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TECHNICAL REPORT

ADS - 14

A STUDY OF THE FLAMMABILITY OF MAGNESIUM

By

Paul Boris

Systems Research and Development Service

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FEDERAL AVIATION AGENCY

Washington, D.C.

April 1964

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This report was prepared by the SRDS under
Project No. 311-2X2 for the Aircraft
Development Service.

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A STUDY OF THE FLAMMABILITY OF MAGNESIUM

By Paul Boris, Systems Research and Development Service

SUMMARY

This study was performed to provide information on the flammability of magnesium alloys. An investigation of the ignition and burning characteristics was conducted on prepared specimens of four common magnesium alloys. Standard flat specimens were of the same dimensions except for thickness. In addition, typical reciprocating engine castings were tested to determine ignition and burning characteristics under fire conditions closely representing the intensity of an aircraft power plant fire. Each casting varied in thickness from 1/4 inch to 1 inch maximum and was devoid of all internal parts and circulating fluids.

The major results of the prepared specimen tests are presented as a family of curves which indicate that time to ignition did not vary significantly among the alloys tested, but varied directly with thickness of specimen and airflow over the specimen. After ignition, the airflow accelerated the alloy's burning rate. Tests on the castings revealed a minimum time to ignition of 2 minutes for the smallest (23 pounds) and 4 minutes for the largest (91 pounds).

In general, tests indicated that it would be good practice to eliminate sharp edges and protrusions from magnesium alloy castings where possible since these areas were observed to be mora susceptible to ignition. Small magnesium components that are not an integral part of the engine could represent a substantial fire hazard in that they will ignite in a short period of time under intense fire conditions. Previous experience has shown that magnesium fires cannot be extinguished by extinguishing agents presently in use in aircraft power plants and therefore could become a source of reignition of flammables.

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INTRODUCTION

Magnesium as an aircraft construction material is desirable because of qualities such as light weight, mahcinability and casting characteristics. Its use is not new in the field of aviation and the design criteria of components of magnesium have generally been based on structural integrity. However, under conditions of proper heat balance, it ignites and burns. The degree of ignition resistance required of magnesium, therefore, depends on its location in the aircraft.

Generally, magnesium usage is in the form of large castings such as gear boxes; therefore, it possesses some ignition resistance by virtue of its mass. In addition, these castings generally contain internal parts and circulating fluids which contribute to the total amount of heat that can be absorbed before an ignitible temperature is reached.

Magnesium appears on both commercial and military aircraft where weight is an important design consideration; for example, one commercial airliner contains 360 pounds of magnesium in each power plant installation. If the magnesium is substituted by another metal such as aluminum, on a volume basis there would be a weight increase of 180 pounds per engine or an overall increase in aircraft weight of 720 pounds.

Previous studies have been conducted in regard to magnesium fire hazards in aircraft[1] and the following are brief summaries of those findings:

(1) Magnesium, except in the form of dust or thin sheet, ignites with difficulty.

(2) Exposure time necessary to affect burning varies with heat source, and shape and size of magnesium component.

(3) Magnesium fires are usually initiated by intense fires of other combustibles.

(4) The addition of small amounts of beryllium appears to increase the ignition resistance of magnesium.

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[1] Kling, A. L., Blair, E. A., Cousin, E. W., Hurst, A. S., and Tuello, C. F., Protection of Aircraft Against Magnesium Fires, Army Air Forces Technical Report 5326, August 1946.

(5) It was indicated that the probability of any magnesium parts being the primary cause of aircraft loss appears so slight that the substitution of magnesium by other metals would hardly be justified. (This statement was made in reference to the B-29 airplane.)

(6) Aircraft landing wheels weighing approximately 25 pounds, when directly exposed to a flammable fluid fire, required 5 minutes for ignition.

(7) Airflow directly over a magnesium component offers some protection against ignition.

(8) Burning magnesium can be a source of reignition for other flammables since it is not readily affected by standard extinguishing agents and would continue to burn after the agent is expended.

(9) There is ample time to extinguish flammable fluid fires in flight before magnesium becomes involved, provided detector systems are functioning properly and extinguishing agents are effective.

A review of literature concerning the conduct of past studies on the flammability of magnesium indicates that there is not always agreement with regard to results. This is probably due to differences of interpretation as to the definition of ignition as well as a wide variety of test methods. The burning of magnesium can manifest itself as either a brilliant white flame or a slow flameless oxidation. For instance, if a match is held to the edge of a piece of magnesium ribbon, it burns with an intense white light. Similarly, if a more massive piece is subjected to a heat source which is controlled to result in a slow temperature rise of the specimen, a point is reached where the magnesium heats spontaneously. In this case, even if the heat is removed, the magnesium would reach a point where it bursts into flame. The curve shown on Fig. 1 represents this phoenomenon whereas the dotted line portion of the curve would represent the time-temperature history of a thinner specimen, such as the ribbon. The "X" denotes the point where both burst into flame. Two points on this curve could then be considered ignition points; namely, where self heating begins as indicated by the sudden upward trend of the curve, and where the metal bursts into flame. Heat source and time are also interrelated and these factors as well as different interpretations of the ignition point could be responsible for difference in test results. For the purpose of the tests presented herein, ignition is defined as that point where the white flame appears and starts to propagate.

The combustion process of magnesium produces oxides which vary in shade between black and white. Apparently, the oxide shade reflects the completeness of the process. Shades of yellow in the residue indicate the presence of nitrides. Two of the reaction equations are:

$$3\,Mg + O_2 \longrightarrow MgO + 10{,}800 \text{ Btu/lb. Mg} \qquad (1)$$

$$3\,Mg + N_2 \longrightarrow Mg_3N_2 + 2{,}860 \text{ Btu/lb. Mg} \qquad (2)$$

Equation No. 1 reflects the normal combustion expected to occur. To sustain burning of bulk magnesium, at least a 5-percent concentration of oxygen is necessary (see Footnote 1). Equation No. 2 reflects a reaction with nitrogen. Ordinarily, nitrogen does not take part in a combustion reaction. However, in the case of magnesium, the temperature of combustion is so great that nitrides are produced.

The magnesium nitrides react with water vapor in the atmosphere to produce ammonia. (This was indicated after magnesium fire tests by the presence of a strong odor of ammonia in the vicinity of the residue). The following equation shows this reaction:

$$Mg_3\,N_2 + 6H_2O \longrightarrow 2\,NH_3 + 3\,Mg\,(OH)_2 \qquad (3)$$

Equations Nos. 4 and 5 show the reactions that follow the application of water directly to burning magnesium. These reactions are:

$$Mg + 2H_2O \longrightarrow Mg\,(OH)_2 + H_2 + 6{,}000 \text{ Btu/lb. Mg} \qquad (4)$$

$$2H_2 + O_2 \longrightarrow 2H_2O + 51{,}600 \text{ Btu/lb. } H_2 \text{ (approx.)} \qquad (5)$$

These reactions are again attributed to the high flame temperature of burning magnesium, reported to be between 8000° and 9000° F. (see Footnote 1). At such temperatures normal extinguishing agents tend to break down into their elemental components. In some cases explosive mixtures can result; for example, the reaction of water with burning magnesium results in the liberation of free hydrogen which, in turn, reacts violently with the oxygen in the air as shown in Equation No. 5.

In addition to magnesium reacting with nitrogen, it will also react with carbon dioxide. The heat of combustion of magnesium in nitrogen and carbon dioxide atmospheres is about 25 and 60 percent, respectively, of that in air.

DISCUSSION

Test Equipment

The heat source for all prepared specimens was a small laboratory Fisher burner which utilized propane gas. Two similar type burners were used for different phases of this testing. For tests requiring an airflow over the specimen, a burner which operated with a supply of compressed air was used. A stainless steel housing was fabricated and placed over the burner to minimize the effects of the airflow on the flame. Both burners had a 40-millimeter (mm) grid and produced a flame having a temperature of approximately 2000° F. The test setup for the no-airflow tests is shown in Fig. 2 and for the airflow tests, Fig. 3.

The heat source used for all engine components tests was a commercial conversion-type oil burner adjusted to burn 12 gallons of kerosene per hour. The burner was equipped with a diffuser having an elliptical open end of major and minor axes, 16 and 8 inches, respectively. The average temperature of the flame at a distance of 8 inches in front of the diffuser was 2000° F. The test setup is shown as Fig. 4.

All temperatures were recorded on Minneapolis-Honeywell temperature recorders calibrated for chromel-alumel thermocouples. Both circle- and strip-chart type instruments graduated from 0 to 2400° F. were used. Twenty-two gauge chromel-alumel thermocouple wire with fiberglas insulation was used for the temperature measurement of prepared magnesium alloy specimens and ceramic-inconel sheath; 22-gauge thermocouple wire was used for temperature measurement of the large castings.

The airspeed measurement for tests requiring an airflow condition was obtained with the use of an Alnor valometer. The airflow was produced over the specimen by a 5-horsepower (hp) ceiling fan aspirating air through a 2- by 2-foot duct. A sketch of this apparatus is shown as Fig. 5. Control of the airflow was provided by varying the position of a damper as shown on the sketch. Airflow was varied from 0 to 2000 feet per minute (fpm) during tests.

Test Specimen Preparations

All the prepared magnesium alloy specimens were cut oversize from 2½- by 5½-inch bar stock and milled to the desired thickness. The range of thickness for the tests not requiring an airflow was 0.031 to 1 inch. For the tests requiring an airflow, the thickness was 1/2 inch. The thermocouple leads were peened into the surface of the specimen about 1 inch apart. The chemical compositions of the prepared magnesium alloy specimens are shown in Table I.

The engine castings were secured to a metal test rig. Holes were drilled in the castings and thermocouples were inserted at these locations just under the surface. The locations of the thermocouples were chosen to cover both thick and thin sections. Section thickness varied from about 1/4 to 1 inch.

Test Procedures

The prepared magnesium alloy specimens were placed 1 1/2 inches from the burner grid. This distance was maintained for both the no-airflow and airflow tests. Time-temperature histories were recorded for each test from the instant the burner was turned on. As soon as a sustaining white flame was observed, the burner was removed and the time was noted. This procedure was followed for all tests, both with and without an airflow condition.

Test Results

1. Ignition Tests (No-Airflow Conditions): The curves in Figs. 6 to 9 present the time temperature to ignition data obtained during the no-airflow tests. Photographs of a typical test are shown in Fig. 10. The alloys tested were of the magnesium-aluminum composition except alloy ZK60A which was of a magnesium-zinc composition. Test results indicated that with the same heat source conditions, ignition time increased as the thickness of the specimen increased. Furthermore, with an increase in specimen thickness, the shape of the time-temperature curve approaches the solid line portion of that presented in Fig. 1 of the "Introduction".

