Optical Company, Rochester, New York) were used. The Fastax film speed throughout these tests was approximately 4000 frames/sec.

The photomultiplier-tube system was calibrated by photographing the hot wire and its immediate surroundings during a hot-wire-ignition test in which the wire melted shortly after ignition was initiated. The output of the photomultiplier tube, the voltage across the hot wire, and the current through the wire were recorded by the oscillograph. At the instant of local fusion and separation (i.e., burnout) at some point along the wire, an electrical arc occurred which was visible on the high-speed film. Burnout was indicated on the oscillograph record by a sudden increase in indicated voltage and an abrupt decrease in indicated current. (The voltage indicated immediately after burnout was essentially the voltage applied to the entire system while current dropped to zero.)

In this manner, one point in time, namely, burnout, was common to both the Fastax and oscillograph records. The time of "incipient" ignition relative to burnout was determined from the Fastax film by counting the number of frames between ignition and burnout and dividing by the frames exposed per second. (Sixty-cycle signals on the Fastax film established the film speed.)

The time increment between "incipient" ignition and burnout, as determined by the Fastax, could be transposed to the oscillograph record. Figure 4 is a typical oscillograph record. The time of ignition, as determined by the Fastax film, is indicated on this record. The time of "incipient" ignition, as determined by the photomultiplier tube, was found to correlate with the Fastax film in several trial runs, and was therefore used as the sole means of determining ignition in practically all the hot-wire tests.

The photomultiplier tube was sensitive to light emission from the hot wire and from the arc at wire burnout as well as light due to the combustion process. The output of the photomultiplier tube due to combustion, as separate from that output due to wire heating and fusion, was determined by comparing the photomultiplier-tube output of a combustion test to that output obtained when no fuel was present in the test chamber, all other test parameters being maintained constant.

"Incipient" ignition is said to have occurred when any part of the region immediately adjacent to the hot wire shows indications of combustion.

The time period between application of voltage across the wire and the occurrence of incipient ignition is thus defined as ignition time.

SPARK-PLUG EQUIPMENT

Two different techniques were used in triggering the spark. The first method employed an automobile ignition coil and distributor. The distributor rotor was turned by an electric motor. This resulted in repeated sparking. Upon viewing the high-speed pictures of spark ignition due to repeated sparks, it was decided to alter the system so that only one spark was triggered. The single-spark system also employed typical automotive equipment, except that the distributor was replaced by a relay switch which was opened at the instant a single spark was desired. Fastax photography was used in conjunction with both the repeated- and single-spark systems.

EXPERIMENTAL RESULTS

EFFECT OF PRESSURE ON IGNITION TIME

Experimental ignition data obtained with heated 28-gage nickel wire are plotted in Fig. 5. Similar data are obtained by using 24-, 30-, and 32-gage nickel wires. These tests were conducted while using the various wire sizes at various heating rates and propane-air mixture pressures.

Figure 5 indicates the existence of a relation in the form of

$$P = Ae^{Bt},$$

where

P = mixture pressure, atmospheres,
A = the logarithmic intercept,
e = the natural logarithmic base,
B = slope of the line, and
t = ignition time, milliseconds.

The slope B in Fig. 5 is close to zero, and it is indicated that the initial mixture pressure has only a slight effect on ignition time.

It was intended to conduct all the nickel-wire experiments at a constant mixture ratio, but subsequent analysis showed that such was not the case and the actual ratios are:

Pressure, atm	Wire Gage	Propane-Air Ratio
1	24, 28, 30, 32	0.0803
2	24, 28, 30, 32	0.085
3	30, 32	0.085
3	24, 28	0.059
4	24, 28, 30, 32	0.059

Initial mixture also varied due to variation in ambient temperature, heating of the combustion chamber due to successive explosions, and the different expansions of the fuel-air mixture from storage into the combustion chamber. These variables influence initial wire temperature and, using the theoretical analysis, it is estimated that a ten-percent variation in wire-temperature results in a variation of ignition time of the order of a factor of 2. No experimental investigation has yet been made of the effect of initial wire temperature upon ignition time.

In seven out of eight of the tests using 32-gage nickel with atmospheric pressure propane-air, burnout of the wire occurred prior to ignition and some deviation from the semilogarithmic straight-line relation occurs.

EFFECT OF WIRE DIAMETER AND HEATING RATE ON IGNITION TIME

Theoretical considerations indicate that, for constant initial mixture pressure and fuel-air ratio, a straight-line relation should be obtained when the average wire-heating rate divided by the square of the wire diameter is plotted against the reciprocal of ignition time.

Figure 7 illustrates experimentally this straight-line relationship for ignition tests using nickel wire (gages 24, 28, 30, and 32) with propane-air mixture pressures ranging from one to four atmospheres and the fuel-air ratios listed in the preceding section on the effect of pressure on ignition time.

A graph of $\overline{EI}/d^2$ directly against ignition time for the data of Fig. 7 is given in Fig. 8 and it is shown that ignition time may be reduced by increasing the wire-heating rate. Or, for constant wire-heating rate, ignition time may be decreased by using smaller wire diameter.

EFFECTS OF WIRE MATERIAL ON IGNITION TIME AND ENERGY

The only variations in ignition times and energies noted for the various materials tested were those effects that could be attributed to the differences in heat capacities of the wires. The data for these materials are shown in Figs. 9, 10, 11, and 12.

HIGH-SPEED MOTION-PICTURE STUDY OF IGNITION

A summary of the conditons under which the high-speed motion pictures of incipient ignition were taken is given in Table I. Where applicable, a comparison of times given by the motion pictures and by the photomultiplier tube is listed.

The Fastax motion pictures show that the first observed combustion is a cylinder of flame enveloping the heated wire and usually extending along the wire length. The volume of the first observed combustion region may reach and remain at some stationary value for a relatively long time interval, and, in some instances, this preliminary combustion zone may become detached from the sagging heated wire. The preliminary combustion zone may move away from the proximity of the wire binding posts. Subsequent to the preliminary combustion, when the chemical reaction becomes completely self-sustaining, the flame propagates quite rapidily throughout the entire volume of the combustion chamber.

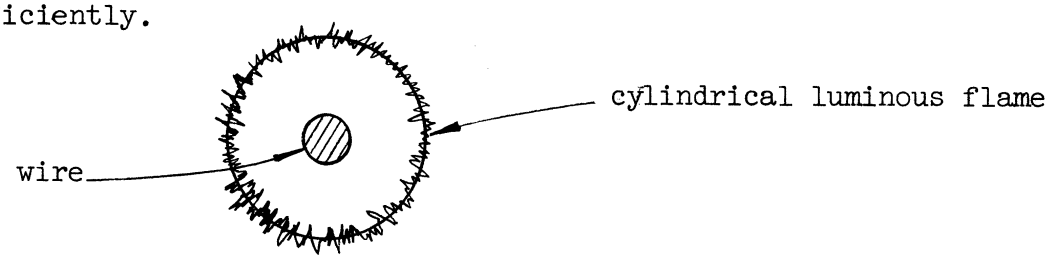
ANALYSIS

The solution to the ignition problem would involve solving the Navier-Stokes equations in rather general form. This is impossible to accomplish at this time since the equations are nonlinear. However, with the aid of experimental observations it is often possible to formulate a mathematically simpler model of a specific problem which conforms in the important physical aspects with the actual phenomena. Using this model, then, the equations can be simplified and a solution

may be obtained. More basic, however, is the fact that if the model is correctly formulated, only the essential terms are left in the equation, and nondimensionalizing these terms results in a knowledge of the parameters which are most important. Hence, setting up the properly simplified equations and the boundary conditions can give parametric relations which may be used in correlating the experimental data. The worth of an actual mathematical solution then depends on the accuracy of this correlation.

In applying the above-mentioned method to the present problem, then, it was necessary to formulate a mechanism which was consistent with the observed facts. From the high-speed photographs of the ignition process, it was found that the following series of events occurs during the ignition of a gaseous fuel by a hot wire.

(A) - As heat is transferred from the wire to the surrounding combustible gas (at rest), the first noticeable combustion is a ring of flame around the wire. This occurs after the wire has been heated sufficiently.



Cross Section of Cylindrical Flame and Hot Wire

This flame is positioned at a small distance from the wire, perhaps creeping outward at a very low rate.

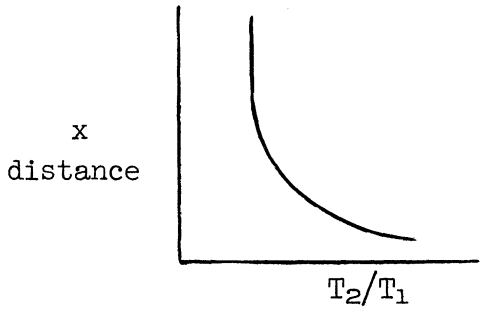
(B) - At a certain time after the first luminous zone has been noticed, the flame moves out with a very high velocity and quickly burns the gas in the container. This time interval is very small (of the order of a hundredth of a second).

The following mechanism is proposed as a possible explanation of this ignition process.

As the time during which current is being fed to the hot wire increases, and thus as more and more heat is conducted to the fluid, the mixture begins to react, starting at the surface of the wire. This combustion soon reduces the concentration of fuel at the wire surface to zero and gives off some heat; this heat, small though it is, added to the heat being conducted from the wire, maintains the combustion, the zone of reaction moving slowly outward. This flame must be fed by diffusion of combustibles into the flame zone if it is standing almost still, or it must move outward at its laminar flame velocity, in which

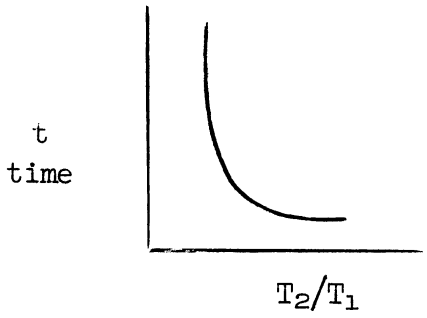
case diffusion may or may not play an important part. The usual flame speeds of hydrocarbon fuels are of the order of one to two feet/sec, so that the distance covered during the interval of slow burning would be of the order of .02 to .04 foot or .24 to .48 inch. Since no distances approaching this magnitude were observed, it is concluded that the flame was relatively steady in position during this slow-burning time interval, and thus almost completely fed by diffusion. The diffusion of fuel and air into the flame zone is a result of the high-concentration gradients existing between the burned and unburned regions. Thus, an almost stable situation is set up where hot products of combustion are being stored between the flame and the wire, with the flame being fed entirely by diffusion of fuel and air toward the wire. During this semi-stable interval, heat is being conducted from the flame and hot region behind it, outward over the whole region of unburned gas. At some temperature which is characteristic of the fuel at the given pressure, the reaction rate reaches a value high enough so that the reaction is self-sustaining, and then the flame propagates very quickly throughout the whole region.