Test data pertaining to the thicker specimens show a more accurate picture of the ignition phenomenon. First, it can be seen that the rate of temperature rise decreased with specimen temperature increase. This is due to the following factors: (1) the specimen is approaching the temperature of the heat source, (2) the radiation loss is increasing in proportion to the fourth power of the absolute temperature, and (3) the specific heat is increasing.

The second noticeable feature of the curves manifests itself as a levelling off of the temperature. This can be attributed to the heat loss approaching the heat input and an apparent phase change to the metal in this particular temperature zone. To illustrate, Fig. 11 represents a portion of a phase diagram of magnesium and aluminum. The phase change indicated would probably occur across the boundary separating the areas labeled $\epsilon + L$ and ϵ. The $\epsilon + L$ area represents the portion of the phase diagram where a liquid begins to form. In Fig. 11, an arbitrary alloy of 94 percent magnesium and 6 percent aluminum, represented by the dashed line, was selected to show where the phase changes occur. From room temperature to 780° F. this alloy exists as two separate solid solutions, S and ϵ. At 780° F. a phase change occurs. With a further increase in temperature, another phase change occurs at 1040° F. where a liquid begins to form. At 1145° F. the alloy enters completely into the liquid phase, represented by L on the diagram. The third change in the shape of the time-temperature curve, Figs. 6 to 9, occurs with a sudden rise in temperature. This can be attributed to a completion of the phase change (ϵ to $\epsilon + L$), but primarily the magnesium undergoes a phenomenon of self heating and raises its own temperature to a point where it will burst into flame. Test data indicate that ignition occurs in the temperature range denoted by t + L of Fig. 11, since local melting preceded ignition and this ignition temperature is beyond the inflection point of the curve.

Several tests were conducted to illustrate the phenomenon of self heating. Figure 12 is the result of one of these tests and is typical of all the tests conducted. The time-temperature history of a 2- by 2- by 1/2-inch AZ31B magnesium alloy specimen was recorded as it was heated in a metal pan utilizing the propane burner as the heat source. Within a matter of minutes, the temperature began leveling off and the heat was regulated to maintain a constant temperature of the specimen. This temperature was maintained for approximately 1/2 hour, and at the end of this period an increase in specimen temperature was noted even though there was no increase in the burner heat output. At this point the burner was removed and within the next few minutes the temperature of the specimen increased to a point where it ignited. It appeared that ignition was initiated in the area of an oxide formation. This suggests that local oxidation supplies the necessary boost in temperature to initiate burning. The oxidation spread over the entire specimen resulting in the entire mass burning. In addition, the edges of the specimen were observed to oxidize and burn initially. From this observation it is deduced that time to ignition can be increased by minimizing sharp edges and protrusions on magnesium alloy castings.

With respect to the thicker magnesium alloy specimens of Figs. 6 to 9, the point where the curves undergo self heating, as indicated by a sudden increase in temperature, could be regarded as an ignition point. The thinner specimens heated and burned so rapidly that the self-heating phenomenon was apparently bypassed completely. In regard to these thin specimens, the first indication of ignition occurred with the appearance of a white flame; therefore, the ignition point common to all phases of testing is defined as that where the flame was initially observed.

Figure 13 was prepared from the data shown on Figs. 6 to 9. The ordinate was chosen to reflect the effect of area/volume ($^A/V$) ratio on ignition time. A critical section of the curve for all alloys is shown to occur at $^A/V$ between 10 and 30. For an $^A/V$ value greater than 30, change in ignition time is insignificant. Conversely, for a value less than 10, ignition time increases rapidly. These particular data are based on a specific set of test conditions and cannot be regarded as specific criteria for design. Changes in condition such as the magnitude of the heat source, geometry of the specimen and airflow would result in a displacement of the curves. However, a trend that similar tests would follow is established. The data also point out the importance that relative surface area has on either increasing or decreasing the exposure time necessary to cause ignition of the magnesium alloy. Large surface areas available for heat transfer having small volumes to heat, represent a need for caution, particularly if potential heat sources are in proximity and if these sources are capable of temperatures in excess of 1000° F. Considering the alloys tested and the conditions under which they were tested, 1000° F. appears to be the approximate temperature at which self heating becomes prominent enough to bring the specimen up to its ignition point.

2. Ignition Tests (Airflow Conditions): The next factor considered in the magnesium alloy ignition tests was airflow. Figures 14 to 17 show the effect of airflow on the flammability of prepared magnesium specimens. Figure 18 is a curve showing the percent increase in ignition time with airflow and is based on the average ignition time of the four alloys tested. Airflows ranged from 0 to 2000 fpm. Tests indicated that by increasing the flow of air around a magnesium alloy specimen, the time to ignition is extended; however, once ignition is effected, airflow increases the intensity of the magnesium fire. The only unusual event was that alloy AZ31B did not ignite in the 2000-fpm airflow test condition. This is represented by the dotted line in Fig. 16. Since the test conditions to which this alloy was subjected were identical to those under which all other alloys were tested, it was concluded that chemical composition of the alloy in question was a factor. AZ31B's magnesium content was 95.8 percent, whereas all others contained less. The phase diagram indicates that 100 percent magnesium melts at 1200° F. The compositions having less magnesium to aluminum content melt at lower temperatures. As indicated in Fig. 11, a 94-percent Mg/6 percent Al alloy would melt at 1145° F. Since melting and ignition temperatures were observed to appear very close together, it would seem that an alloy of greater magnesium to aluminum content would ignite at a higher temperature. Under the 2000-fpm airspeed condition, AZ31B alloy apparently did not reach its ignition temperature.

3. Engine Casting Ignition Tests: The third phase of testing consisted of subjecting engine castings to a flame produced by a 12-gallon-per-hour (gph) kerosene burner. These tests were designed to serve two purposes: (1) to obtain indication of the exposure time required to ignite a bare magnesium alloy casting, and (2) to determine whether or not burning would be sustained. Table II shows the results of the tests. Figures 19 and 20 show a sequence of operation during a typical test and the resulting fire damage to the magnesium casting. Time to ignition for the 23-, 81½-, and 91½-pound castings were 2, 2, and 4 minutes, respectively. The time that each casting sustained the fire after the burner was shut down was 4, 34, and 50 minutes, respectively. It was noted that initial ignition of each casting occurred at the thin sections. The largest casting (Test No.3) required more exposure time for ignition to commence, and also sustained greater deterioration from fire than the other two castings. This was apparently due to the fact that a more extensive portion of this casting had a wall thickness of about 1/4 inch in comparison with

the other castings. If an airflow had been applied to this particular casting after it ignited, it probably would have been totally consumed. It is apparent that these magnesium alloy components burn slowly and sustain fires of very low heat output in comparison to fuel fires.

The magnesium alloy casting fire tests were considered to be extremely severe in comparison to what could occur in an actual aircraft power plant installation. The castings were devoid of all internal parts as well as internal circulating fluids and external airflows expected within a normal power plant installation. Also, the castings were exposed to the heat source as a unit in themselves and did not have the normal massive engine environment attached to them which would have provided an extensive heat sink. The addition of all these factors would have contributed to the ignition resistance of the castings tested. Considering this, as well as test results, it appeared that the large magnesium alloy gear housing castings associated with jet or reciprocating power plant installations would not create a substantial fire hazard. Furthermore, if a fire developed in a power plant having the intensity of the 12-gph 2000° F. kerosene burner flame, it would be detected and steps would be taken to eliminate it well before ignition of any large casting would occur. On the other hand, magnesium alloy power plant components which are not an integral part of the engine and which may be of thin-wall construction, such as electrical junction boxes, would be extremely susceptible to ignition from relatively low heat sources. Such components, if once ignited, would probably burn until consumed and although the burning would not be extremely hazardous in itself, these could provide a potential reignition source for other more hazardous flammables after initial extinguishment of the power plant fire.

CONCLUSIONS

Based on the results of laboratory fire tests of prepared magnesium alloy specimens as well as a number of magnesium alloy engine gear-housing castings, it is concluded that:

1. There was no significant difference in ignition-resistance among the alloys tested and under the conditions which they were tested.

2. Bar stock specimens and castings made of magnesium are more susceptible to ignition along sharp edges or protrusions.

3. Prolonged exposure at temperatures just below magnesium alloys' melting temperature could initiate ignition. Test results indicated that self-heating began at approximately 1000° F.

4. A decrease in the area to volume ratio of the magnesium alloy will increase its resistance to ignition.

5. An increase in airflow over the surface of a magnesium alloy will delay time to ignition, but once ignition is established, the alloy will burn at a faster rate than under stagnant air conditions.

6. Large massive magnesium alloy components are not likely to represent a great fire hazard problem in aircraft power plant installations because of the obvious large heat requirement necessary to ignite them.

7. Small thin-wall magnesium alloy components that are not an integral part of the engine itself but are within a power plant fire zone are likely to represent a more serious fire hazard, especially from reignition of flammables standpoint since these will resist normal methods of extinguishment.