The ignition problem may be compared to the following problem.[1] Consider two parallel streams of gas moving at the same velocity. Initially they are separated by a thin flat plate. At the trailing edge of the flat plate, the two streams mix. The upper stream, say, consists of a cool combustible mixture, while the lower stream consists of hot products of combustion. As the two streams mix, cool fuel diffuses into the hot gas and heat is transferred from the hot to the cool. Thus, a reaction is initiated and proceeds faster and faster until a flame is established. It has been found that the distance from the trailing edge of the plate to the flame increases exponentially as the temperature of the lower stream goes down. (See sketch.)



$_2$ refers to hot lower stream
$_1$ refers to cool upper stream

Now, if instead of two streams mixing, one considers a fuel being ignited by contact with a hot gas, both at rest, then the same plot obtains, except that one is concerned with the time it takes for a fully developed flame to form instead of the distance as used in the above problem with flowing gases. (See sketch.)



2 refers to hot gas
1 refers to cold gas

Finally, with the exception of the effects of diffusion at the wall, the above problem is a two-dimensional approximation to the one under consideration; that is, one could substitute a hot plate for a hot gas and t would be the time that passes before the semistable flame changes into the rapid combustion which burns the whole region. T_2/T_1 would then be the ratio of the temperature at the wire surface to the initial temperature of the fuel-air mixture. For constant initial fuel-air mixture temperature, T_2/T_1 then depends on the electrical input into the wire. Experiments designed to corroborate this idea would consist of putting energy into the hot wire for varying intervals of time and timing the semistable interval. It is proposed that these experiments be carried out at a later time. The above considerations are used in defining a characteristic chemical time in the subsequent mathematical descriptions.

Next, a mathematical description of the phenomenon may be set up. While a complete analytical solution of even the approximate equations would probably involve too much labor at the present time, setting up the mathematical problem can give much information for little labor. In particular, it is useful to write both the equations and the boundary conditions in nondimensional form. If it is possible to nondimensionalize the equations and the boundary conditions completely, then a solution of this nondimensional problem should be good for all fuels, boundary conditions, and wires. Thus, one must be able to find the conditions such that the equations and boundary conditions remain the same for all cases to be studied. These conditions then give the parametric relationships which should correlate the experimental data if the model chosen is correct.

In view of the length of the wire compared to its diameter, it is assumed that the equations can be written in two-dimensional polar coordinates; in fact, variations along the circumference of any circle concentric with the hot wire are neglected, so that the radius is the only important space variable. The conservation equations, for a nonsteady flow, are then:

Conservation of Mass;

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial(\rho u r)}{\partial r} = 0 \qquad (1)$$

$$\rho \frac{\partial k_i}{\partial t} + \rho u \frac{\partial k_i}{\partial r} = -\frac{1}{r}\frac{\partial}{\partial r}(\rho_i \bar{u}_i r) + m_i K_i$$

Conservation of Momentum;

$$\rho\frac{\partial u}{\partial t} + \rho u\frac{\partial u}{\partial r} = -\frac{\partial P}{\partial r} + \frac{4}{3}\frac{\partial}{\partial r}\left(\frac{\mu}{r}\frac{\partial}{\partial r}(ru)\right) + \frac{\partial}{\partial r}\left(u\frac{\partial \mu}{\partial r}\right) - \frac{u}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \mu}{\partial r}\right) - \frac{1}{r}\frac{\partial \mu}{\partial r}\frac{\partial}{\partial r}(ru) \qquad (2)$$

Conservation of Energy;

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p\, u \frac{\partial T}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right) + u\frac{\partial P}{\partial r} - \sum_i m_i k_i K_i + \Phi \qquad (3)$$

and the equation of state is

$$P = \rho RT/M\,, \qquad (4)$$

where

ρ = local density of mixture,
u = velocity in radial direction,
ρ_i = density of ith species,
k_i = mass concentration of ith species = ρ_i/ρ,
$\bar{u}_i$ = radial diffusion velocity of ith species
m_i = mass of molecule of ith species,
K_i = rate at which molecules of the ith species are produced,
P = pressure,
μ = dynamic viscosity,
C_p = specific heat at constant pressure,
T = temperature,
λ = coefficient of thermal conduction,
h_i = enthalpy of ith species per unit weight,
Φ = viscous dissipation function,
M = molecular weight of mixture,

R = universal gas constant,
r = radial distance, and
t = time.

Next, in view of the mechanism formulated above, one can make the following assumptions:

1. Since the only perturbations in pressure are those introduced by the flame, until the quasi-stable or "slow" flame has changed into the fast flame, changes in pressure are neglected. This is in accordance with the usual flame theory where ΔP across a deflagration is considered negligible. This means that the momentum equation need not be considered.

2. A binary (two-component) mixture is considered, one component being the fuel-air mixture, the other being the products of combustion. This means that a first-order reaction of the type $A \rightarrow bB$ is considered. (A = fuel-air mixture, B = products, and b = number of moles of B formed by each mole of A.) Actually, the assumption is that the physically correct combustion, consisting of many reactions of varying rate and order, may be replaced by an overall or global reaction of first order. The results of this assumption are as follows:

$$\rho_i u_i r = -r\rho D_{12} \frac{\partial k_1}{\partial r}, \tag{5}$$

where D_{12} = binary diffusion coefficient, and

$$m_1 K_1 = -\frac{\rho k_1}{\tau} e^{-A/RT}, \tag{6}$$

where τ = characteristic chemical time of reaction and A = activation energy. Since a two-component system is considered ($i = 1$ or 2), one need consider only one component mass-flow equation and the overall mass-flow equation. Hence, if k_1 = concentration of combustible, and k_2 = concentration of products (note $k_1 - k_2 = 1$), then one could write an equation involving only k_1. Finally, for simplicity, the subscript is dropped and, henceforth, k = concentration of combustible and 1-k = concentration of products.

3. u is small enough that the convection terms are small compared to the nonsteady and molecular-transport terms.

4. Φ can be neglected, since the heat energy is so much more than the kinetic energy.

With the above assumptions, Equations 1-4 are then

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u}{\partial r} + u \frac{\partial \rho}{\partial r} = 0$$

$$\rho \frac{\partial k}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \rho D_{12} \frac{\partial k}{\partial r} \right] - \frac{\rho k}{\tau} e^{-A/RT} \tag{7}$$

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[r \lambda \frac{\partial T}{\partial r} \right] + \overline{\Delta H}_{12} \frac{\rho k}{\tau} e^{-A/RT}$$

$$\rho = MP/RT,$$

where $\overline{\Delta H}_{12}$ = average heat release per unit mass of fuel.

Now, for constant pressure, D_{12}, the diffusion coefficient is proportional to T^{s+1}, where s depends on the type of molecule considered and, thus, on the fuel used. Also, λ and μ are both proportional to T^s. Thus,

$$D_{12}/(D_{12})_o = (T/T_o)^{s+1} \tag{8}$$

and

$$\lambda/\lambda_o = (T/T_o)^s,$$

where T_o is the temperature of the wire.

Finally, the following dimensionless groups are considered:

$$\begin{aligned} \overline{T} &= T/A/R \quad \text{and} \quad \overline{T}_o = T_o/A/R \\ \overline{t} &= t/\tau \, e^{A/RT_o} \\ \overline{u} &= u/r_o \, \tau \, e^{A/RT_o} \end{aligned} \tag{9}$$

$$\overline{\rho} = \rho/\rho_o$$
$$\overline{C_p} = C_p T_o/\overline{\Delta H}_{12}$$

$$\overline{\lambda_o} = \frac{\lambda_o \tau e^{A/RT_o} T_o}{\rho_o r_o^2 \overline{\Delta H}_{12}}$$

$$\overline{r} = r/r_o$$

$$\overline{D_{12_o}} = \frac{D_{12_o}}{r_o^2} \tau e^{A/RT_o}$$

$$\overline{M} = M/M_o \ .$$

In these dimensionless parameters, r_o is the radius of the wire, T_o is the temperature of the wire surface (considered constant), ρ_o and M_o are the density and molecular weight calculated at the given pressure and T_o, and at $k = 0$. $\tau e^{A/RT_o}$ is a characteristic time of ignition. It is formed from the characteristic chemical time of reaction and the exponential which gives the order of magnitude of the reaction rate, calculated at the wire temperature. It is, then, a time which is surmised to be characteristic of the time to ignite. With the assumption of a binary system, no dependence on initial fuel-air ratio can be accounted for. However, this dependence can be found by working with a ternary (three-component) system; this would involve a more complicated analysis.

In terms of the nondimensional functions, given in Equations 8 and 9, Equations 7 become,

$$\frac{\partial \bar{\rho}}{\partial \bar{t}} + \bar{\rho}\frac{\partial \bar{u}}{\partial \bar{r}} + \bar{u}\frac{\partial \bar{\rho}}{\partial \bar{r}} = 0$$

$$\bar{\rho}\frac{\partial k}{\partial \bar{t}} = \frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left[\bar{r}\bar{\rho}\left(\frac{\bar{T}}{\bar{T}_o}\right)^{s+1}\overline{D_{12_o}}\frac{\partial k}{\partial \bar{r}}\right] - \bar{\rho}ke^{-\left(\frac{1}{\bar{T}} - \frac{1}{\bar{T}_o}\right)} \qquad (10)$$

$$\bar{\rho}\bar{C}_p\frac{\partial \bar{T}}{\partial t} = \frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left[\bar{r}\bar{\lambda}\left(\frac{\bar{T}}{\bar{T}_o}\right)^{s}\frac{\partial \bar{T}}{\partial \bar{r}}\right] + \bar{\rho}ke^{-\left(\frac{1}{\bar{T}} - \frac{1}{\bar{T}_o}\right)}$$

$$\bar{\rho} = \bar{M}\,\bar{T}_o/\bar{T} \ .$$

The boundary and initial conditions can be written in terms of the dimensionless variables also. The initial conditions are that at time zero, all variables are at their undisturbed state.

Thus,

$$\begin{aligned} \bar{\rho}(0,\bar{r}) &= 1 \\ \bar{T}(0,\bar{r}) &= T_i/AR = \left[T_i/T_o\right]\left[T_o/AR\right] = \left[T_i/T_o\right]\left[\bar{T}_o\right] \\ \bar{u}(0,\bar{r}) &= 0 \\ k(0,\bar{r}) &= 1, \end{aligned}$$

where T_i = initial temperature of the system.

Considering only the semistable period of burning, the boundary conditions are as follows:

1. At the wire surface ($\bar{r} = 1$).

At $t = 0$, the concentration of fuel at the surface is one ($k = 1$). As more and more current is passed through the wire, the surface temperature goes up. Thus, a reaction takes place at the surface and continues until $k(\bar{t},1) = 0$. The equation expressing this condition is: $dk/d\bar{t} = -ke^{-(1/\bar{T} - 1/\bar{T}_o)}$ for $1 \leq k \leq 0$, and $k(t,1) = 0$ at $t >$ time for k to go to 0 at the surface. Since this probably happens almost immediately, a good boundary condition would be $k(t,1) = 0$ for all time.

Also:

$$\bar{u}(\bar{t},1) = 0.$$

Next, if $\phi = \phi(t)$ is the heat being transferred per unit area per unit time at the surface of the wire, then

$$-\lambda \frac{\partial T}{\partial r}\bigg|_{\bar{t},\bar{r}=1} = \phi(t)$$

or

$$-\bar{\lambda}\frac{\partial \bar{T}}{\partial \bar{r}}\bigg|_{\bar{t},\bar{r}=1} = \bar{\phi} = \frac{\phi \tau e^{A/RT_o}}{\rho_o r_o \overline{\Delta H_{12}}}$$

Finally:

$$\bar{T}(\bar{t},1) = \bar{T}_o ,$$

$$\bar{\rho}(\bar{t},1) = \bar{T}_o\bar{M}_o(\bar{t},1)/\bar{T}_o = 1 .$$

2. At infinity

$$\lim_{\bar{r}\to\infty} k(\bar{t},\bar{r}) = 1 \qquad \lim_{\bar{r}\to\infty} \bar{T}(\bar{t},\bar{r}) = \bar{T}_o$$

$$\lim_{\bar{r}\to\infty} \bar{u}(\bar{t},\bar{r}) = 0 \qquad \lim_{\bar{r}\to\infty} \bar{\rho}(\bar{t},\bar{r}) = 1$$

where all $\bar{t}$ are for $\bar{t} < \bar{t}^*$ if $\bar{t}^*$ indicates the dimensionless time to the end of the semistable burning.

Finally, one wishes to have the above dimensionless equations, boundary conditions, and initial conditions hold for any given fuel, any given initial temperature, etc. Therefore, these dimensionless equations, boundary, and initial conditions must remain the same for all problems. This implies that, even though the physical situation changes, $\bar{\phi}$, S, C_p, $\bar{\lambda}_o$, $\bar{D}_{12}$, $\bar{T}_o$, and $\bar{T}_i/\bar{T}_o$ must remain the same. Since the temperature of the wire changes so rapidly from T_i to T_o, and since the reaction rate is exponential in temperature, thus giving a much higher rate at T_o than at T_i, the parameter T_i/T_o is probably not as important as the rest. However, in general, these parametric relations are the important ones, and should, if the model is correctly formulated, correlate the data. In particular, the most important and most easily checked relation is probably the heat transfer boundary condition,

$$\bar{\phi} = \text{constant}$$

or (11)

$$\frac{\phi\tau e^{A/RT_o}}{\rho_o r_o \overline{\Delta H_{12}}} = \text{constant}.$$

This relation may be used in the following way. If ρ_o and $\overline{\Delta H_{12}}$ are unchanged throughout several experiments, then one can write Equation 11 as,

$$\phi/r_o = \text{constant}/\tau e^{A/RT_o} .$$

That is, the heat added per unit surface area of the wire, per unit time, divided by r_o, the radius of the wire, should vary

inversely as the characteristic ignition time, $\tau e^{A/RT_o}$. In fact, if the analogy to the mixing problem is correct, the characteristic ignition time may be replaced by a constant times the actual ignition time, and the result is as follows:

$$\phi/r_o = \text{constant}/t_{ig} , \tag{12}$$

where t_{ig} is the time to ignite.

In order to test the validity of this relation, some relationship between the electrical energy supplied and ϕ must be obtained. This problem is considered in the heat transfer literature,[2] if one is willing to make the assumption of a constant and uniform current density throughout the wire. In view of the experiments which were carried out, where if I = current and E = potential, EI varied with time, this means calculating an equivalent steady power by defining

$$\overline{EI} = 1/t \int_o^t EI\,dt, \tag{13}$$

where $\overline{EI}$ is the equivalent steady power, t is the time the power was on, and EI is the actual power, varying with time. With these simplifications, the equation to be solved, equivalent to that in Reference 2, is,

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \frac{\overline{EI}}{\pi r_o^2 \lambda_w L} = 0$$

where λ_w = coefficient of thermal conduction of wire and L = length of wire. The solution to this equation is

$$T = T_a - \frac{1}{4} r^2 \frac{\overline{EI}}{\pi r_o^2 \lambda_w L} , \tag{14}$$

if T_a is the temperature along the axis of the wire. Now,

$$\phi = -\lambda_w \frac{\partial T}{\partial r}\bigg|_{r=r_o} = \frac{\overline{EI}}{2\pi L r_o} . \tag{15}$$

This may be substituted in Equation 12 to give:

$$\frac{\overline{EI}}{r_o^2} = \frac{\text{const}}{t_{ig}} , \tag{16}$$

since L = constant for all experiments.

This illustrates one correlation which should hold if the model is correct. The other parametric forms could be handled in the same way, but more analysis and perhaps differently controlled experiments would be necessary. The correlation of data by Equation 16, as given in a later section, is encouraging and would seem to indicate a proper model has been chosen.

DISCUSSION

The previous sections have contained the experimental results and a theory as to the actual mechanisms involved in the ignition process. Further, the data has been correlated by one of the parametric relations derived in the analysis. At this point, these results should be evaluated, and in the light of this evaluation, the directions for further study can be indicated.

One of the most important results was that found from the Fastax movies; the ignition process is divided into three separate phases. The first consists of a local ignition and the time taken from the first energy addition to local ignition is the so-called ignition time measured in the above experiments. The second phase consists of a semistable flame where the burning is again localized, being confined to a small region around the hot wire or spark plug. The third phase consists of the ignition of the complete charge when the flame front advances over the unburned mixture at a high rate of speed, being either a detonation or a very fast reaction.

Most of the measured data was gathered for the first phase; the second and third were covered more qualitatively than quantitatively. Clearly, any further experiments should be designed with the idea of trying to emphasize one of these phases so that accurate measurements can be made first to establish the actual mechanisms involved and then to gain data for complete descriptions of the phenomena. In particular, two things should be established. First, although evidence does exist and has been presented to support the idea of the semistable flame being supported by diffusion, a possibility does exist that the flame speed is lowered sufficiently by the large radius of curvature of the flame so that the flame is actually propagating outward. While this possibility seemed more remote than the diffusion flame presented in the analysis, it could be checked by greatly increasing the wire size and thus minimizing the radius-of-curvature effects. Secondly, the

rapid rate of propagation which takes place at the end of the semistable flame should be classified. While it most probably is a detonation wave which sweeps across the unburned mixture, it is possible that it is an explosion which results from a whole region attaining a high enough temperature so that it reacts all at the same time rather than behind a wave which moves across it. This might be determined by different optical techniques or measurements of the speed of the propagation and comparison with detonation wave velocities under the given conditions.

With regard to the given results and correlations, the following remarks apply. While the given analysis and correlation of results, using some of the derived results, seem to be the most physically correct explanations of the ignition process, it is evident that other more gross calculations, while perhaps not physically correct, may be used to give the same relations. In particular, one might assume that since the temperature of the wire is one of the most important parameters, the heat loss through the surface of the wire is negligible and all the energy input to the wire goes into heating it. Further, if an ignition temperature is assumed for the mixture, then the following equation applies:

$$(\rho AL)_w \, C_{p_w}(T_{ig} - T_i) = R\Delta T \quad ,$$

where $(\rho AL)_w$ is the product of the density, area, and length of the wire, C_{p_w} is the specific heat of the wire, T_{ig} is the ignition temperature, T_i is the initial temperature, R is the rate at which power is applied to the wire, and Δt is the time taken to heat the wire to the ignition temperature. Then $R/A \propto 1/\Delta t$ would result, giving the same correlation equation as given in the analysis above.

While the assumptions for this approximation are rather drastic, the whole idea may be proved or disproved by carrying out experiments with extremely small wire diameters. In this case, the heat loss to the gas is certainly not negligible and, hence, the above correlation should not hold. If it does hold, the indication will be that the correct mechanism is given in the analysis section and not by the above ideas.

Further research should be done to help validate and improve the given model for the ignition process. Of the parametric relations derived, only one has really been used for correlation. The others should, of course, be tested by experimental results. Furthermore, some work should be done, both theoretically and experimentally, to test the hypothesis that the characteristic ignition time is dependent

on the reaction rate calculated at the wire temperature. This relation was drawn from a similar problem, as explained in the text of the analysis section, but more work should be done to see if it covers the present problem or whether some additional features are necessary. For instance, the fuel concentration might very easily enter into the calculations.

In conclusion it can be stated that the visual studies were exceptionally instructive, the correlation of data given by the theoretical derivations were most encouraging, and that further definitive work, based on that already accomplished, must be done in order to establish the validity of the proposed theory of ignition.

CONCLUSIONS

For the range of wire sizes and the test conditions it is concluded:

1. The mechanism of ignition appears to be essentially the same for the hot wire as it is for the spark ignition.

2. The time required for a given length of wire to ignite a combustible mixture is directly proportional to the square of the diameter and inversely proportional to the heating rate.

3. The total energy required for a wire of given length and diameter to ignite a combustible mixture is independent of heating rate. This conclusion may not hold in extreme cases.

4. The total energy required for a given length of wire to ignite a combustible mixture is directly proportional to the square of the wire diameter.

5. The effect of initial pressure upon ignition time and energy is apparently very slight, although theoretical analysis indicates that ignition time was a direct function of the gas density and heating value of the fuel. Additional investigation will be required to clarify this point.

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2. Carslaw, H. S., and Jaeger, J. C. Conduction of Heat in Solids, 2nd ed. Oxford at the Clarendon Press, 1950, p. 168.