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APPENDIX 1

Lists of Illustrations and Tables

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LIST OF ILLUSTRATIONS

LIST OF TABLES

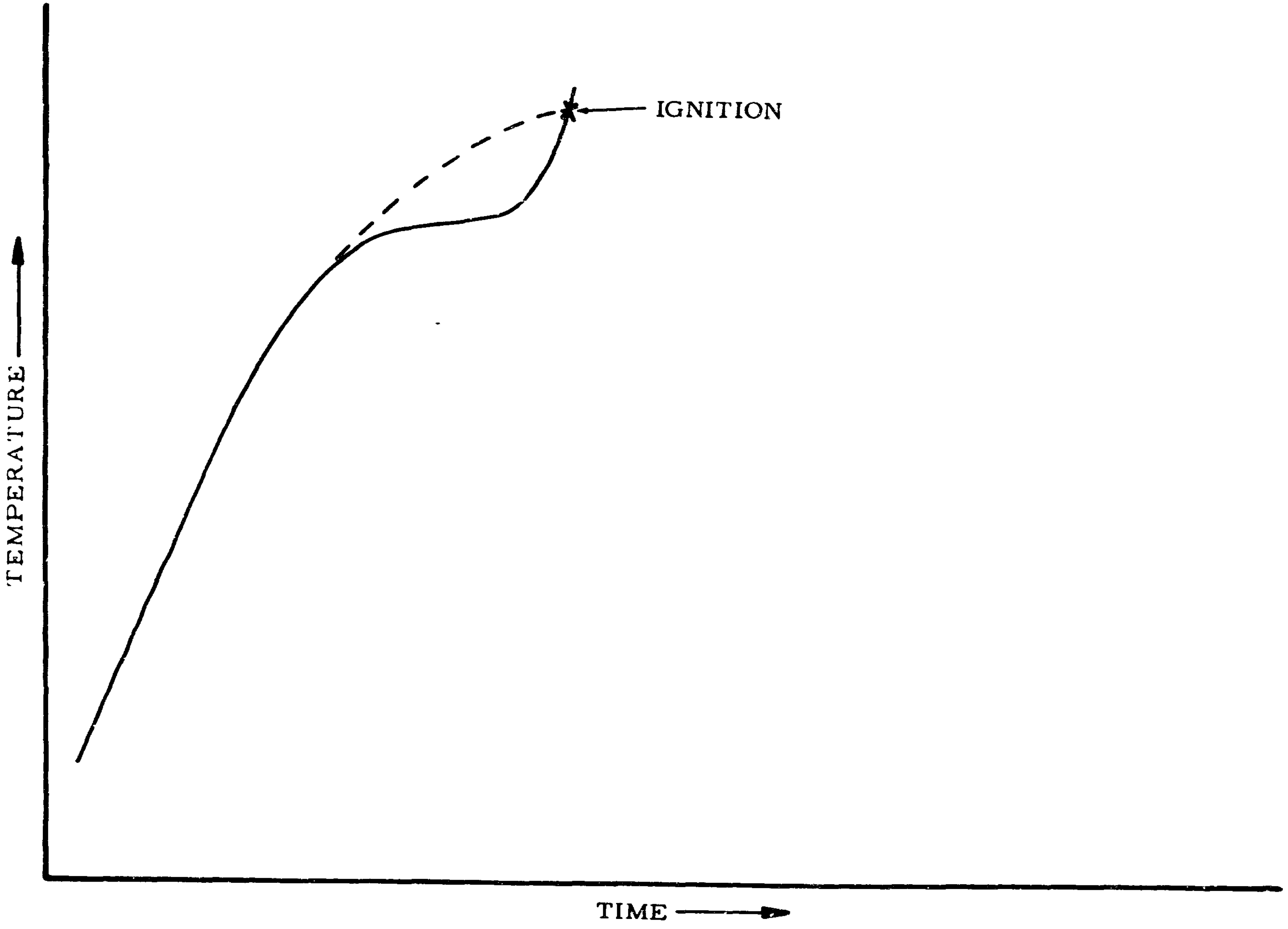
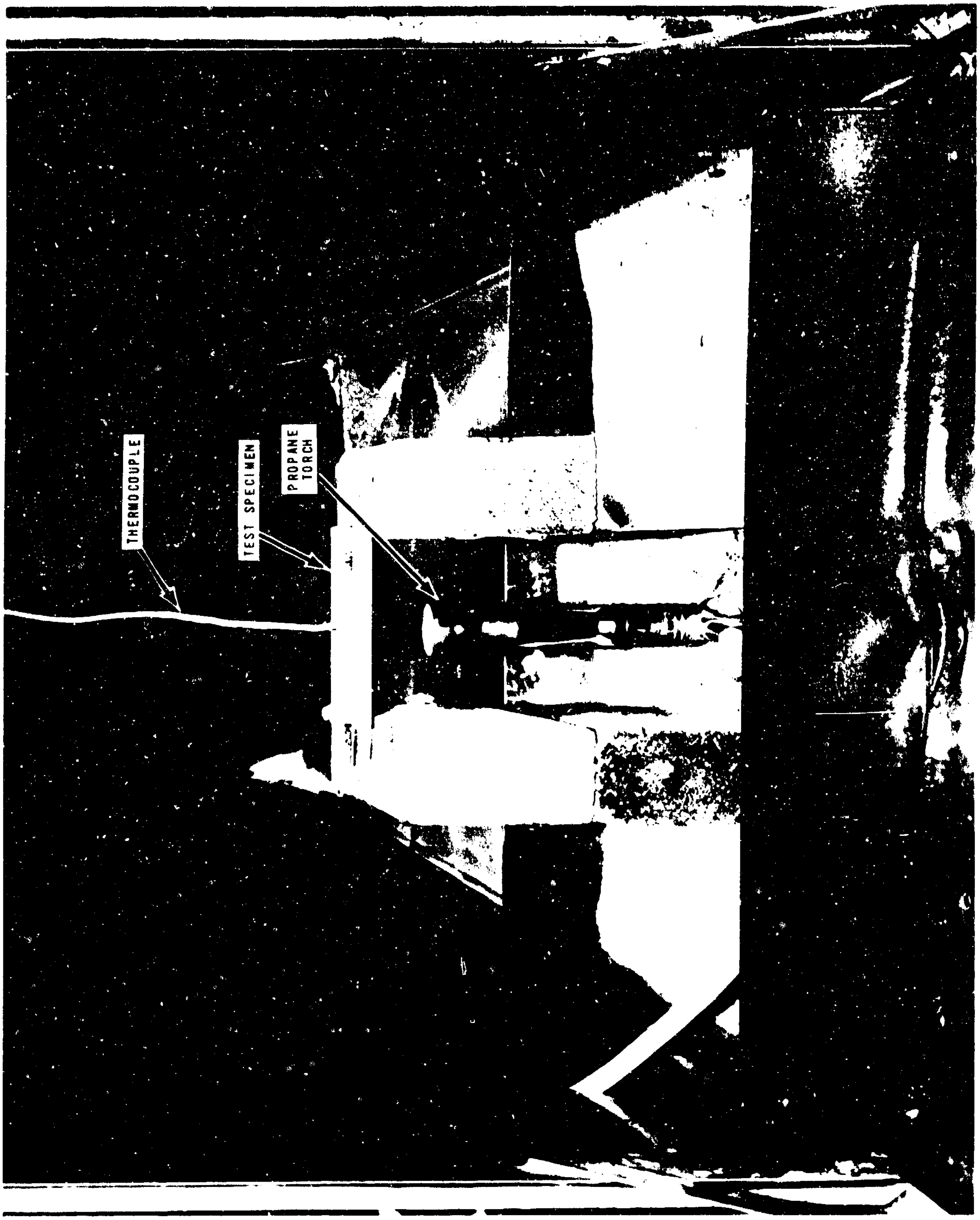