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APPENDIX

TABLE I

HIGH-SPEED MOTION-PICTURE TESTS

Run No.	Gas Pressure	Fuel	Means of Ignition	Ignition Time
1083	atm	Propane	30-gage Ni Wire	(When recorded)
1084	"	"	"	
1085	"	"	"	
1086	"	None	"	
1098 P	"	"	"	
1099 P	"	Propane	"	40.5 (Milliseconds)
1100 P	"	"	"	41.5
1101 P	50 psi	"	"	32.95
1102 P	100 psi	"	"	31.25
1104 P	atm	"	"	26
1105 P	50 psi	"	"	20.6
I-C-001	atm	"	"	
I-C-002	45 psi	"	"	
P-MS-1	atm	"	Multiple Spark	
P-MS-2	"	"	"	
P-MS-3	45 psi	"	"	
P-MS-4	"	"	"	
P-SS-1	atm	"	Single Spark	
P-SS-2	"	"	"	
G-006	"	Gasoline	30-gage Ni Wire	
G-007	"	"	"	
G-SS-1	"	"	Single Spark	
G-SS-2	"	"	"	

Table II

IGNITION TESTS

Test Number	Wire Material	Wire Gage (B and S) or Diameter	Energy Added to Ignition or Burnout, Joules	Time to Ignition or Burnout (milliseconds)
1153	Nickel	30	9.36	131.5
1154	"	30	9.36	132.1
1156	"	30	9.27	78.7
1157	"	30	9.25	78.0
1159	"	30	10.41	58.5
1161	"	30	9.88	54.3
1163	"	30	10.23	41.0
1164	"	30	8.99	39.5
1166	"	32	6.97	87.7
1167	"	32	6.87	84.8
1169	"	32	7.75	53.9
1170	"	32	8.08	56.5
1173	"	32	8.32	37.5
1174	"	32	8.06	37.0
1176	"	32	7.91	25.5
1177	"	32	7.19	25.5
1184	"	28	16.74	26.3
1185	"	28	7.04	95.0
1186	"	28	15.83	27.0
1188	"	28	15.66	150.0
1189	"	28	16.58	161.5
1191	"	28	20.03	106.5
1192	"	28	17.04	105.8
1194	"	28	18.5	78.8
1195	"	28	18.3	77.8
1197	"	24		1600
1198	"	24	20.6	1400
1200	"	24	38.3	888
1201	"	24	41.74	890
1203	"	24	42.28	565
1204	"	24	47.31	400

TABLE II (continued)

Test Number	Wire Material	Wire Gage (B and S) or Diameter	Energy Added to Ignition or Burnout, Joules	Time to Ignition or Burnout (milliseconds)
1205	Nickel	24	40.1	550
1207	"	24	42.5	395
1210	Copper	32	4.0	161
1212	"	32	5.56	95
1214	"	32	5.38	58.5
1216	"	32	5.08	40.1
1219	"	28	7.03	1005
1221	"	28	13.1	486
1223	"	28	11.3	290
1225	"	28	10.46	192
1230	"	24	38.7	1475
1232	"	24	42.8	1932
1233	Tungsten		22.2	1346
1234	"		21.54	708
1235	"		17.9	400
1236	"		25.4	440
1237	"		18.95	295
1244	Nickel	32	5.57	61
1246	"	32	5.9	72
1248	"	32	5.98	43
1249	"	32	6.45	29.5
1250	"	32	6.27	25.4
1252	"	30	9.0	129
1253	"	30	8.12	70
1254	"	30	9.15	67
1255	"	30	10.1	37.7
1256	"	30	9.5	35.5
1259	"	28	14.07	238
1260	"	28	15.53	249
1261	"	28	13.84	139
1262	"	28	14.95	93.5
1263	"	28	16.05	69.1
1264	"	28	14.41	64.5
1267	"	24	44.0	1455
1268	"	24	38.32	742
1269	"	24	41.35	531
1270	"	24	41.34	370

TABLE II (continued)

Test Number	Wire Material	Wire Gage (B and S) or Diameter	Energy Added to Ignition or Burnout, Joules	Time to Ignition or Burnout (milliseconds)
1273	Nickel	32	5.33	68.8
1274	"	32	6.11	43
1275	"	32	7.24	28
1276	"	32	6.54	20.8
1278	"	30	8.72	121
1279	"	30	8.85	71.3
1280	"	30	8.88	46.5
1281	"	30	9.0	33
1290	"	28	12.64	228
1291	"	28	12.97	128
1292	"	28	13.51	85
1293	"	28	13.83	60.5
1296	"	24	40.45	1366
1297	"	24	38.1	696
1298	"	24	34.27	406
1299	"	24	39.78	359
1300	"	24	17.89	514
1303	"	32	5.61	68
1304	"	32	6.05	72.3
1305	"	32	5.66	39.4
1306	"	32	5.81	40.7
1307	"	32	6.22	26
1308	"	32	6.71	25.3
1311	"	30	8.08	118
1312	"	30	8.22	67.2
1313	"	30	8.66	45.5
1314	"	30	8.80	32.1
1317	"	28	12.59	224
1318	"	28	12.46	122
1319	"	28	12.61	122
1320	"	28	12.69	80.3
1321	"	28	13.52	58.3
1322	"	28	14.09	62.3
1325	"	26	38.75	1417
1326	"	26	42.93	713
1328	"	26	40.96	400
1329	"	26	37.95	345

TABLE II (concluded)

Test Number	Wire Material	Wire Gage (B and S) or Diameter	Energy Added to Ignition or Burnout, Joules	Time to Ignition or Burnout (milliseconds)
1330	Nickel	26	37.59	353
1341	Copper	32	4.90	163
1342	"	32	5.89	94
1343	"	32	5.24	58.2
1344	"	32	5.24	41
1346	"	28	12.51	1035
1347	"	28	10.71	466
1348	"	28	10.56	289
1349	"	28	10.66	198
1351	"	24	46.84	1825
1353	Nichrome	0.0015	0.31	21
1354	"	0.0015	0.19	31
1356	"	0.0015	0.19	53
1358	"	0.0015	0.21	86.5
1360	"	0.0045	1.87	13.5
1361	"	0.0045	1.84	18.8
1362	"	0.0045	1.78	30.3
1363	"	0.0045	1.74	50.6
1365	"	30	11.81	35.5
1366	"	30	8.35	36
1367	"	30	8.21	55.3
1368	"	30	8.57	99.6
1370	Platinum	32	4.23	12.8
1371	"	32	3.75	46.3
1372	"	28	8.93	166
1373	"	28	8.57	43.8
1375	"	24	43.03	1222
1376	"	24	56.73	1992
1378	"	40	0.59	12.6
1380	Molybdenum	0.005	1.64	5.3
1381	"	0.005	1.29	15.3
1383	Tantalum	0.020	23.41	151
1384	"	0.020	31.01	604
1385	"	0.020	26.66	296
1386	"	0.020	6.2	207