FIG. 1 TYPICAL TIME TO IGNITION CURVE FOR MAGNESIUM


THERMOCOUPLE
TEST SPECIMEN
PROPANE TORCH

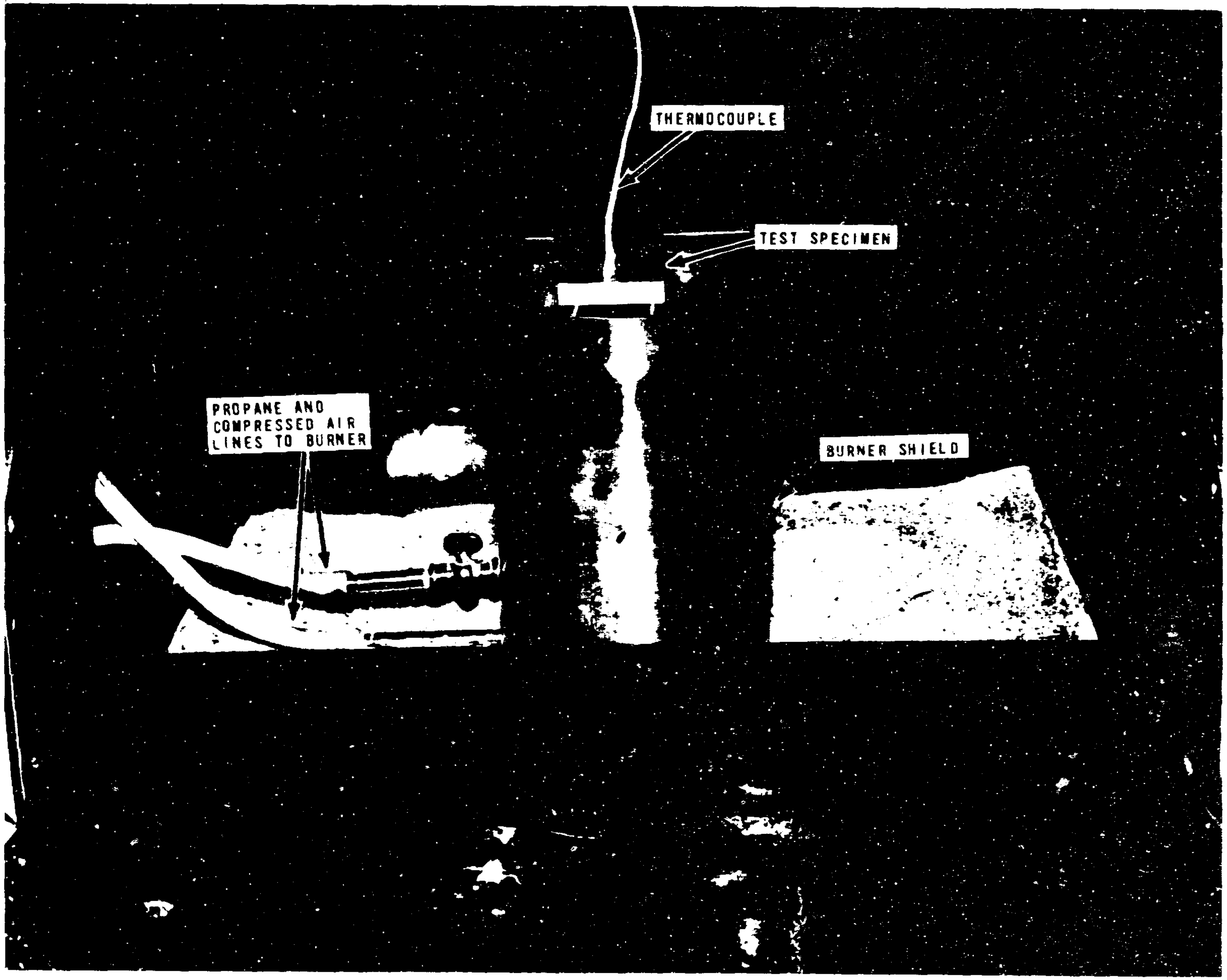


FIG. 3 TEST ARRANGEMENT FOR IGNITION TESTS WITH AIRFLOW

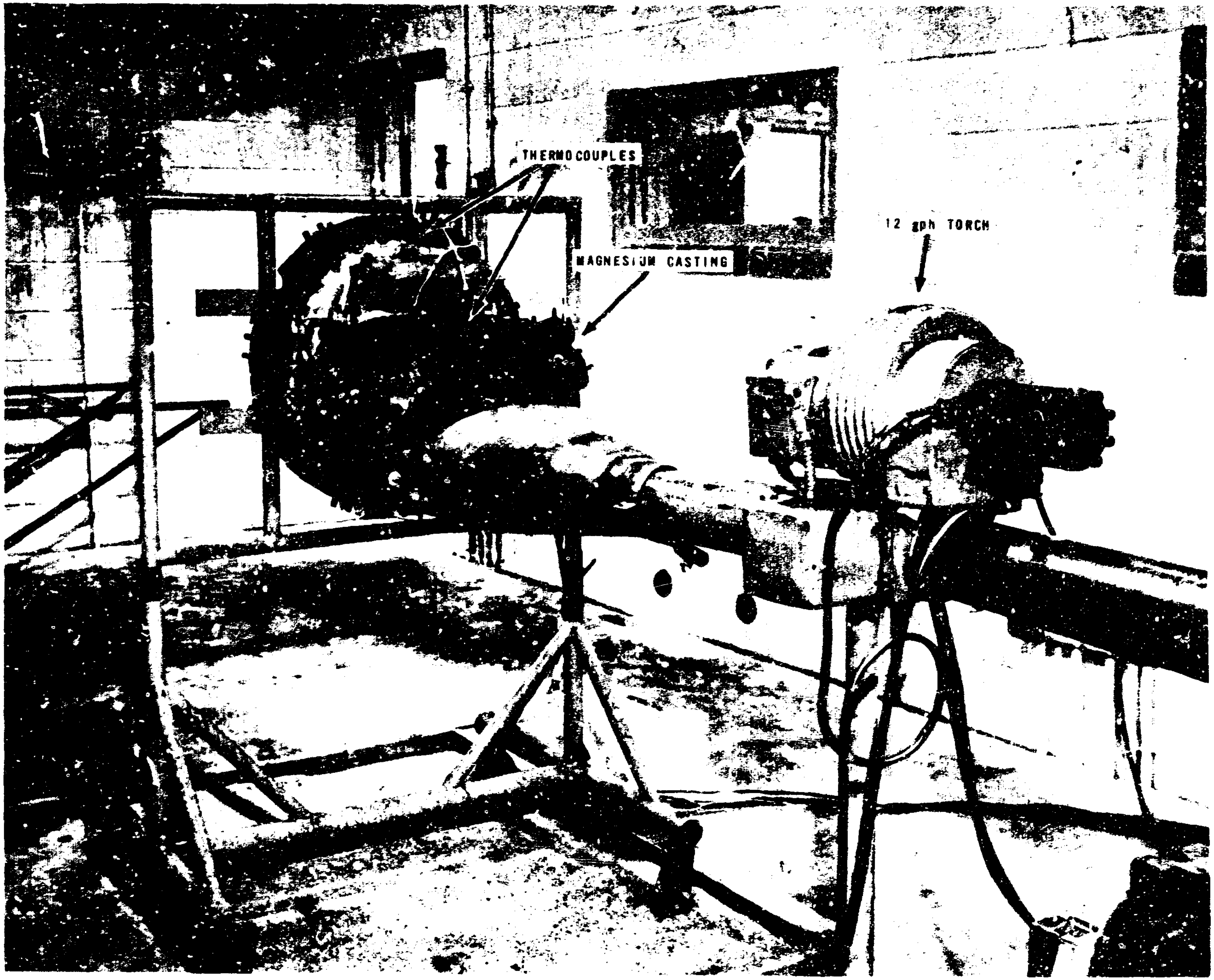


FIG. 4 TEST ARRANGEMENT FOR ENGINE CASTING IGNITION TESTS

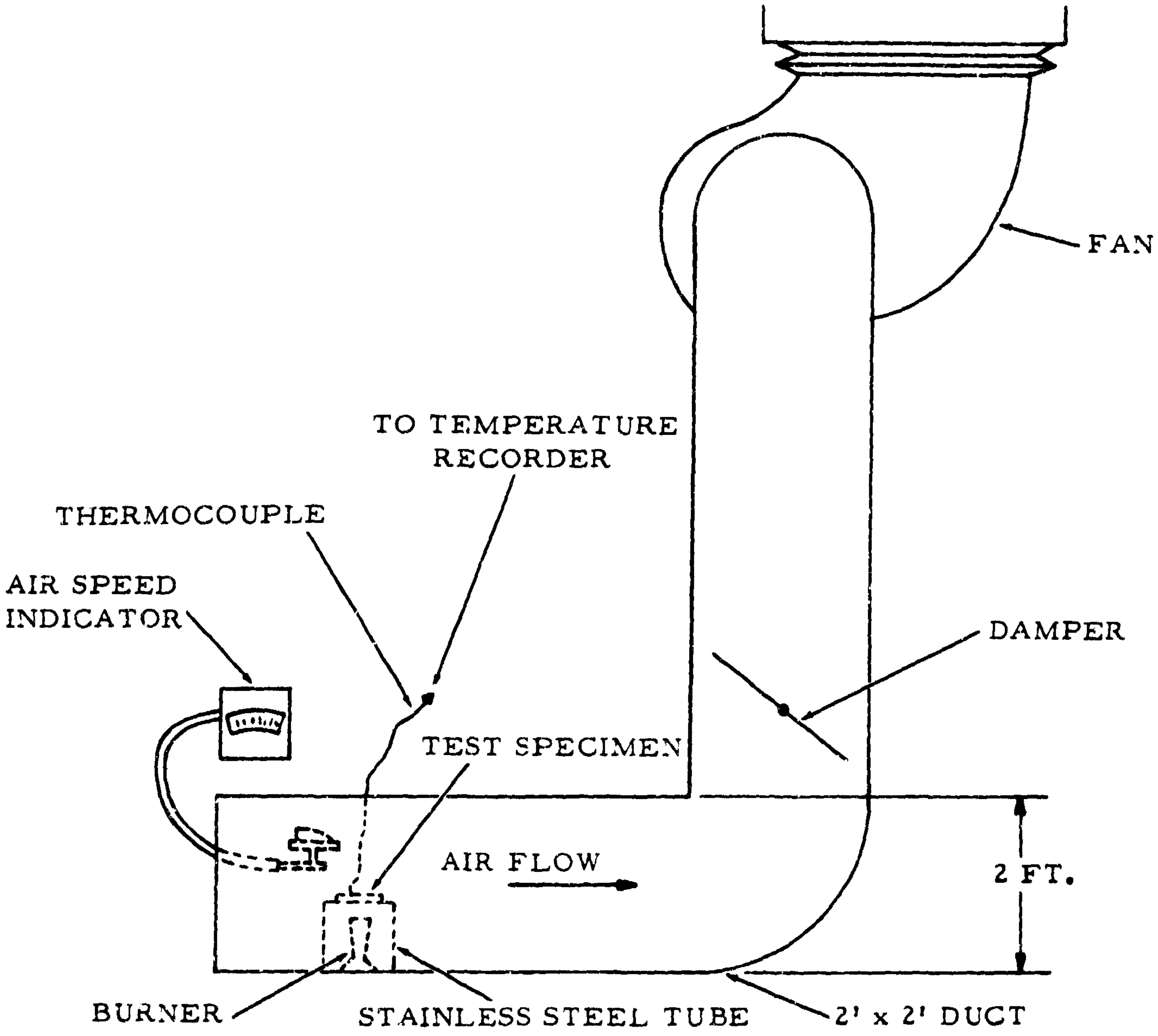


FIG. 5 SCHEMATIC DIAGRAM OF APPARATUS (AIRFLOW TESTS)

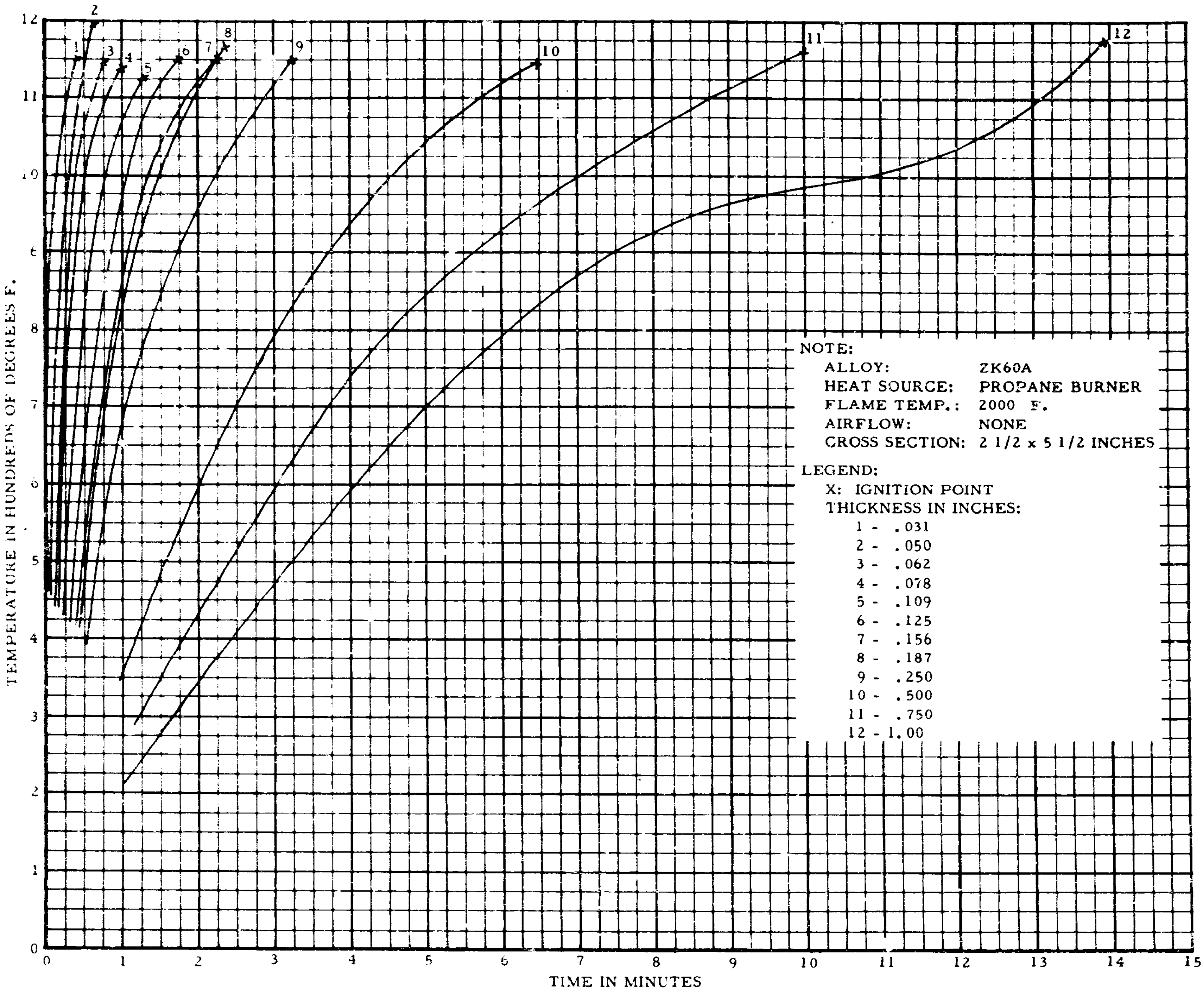


FIG. 6 FLAME RESISTANCE OF MAGNESIUM SPECIMENS (ALLOY ZK60A)

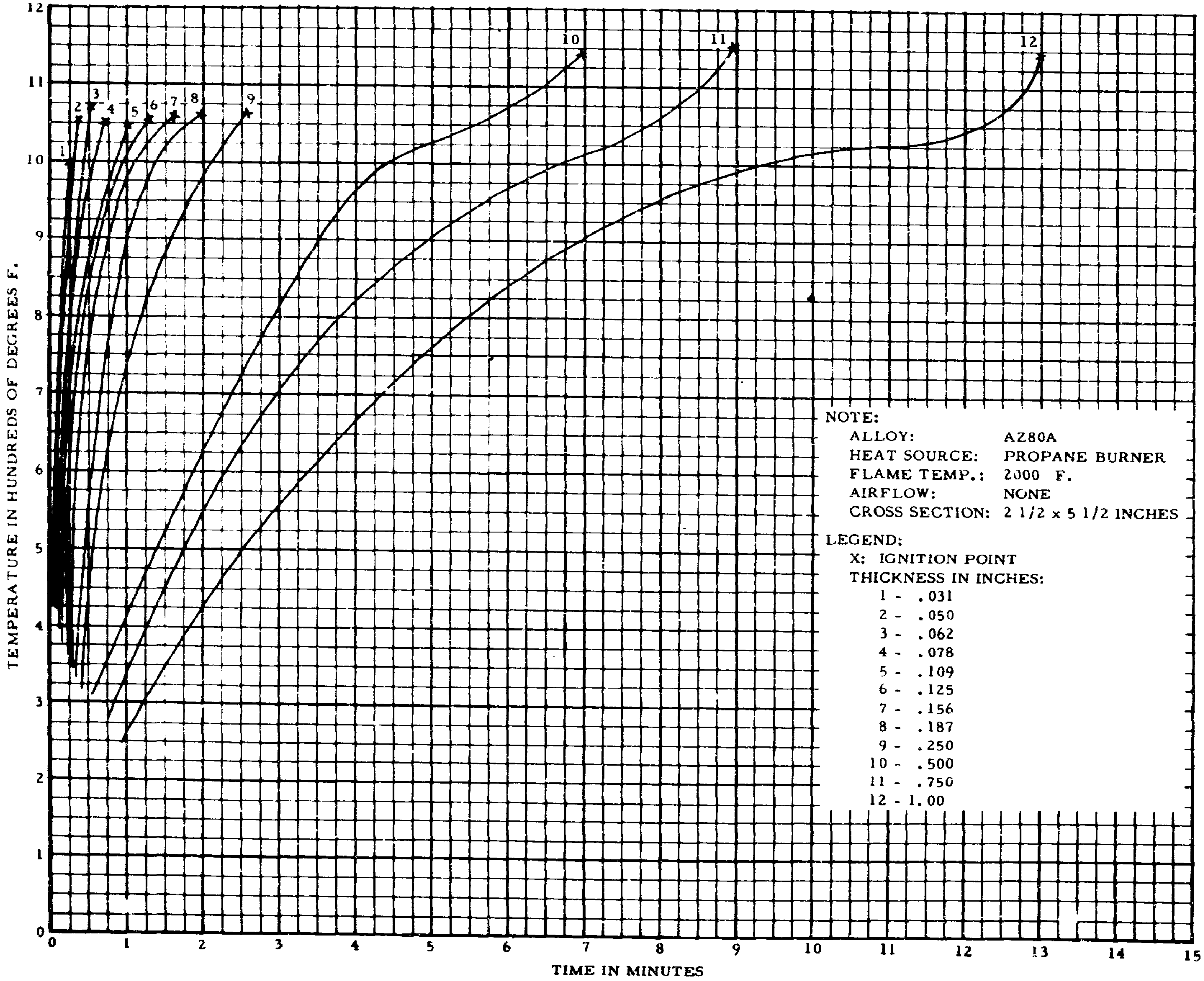


FIG. 7 **FLAME RESISTANCE OF MAGNESIUM SPECIMENS (ALLOY AZ80A)**

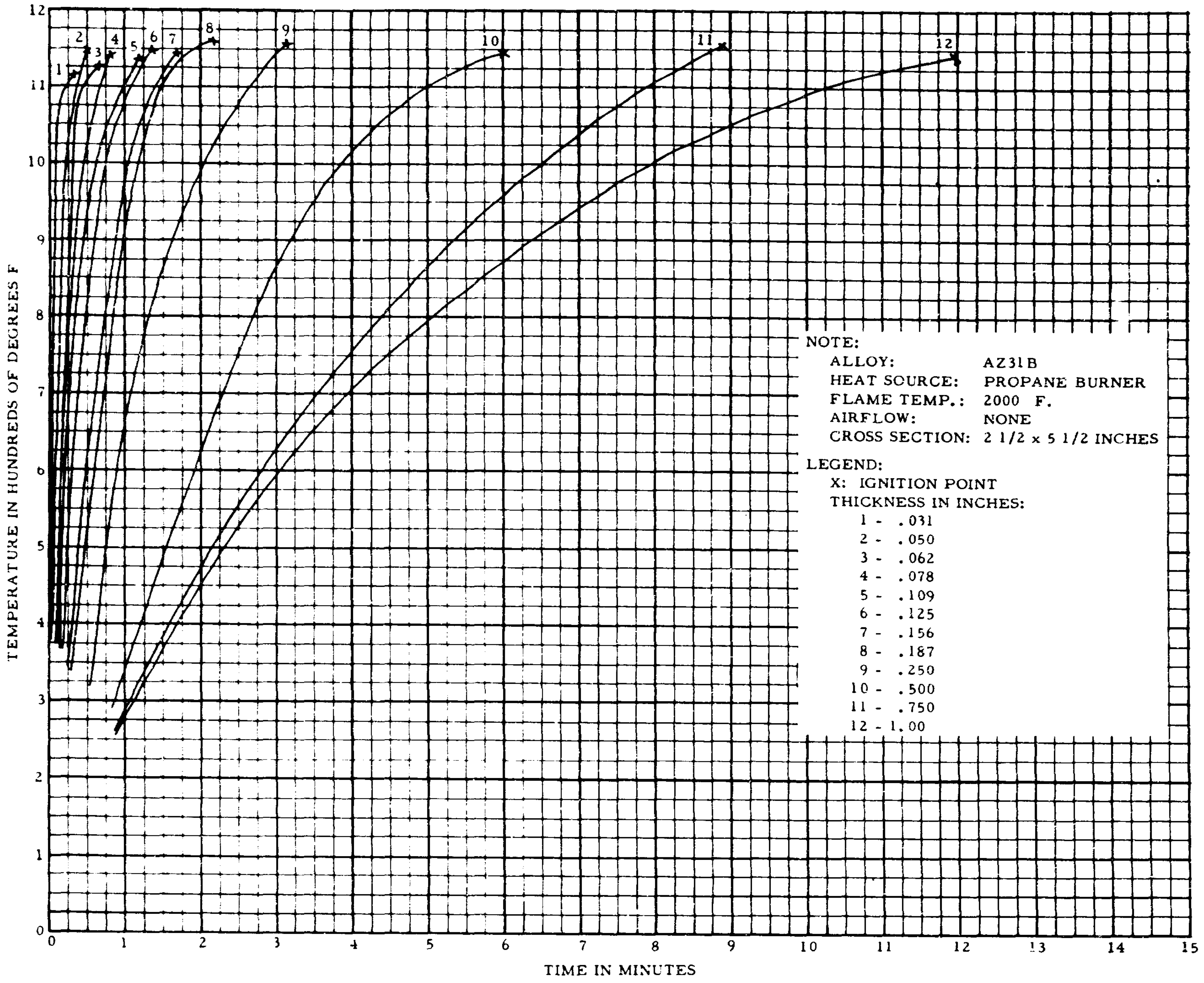


FIG. 8 FLAME RESISTANCE OF MAGNESIUM SPECIMENS (ALLOY AZ31B)