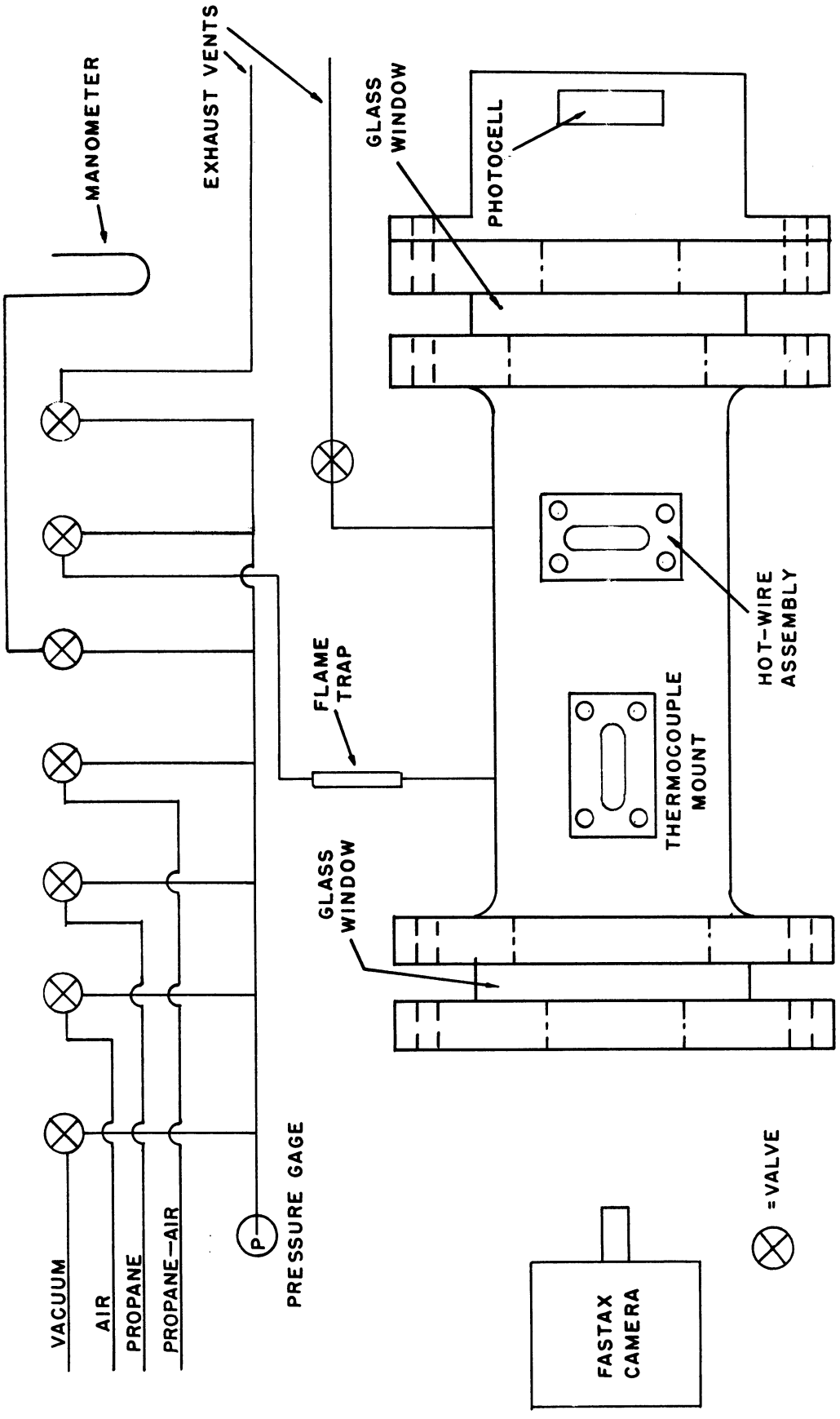

FIG. 1 — TEST EQUIPMENT

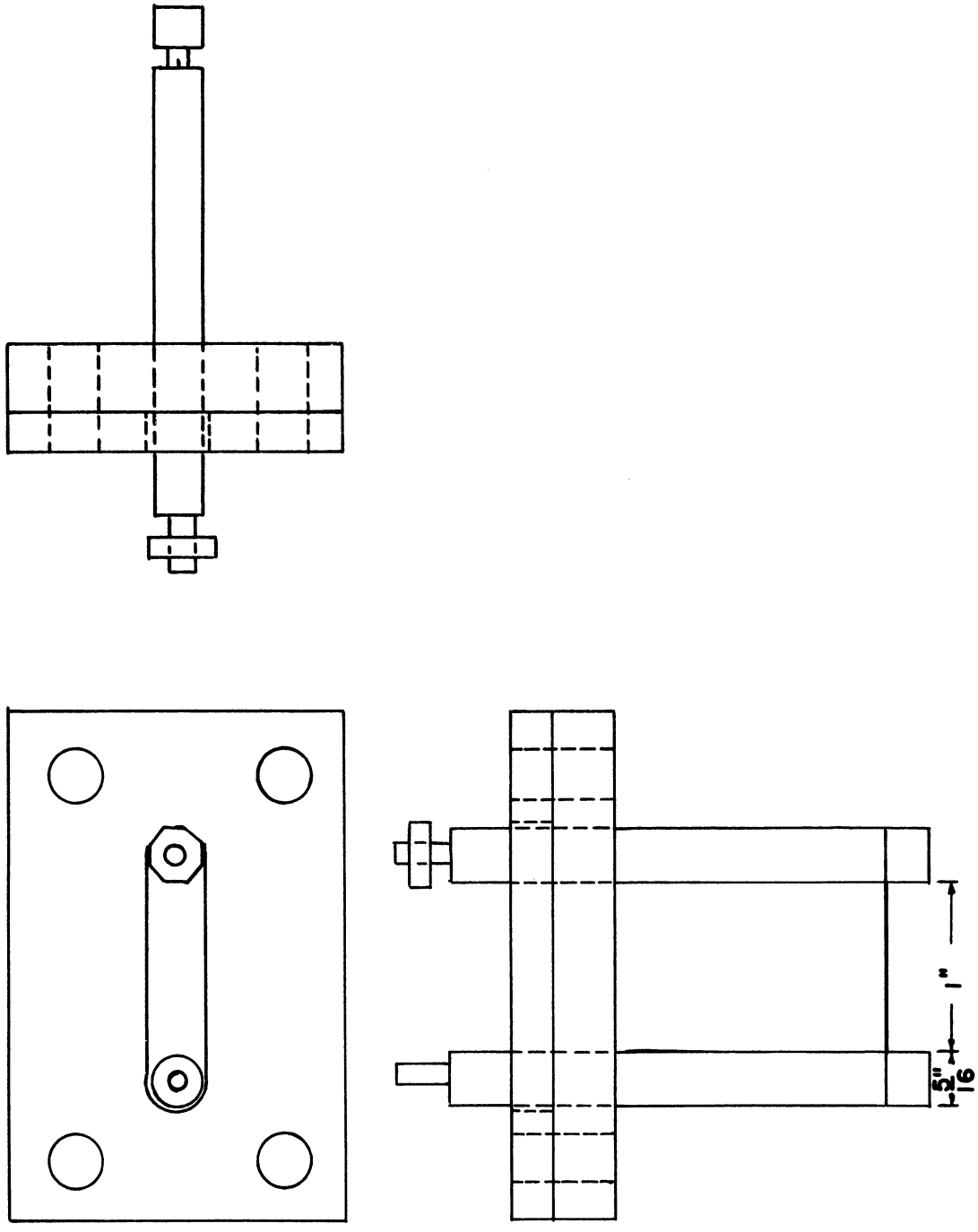

FIG. 2 — HOT — WIRE ASSEMBLY

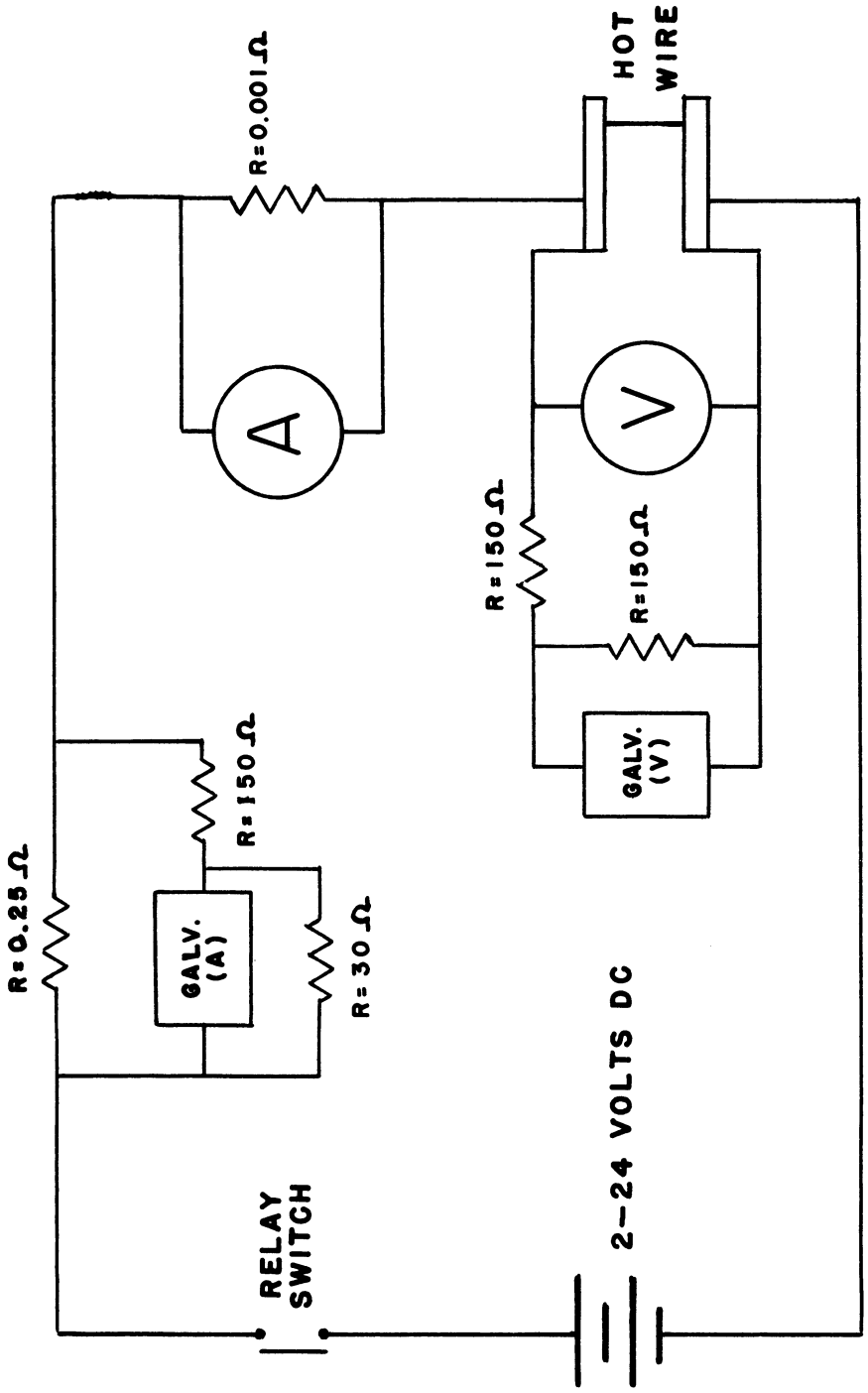

FIG. 3—SCHEMATIC DIAGRAM OF ELECTRICAL CIRCUIT FOR HOT—WIRE IGNITION

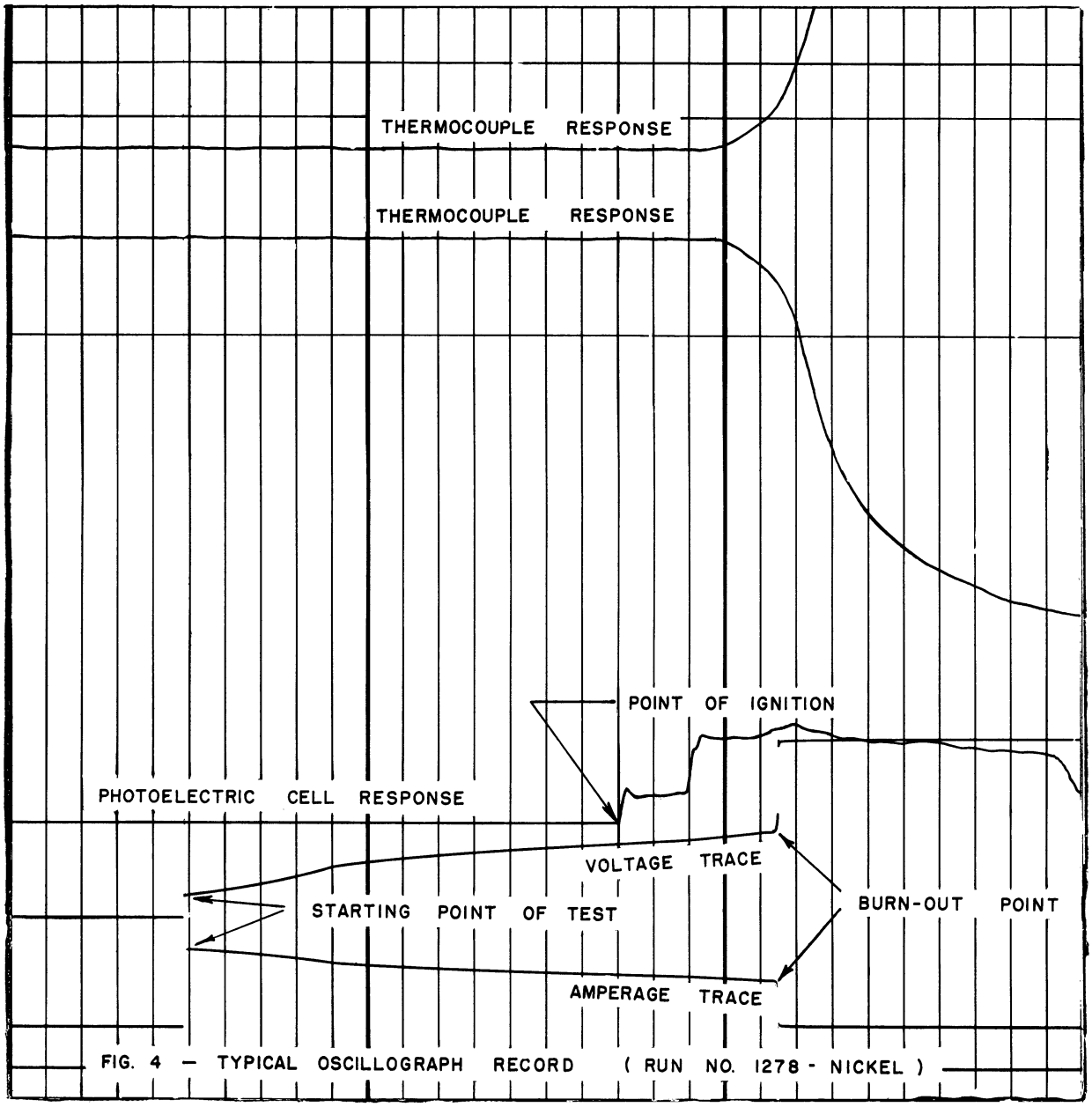

FIG. 4 — TYPICAL OSCILLOGRAPH RECORD (RUN NO. 1278 - NICKEL)