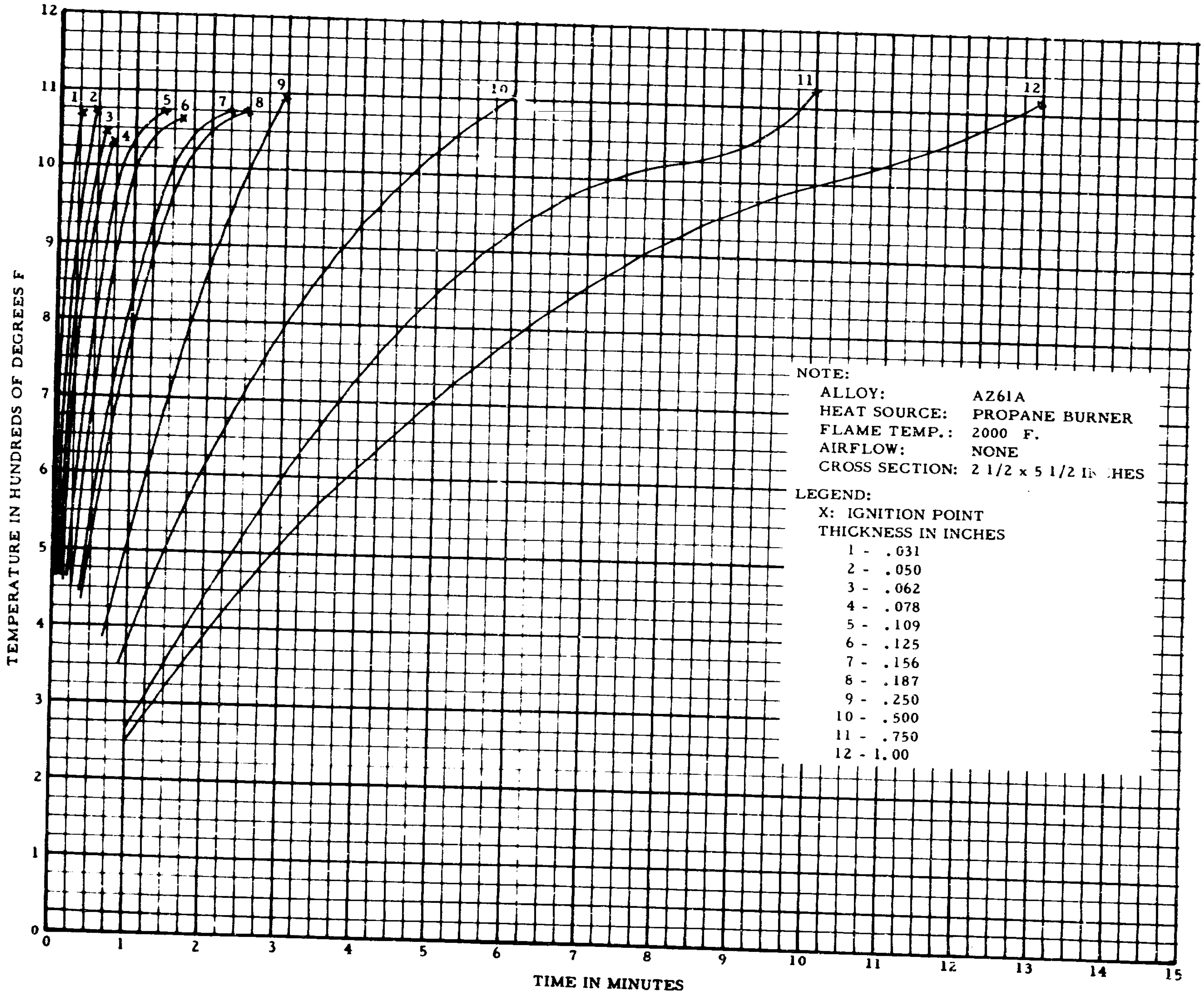


FIG. 9 **FLAME RESISTANCE OF MAGNESIUM SPECIMENS (ALLOY AZ61A)**

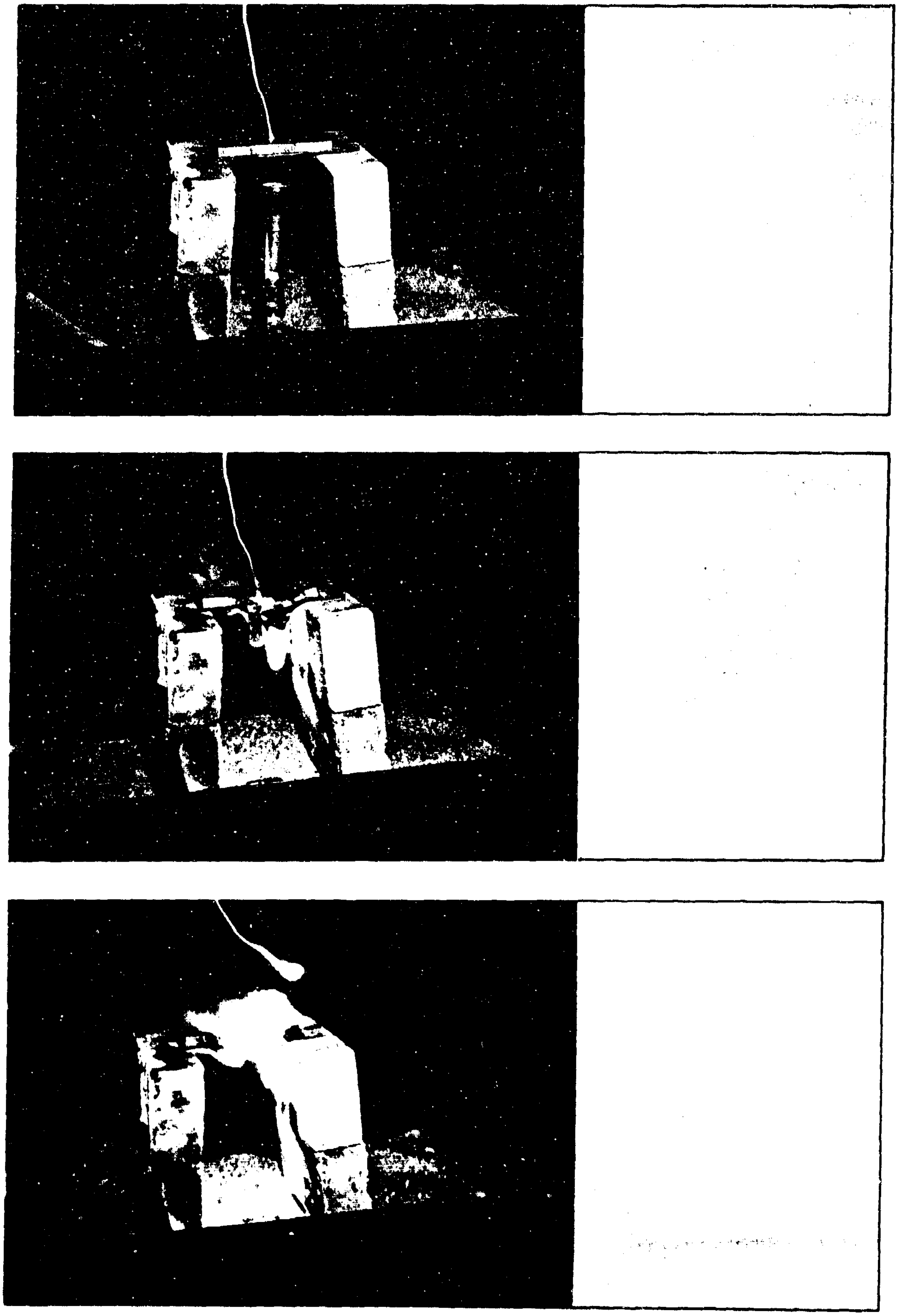


FIG. 10 TEST SEQUENCE FOR PREPARED MAGNESIUM ALLOY SPECIMENS (NO AIRFLOW)