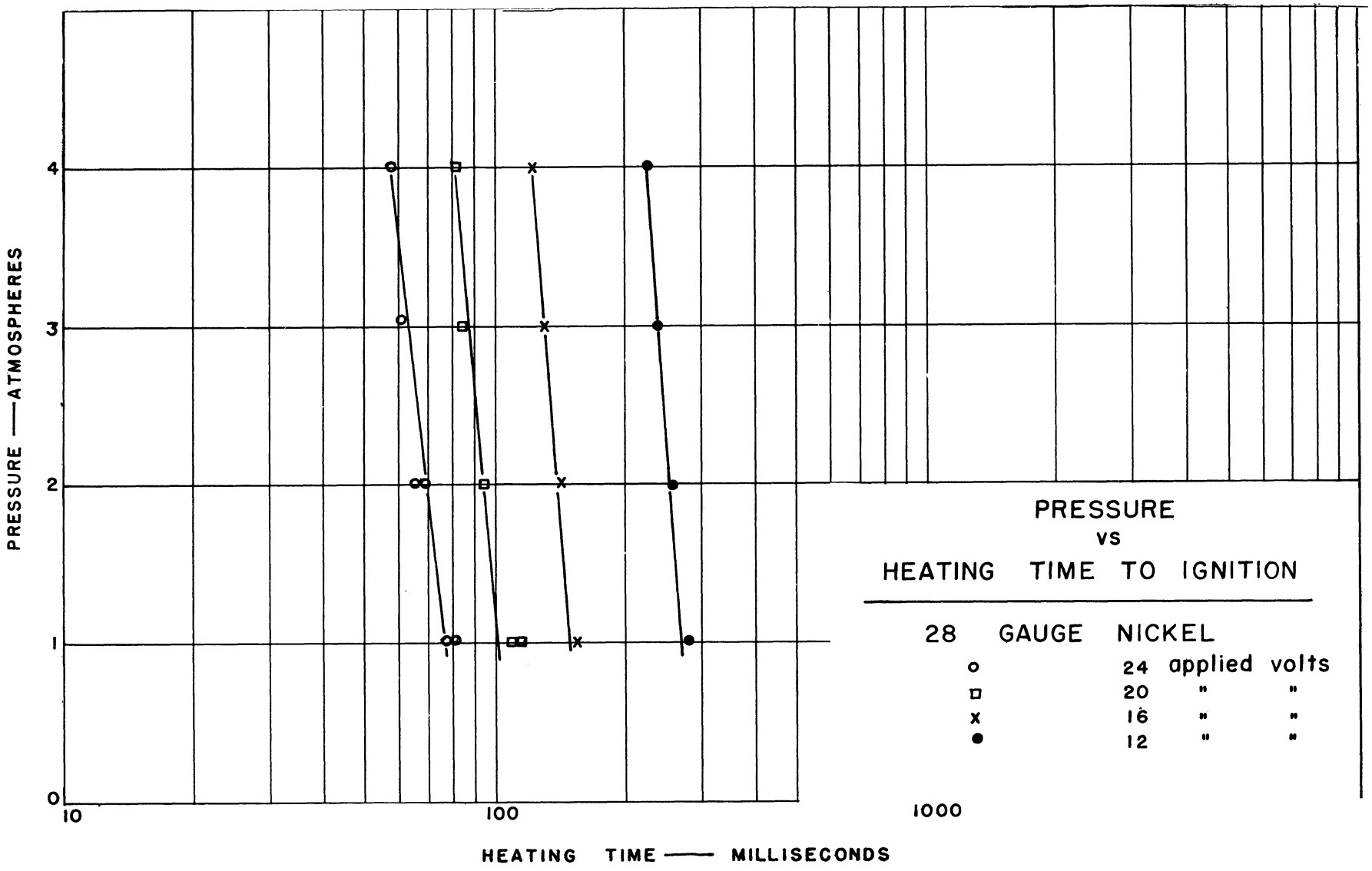

Fig. 5 — VARIATION OF HEATING TIME TO IGNITION AS A FUNCTION OF PRESSURE

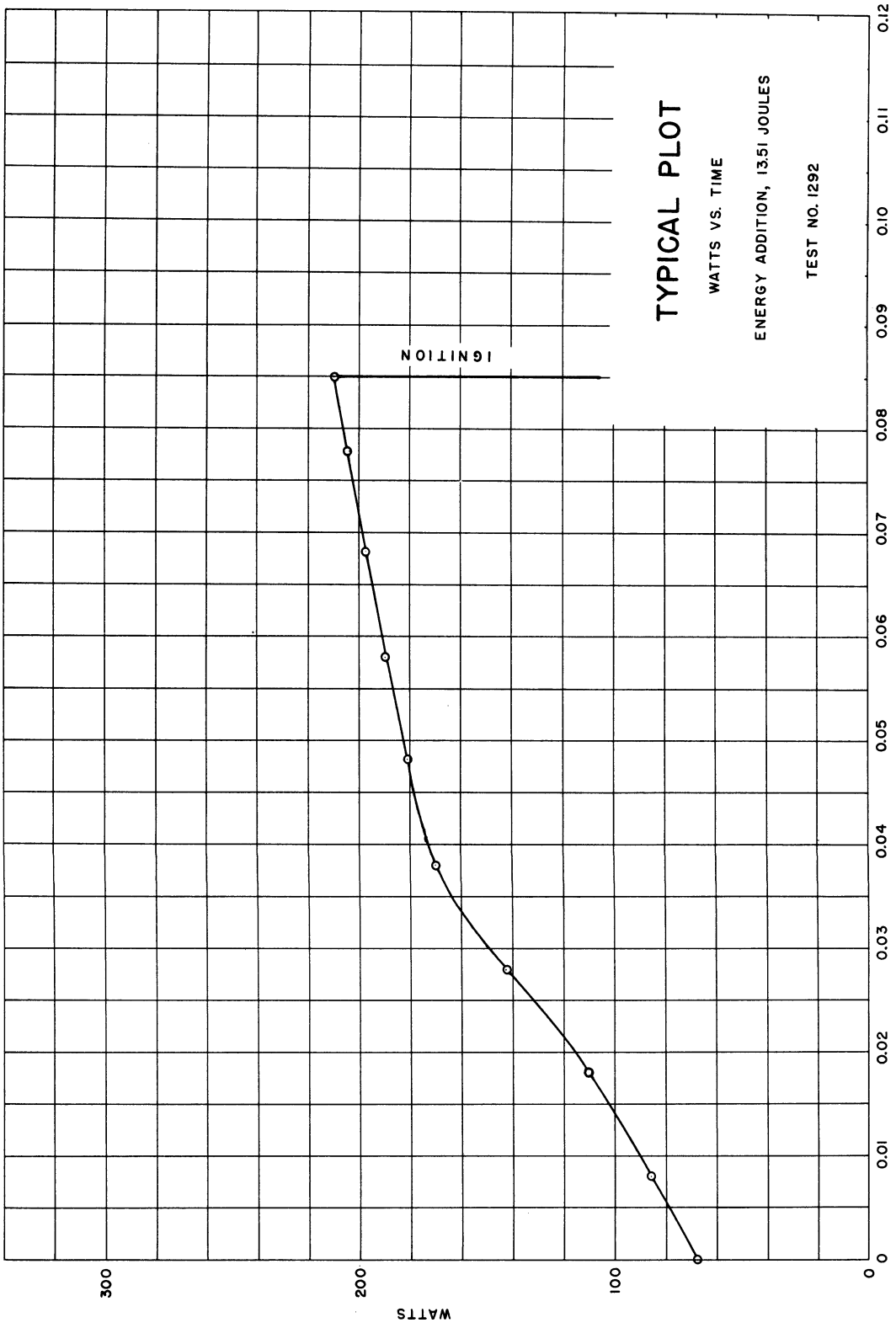

FIG. 6 — EXAMPLE OF CURVES USED FOR DETERMINATION OF ENERGY ADDITON TO THE IGNITION WIRES BY MEANS OF PLANIMETER READINGS