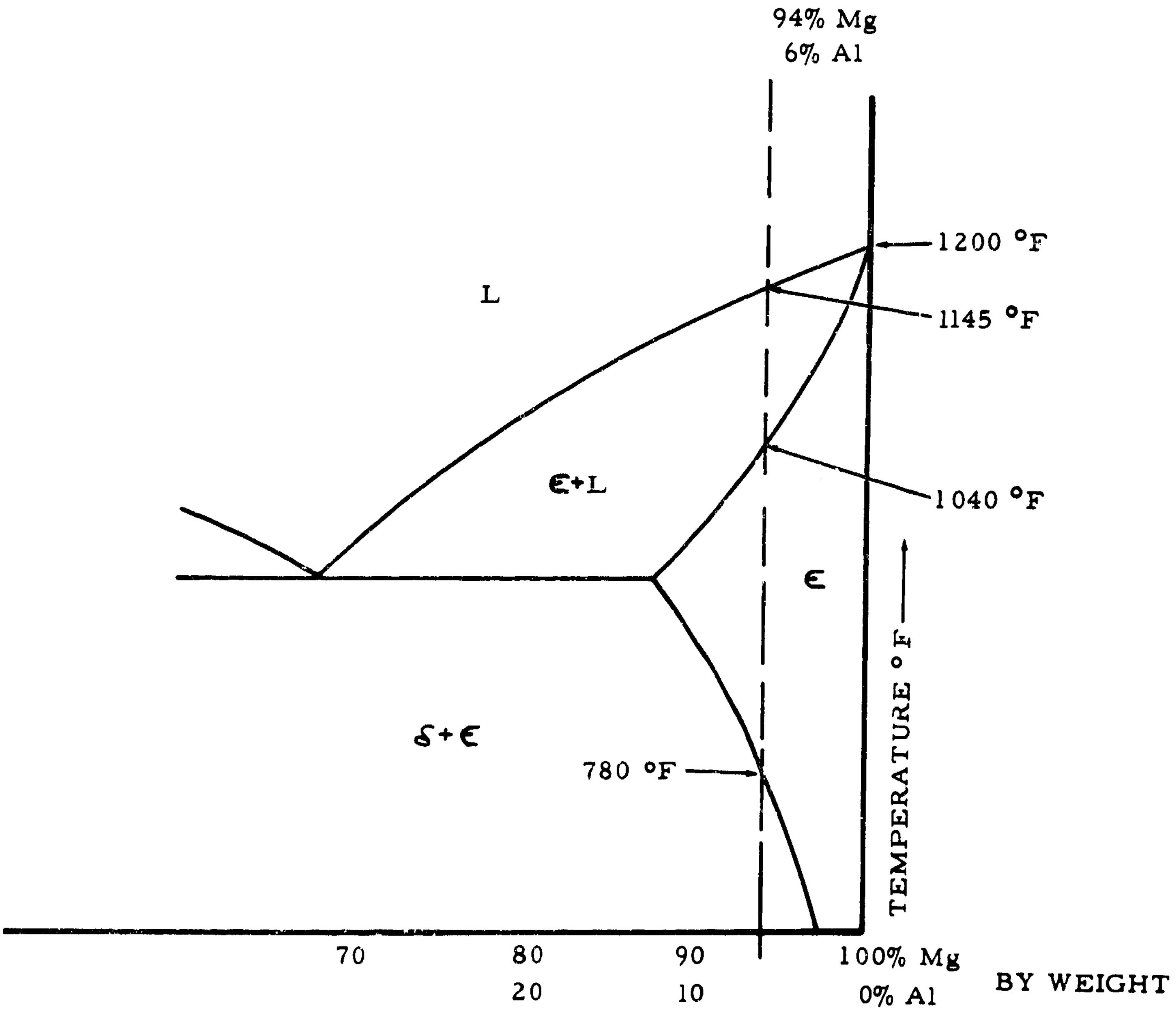


FIG. 11 PARTIAL MAGNESIUM-ALUMINUM PHASE DIAGRAM

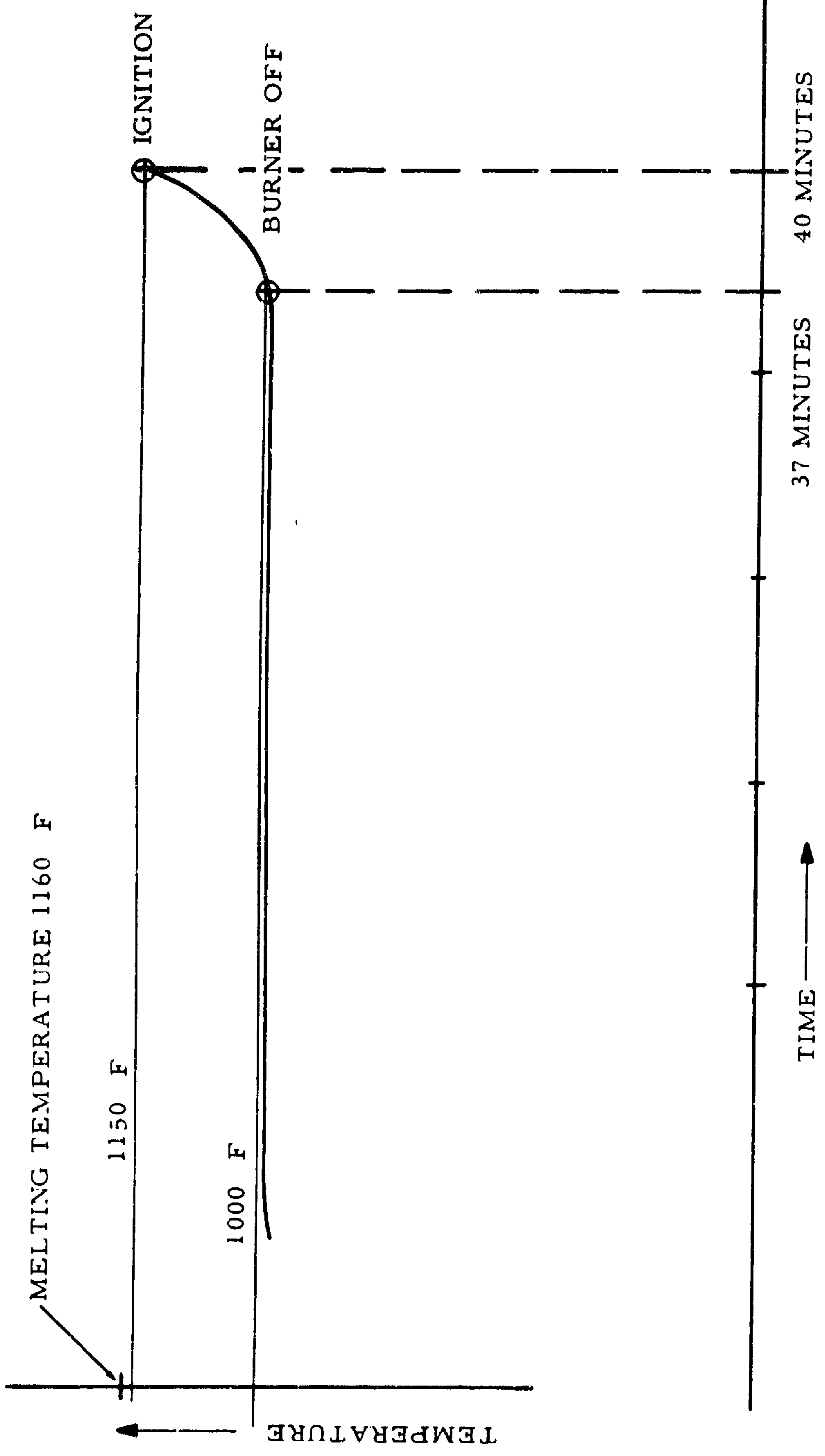


FIG. 12 EXTENDED EXPOSURE IGNITION TEST

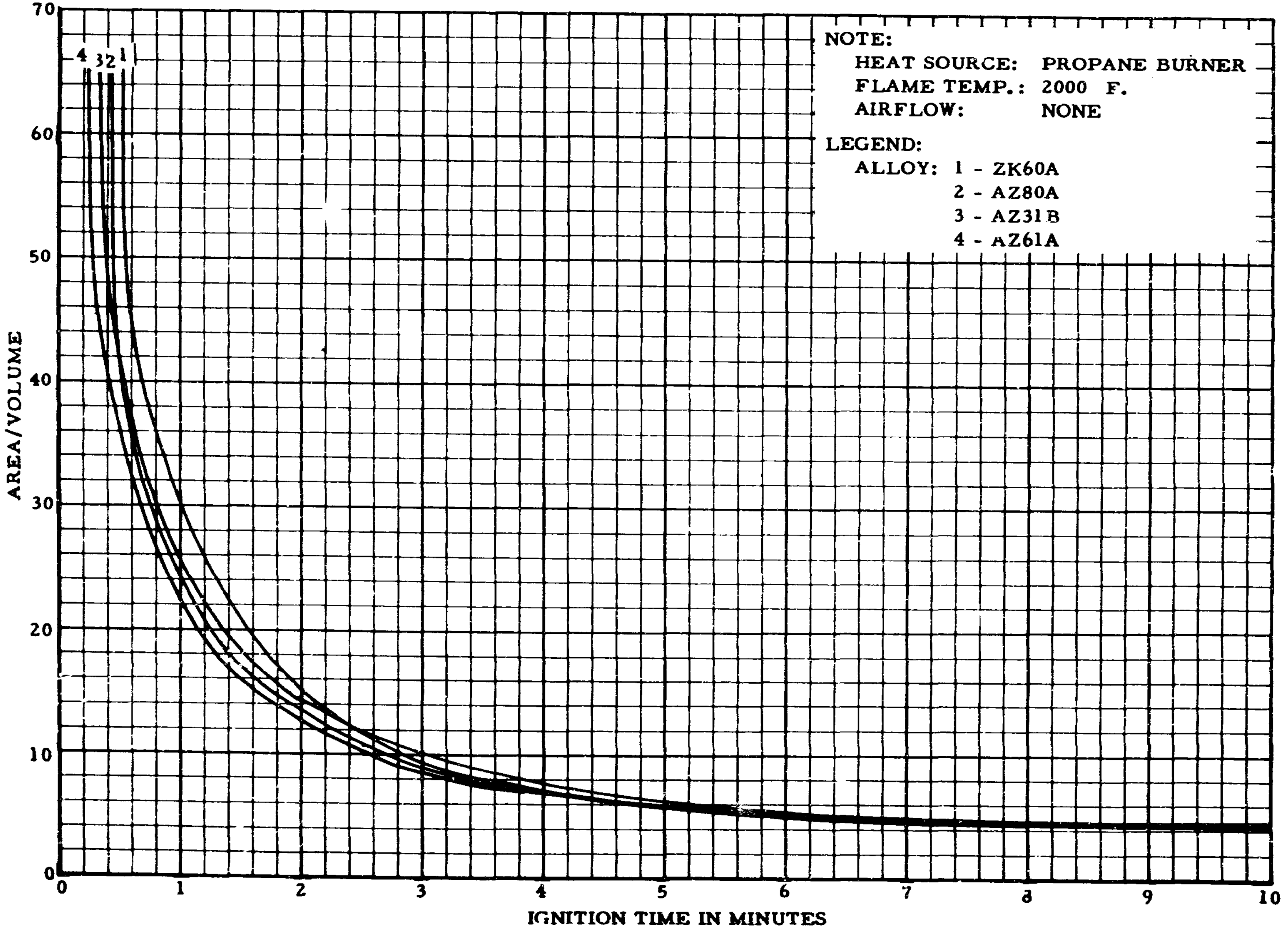


FIG. 13 EFFECT OF AREA/VOLUME RATIO ON IGNITION TIME

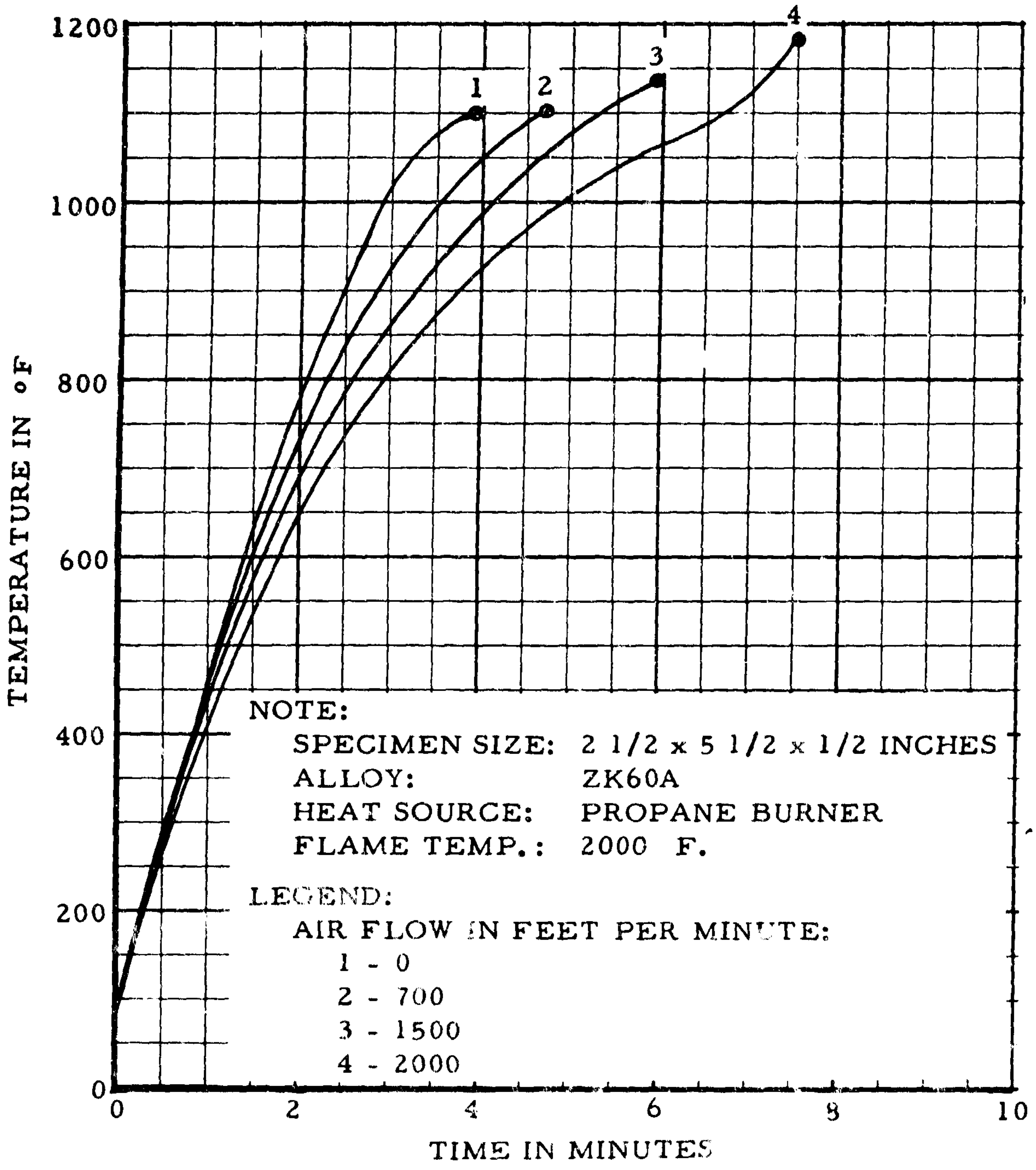


FIG. 14 EFFECT OF AIRFLOW ON IGNITION TIME (ALLOY ZK60A)