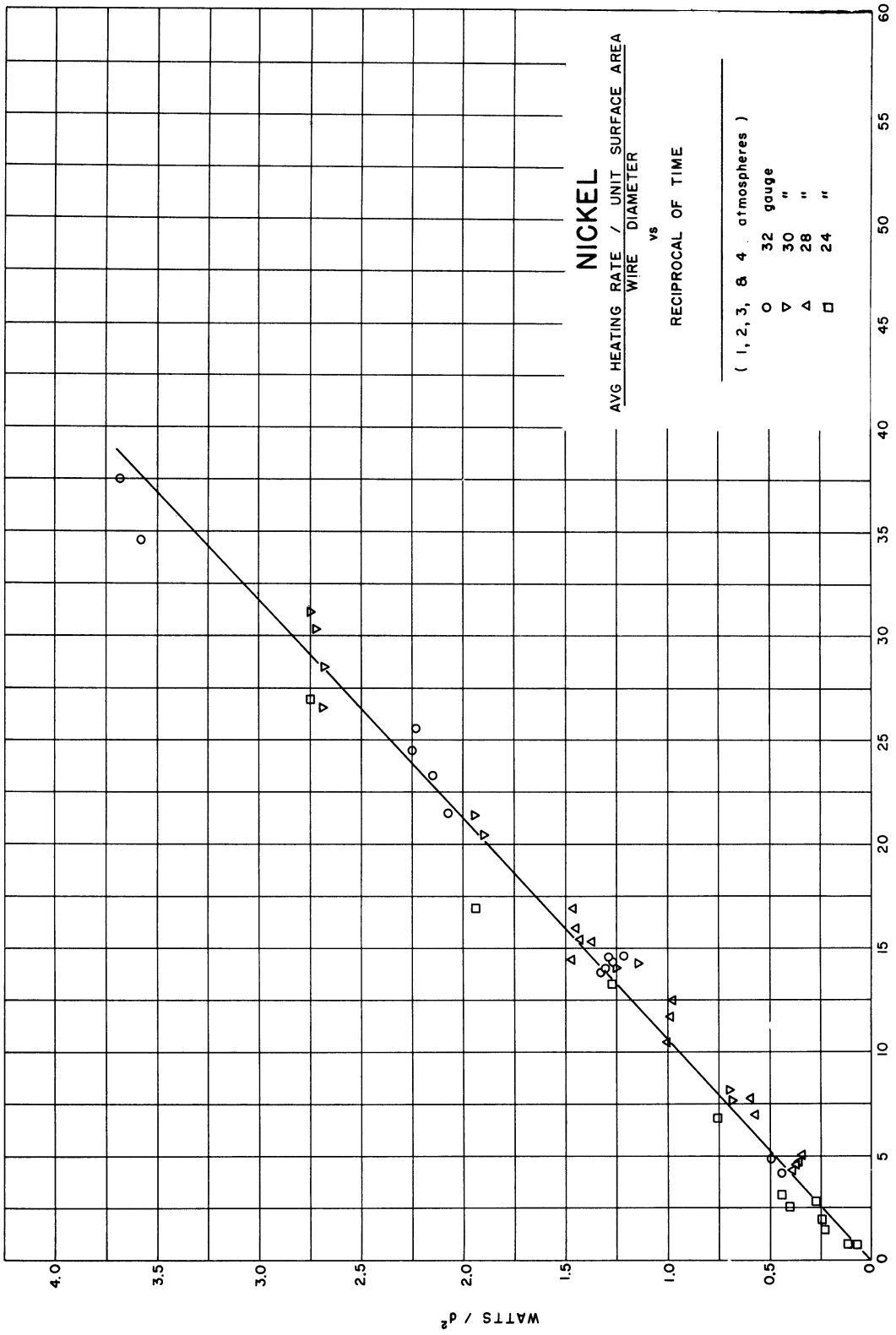

FIG. 7 — EFFECT OF WIRE SURFACE AREA ON THE HEATING TIME TO IGNITION POINT

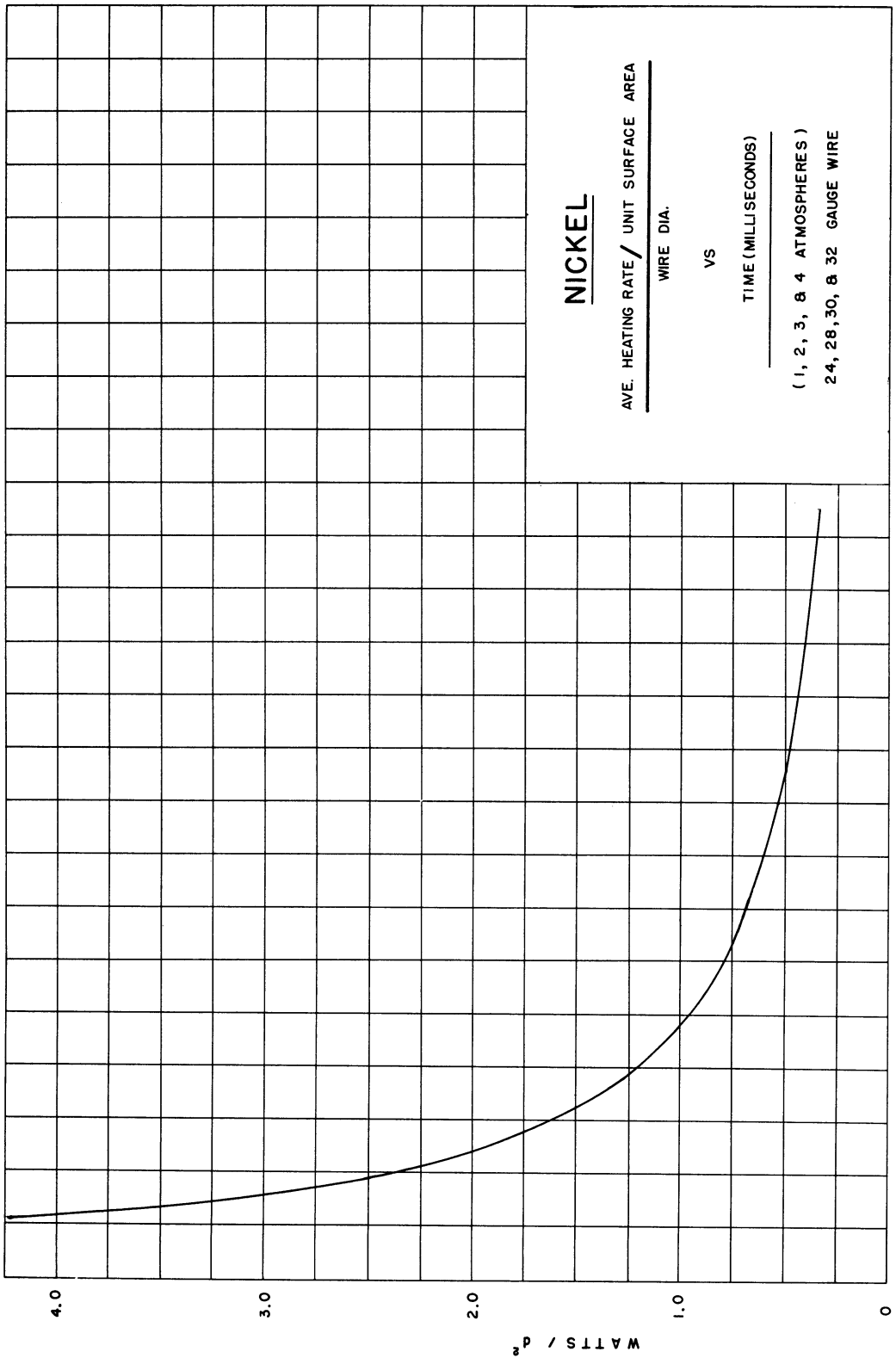

FIG. 8 —— EFFECT OF WIRE SURFACE AREA ON THE HEATING TIME TO IGNITION POINT

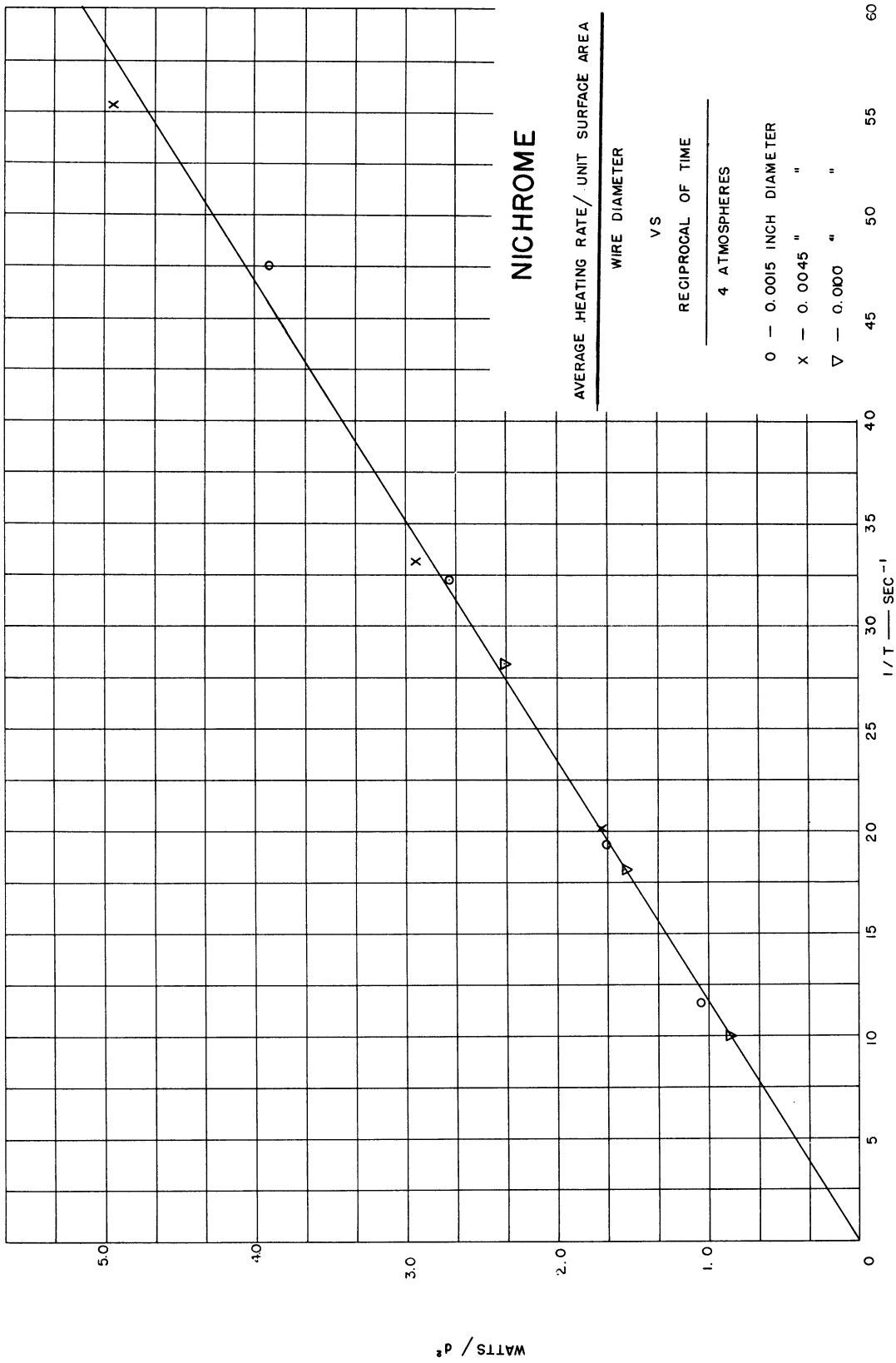

FIG. 9 — EFFECT OF WIRE SURFACE AREA ON HEATING TIME TO IGNITION POINT

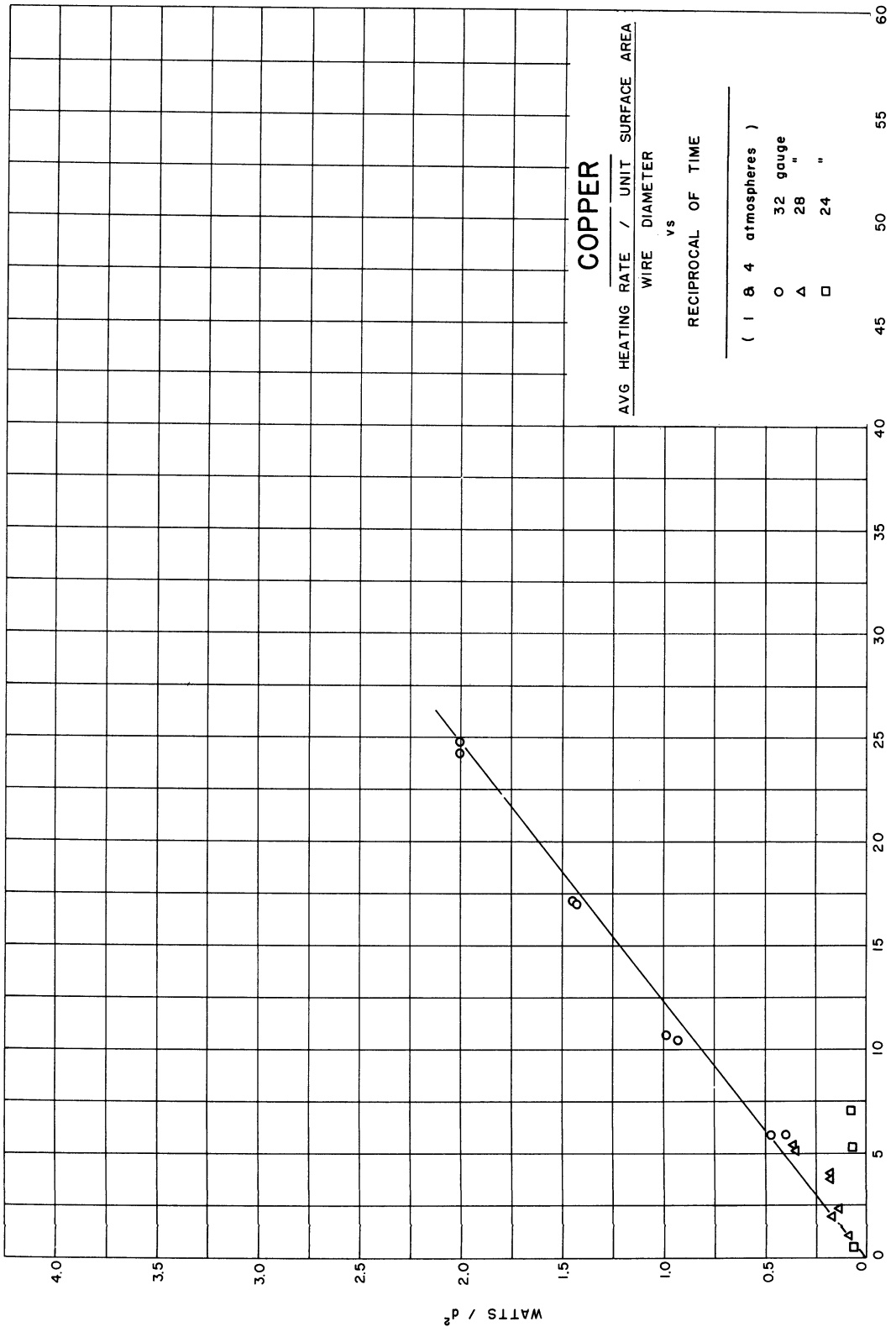

FIG. 10 — EFFECT OF WIRE SURFACE AREA ON THE HEATING TIME TO IGNITION POINT

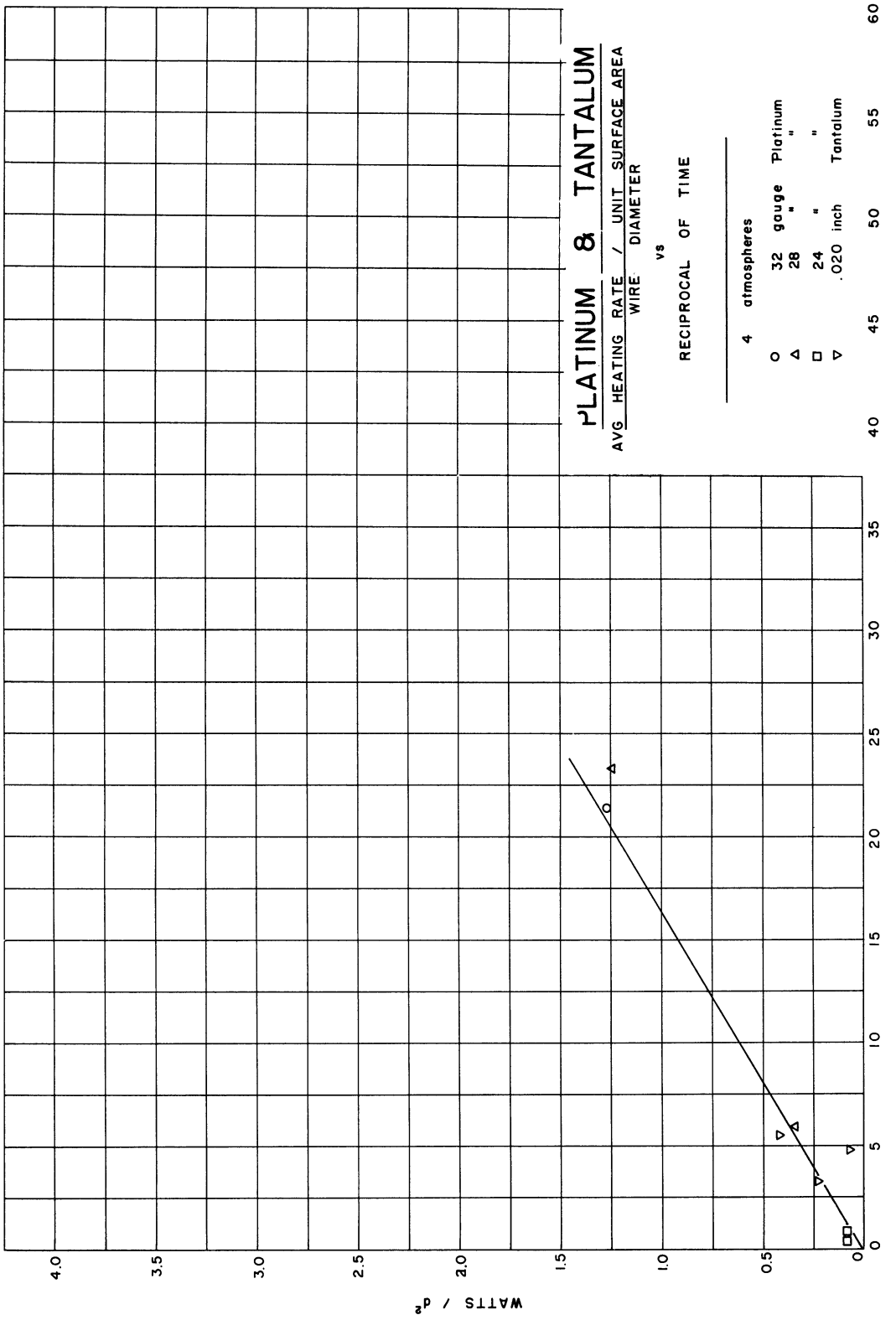

FIG. 11 — EFFECT OF WIRE SURFACE AREA ON THE HEATING TIME TO IGNITION POINT

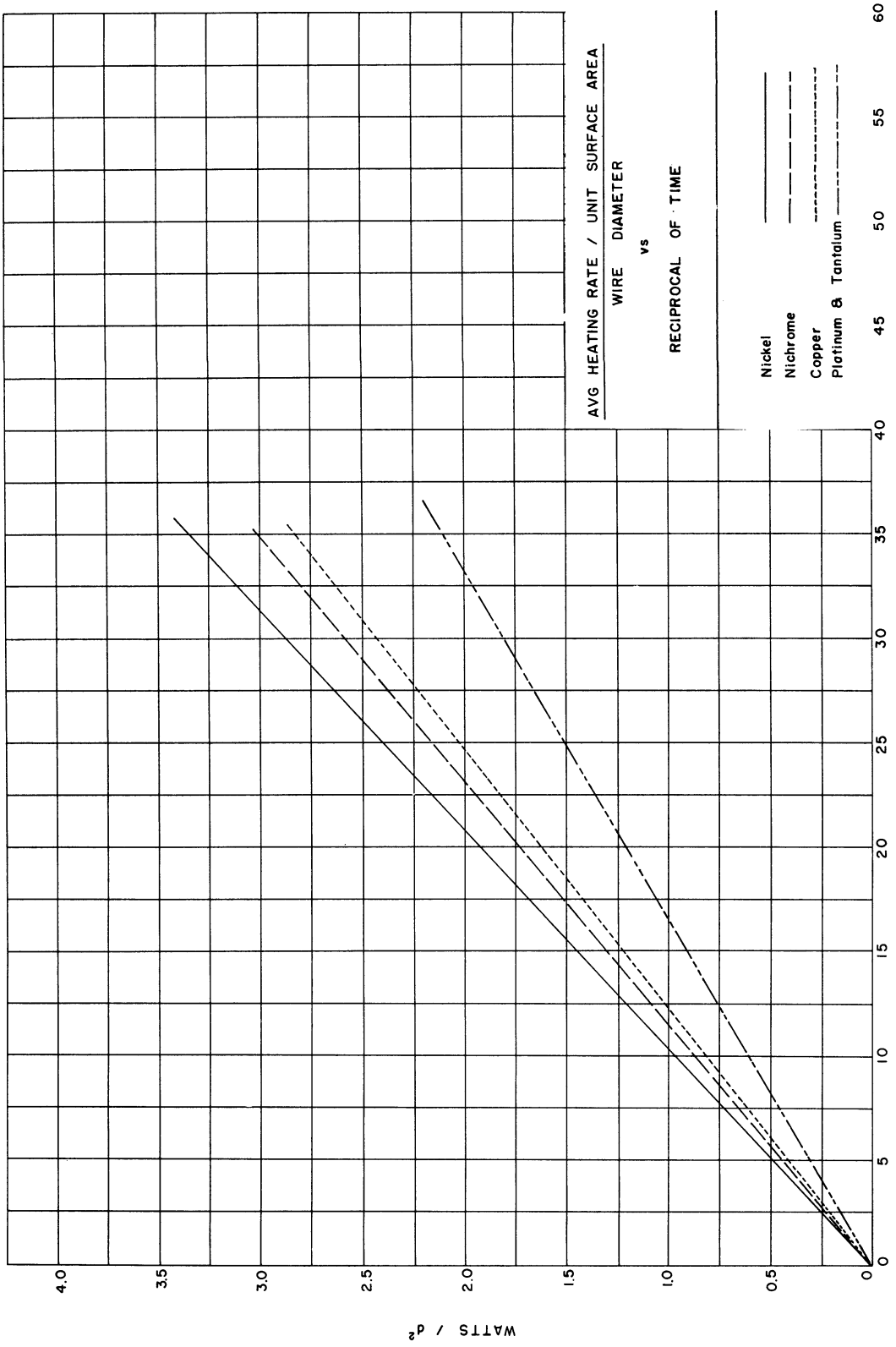

FIG. 12 — COMPARISON OF THE EFFECT OF WIRE SURFACE AREA ON THE HEATING TIME TO IGNITION FOR VARIOUS METALS. (COMPOSITE OF FIGURES 7, 9, 10, & 11)