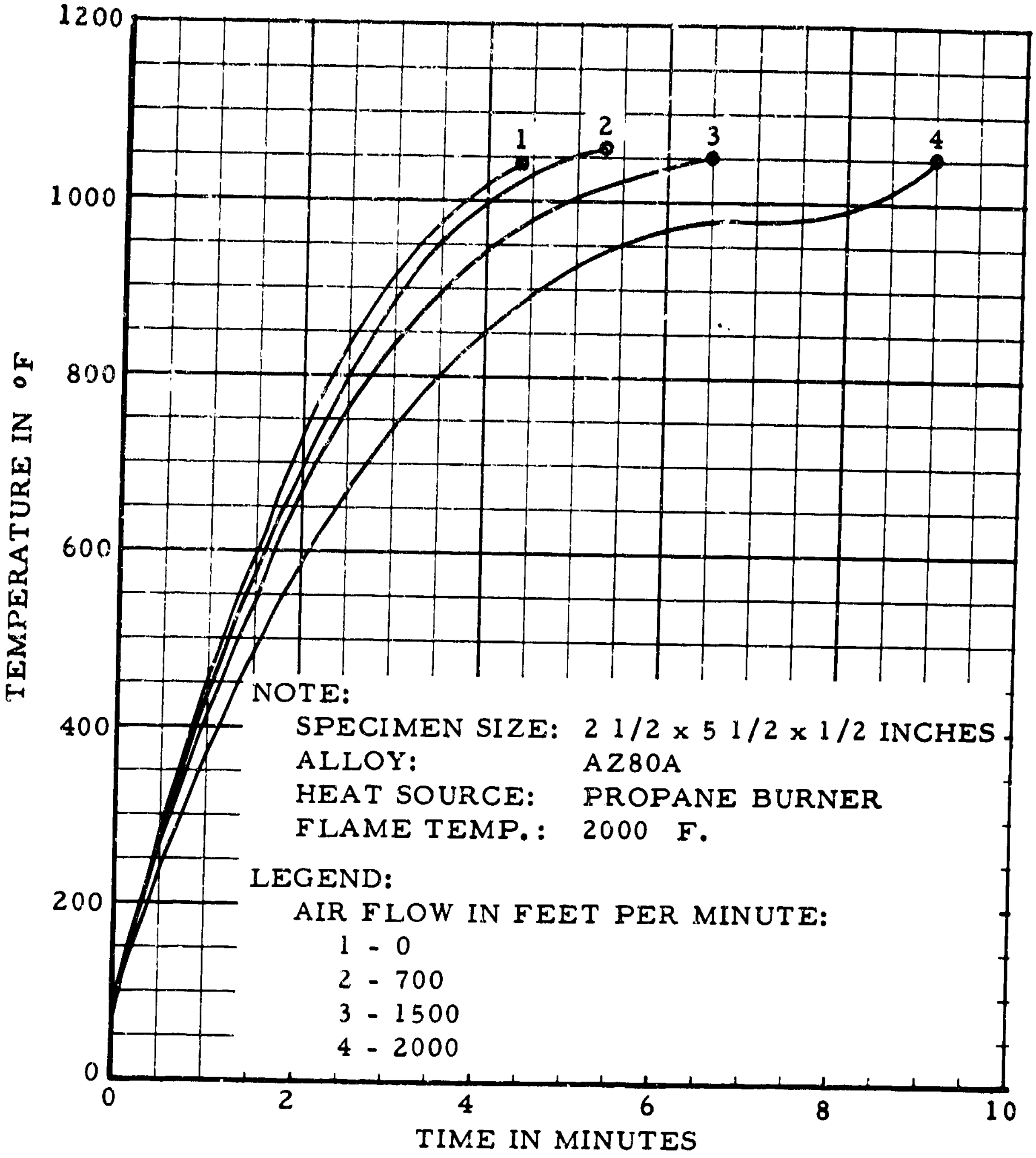


FIG. 15 EFFECT OF AIRFLOW ON IGNITION TIME (ALLOY AZ80A)

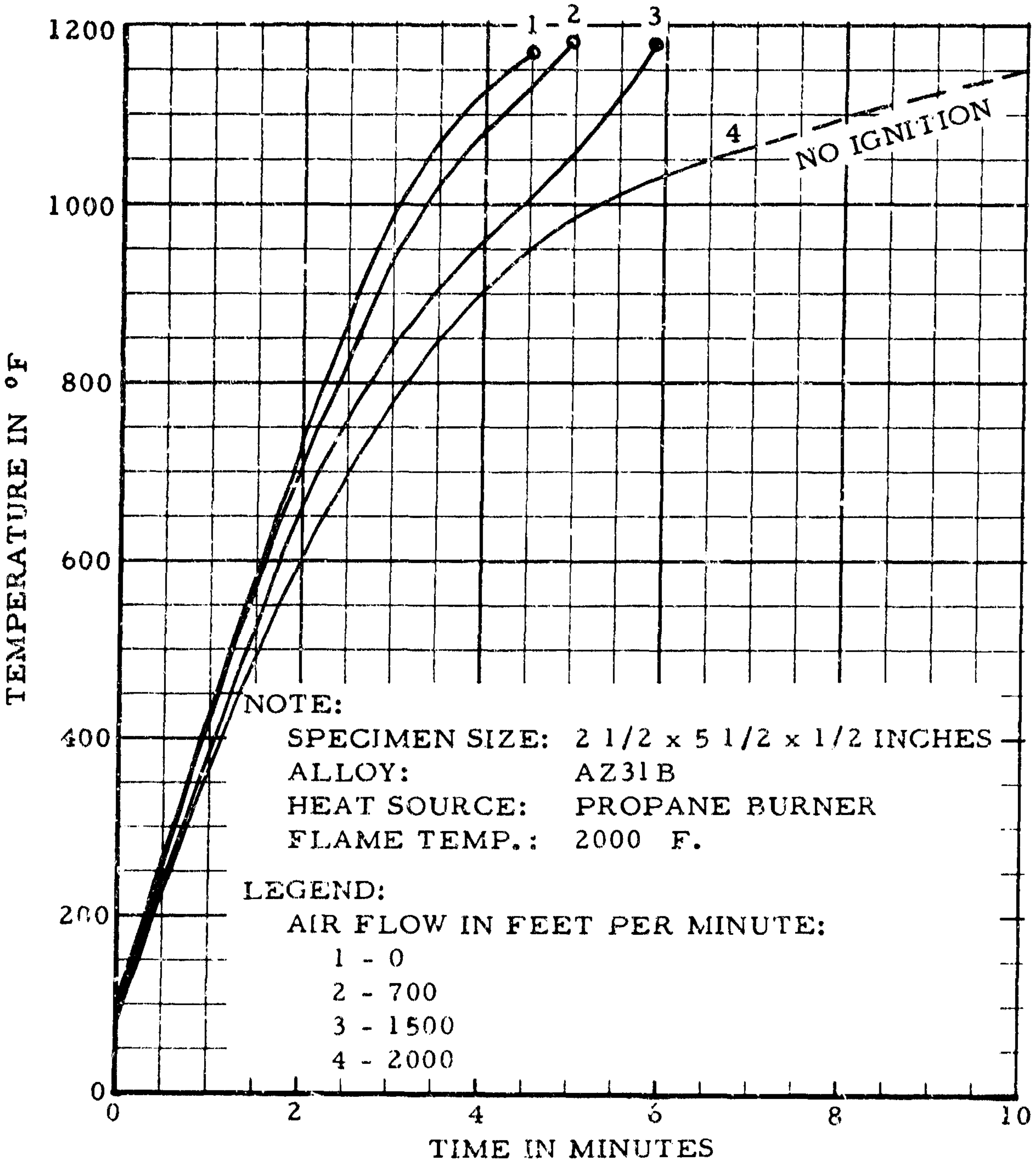


FIG. 16 EFFECT OF AIRFLOW ON IGNITION TIME (ALLOY AZ31B)

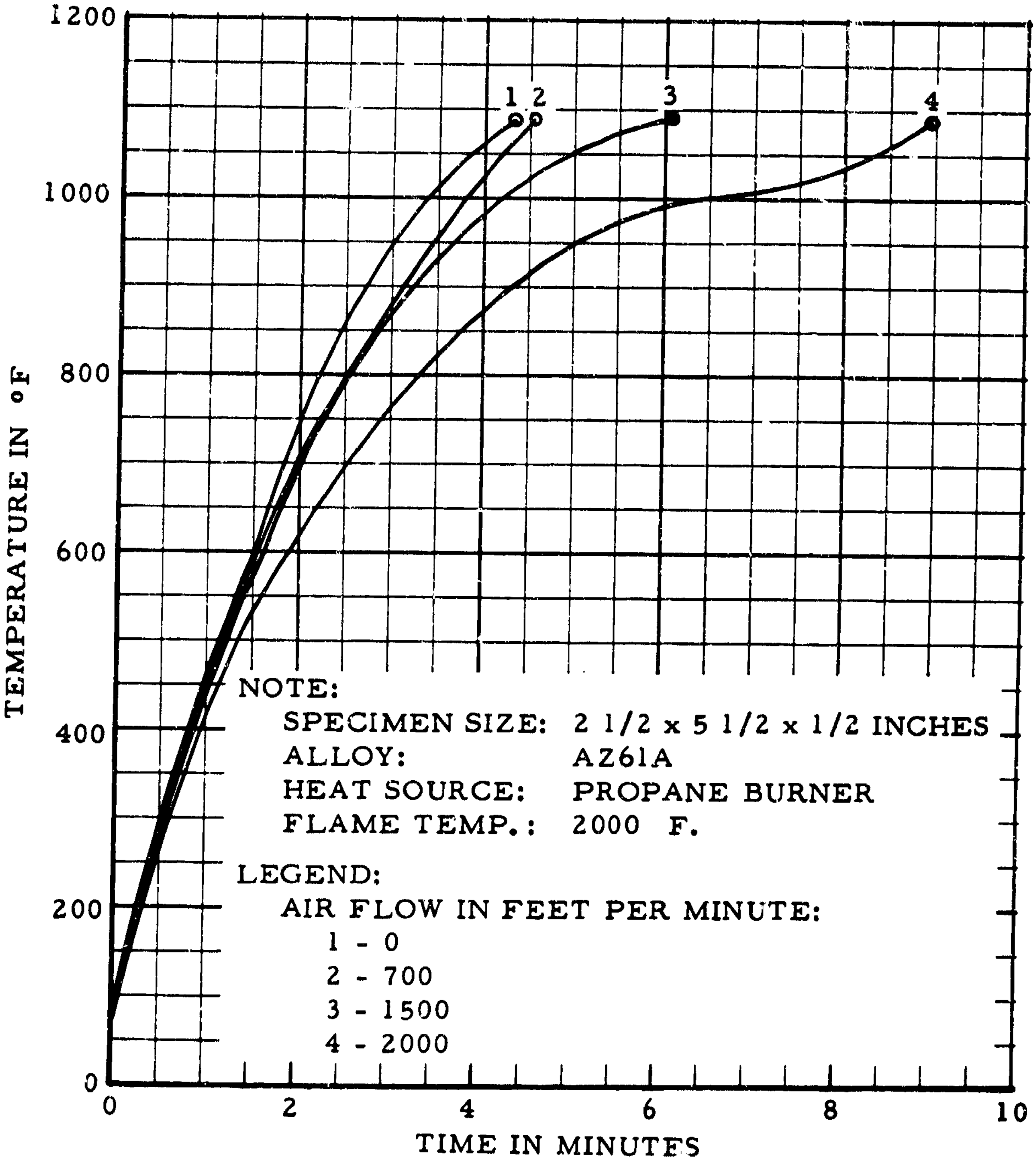


FIG. 17 EFFECT OF AIRFLOW ON IGNITION TIME (ALLOY AZ61A)

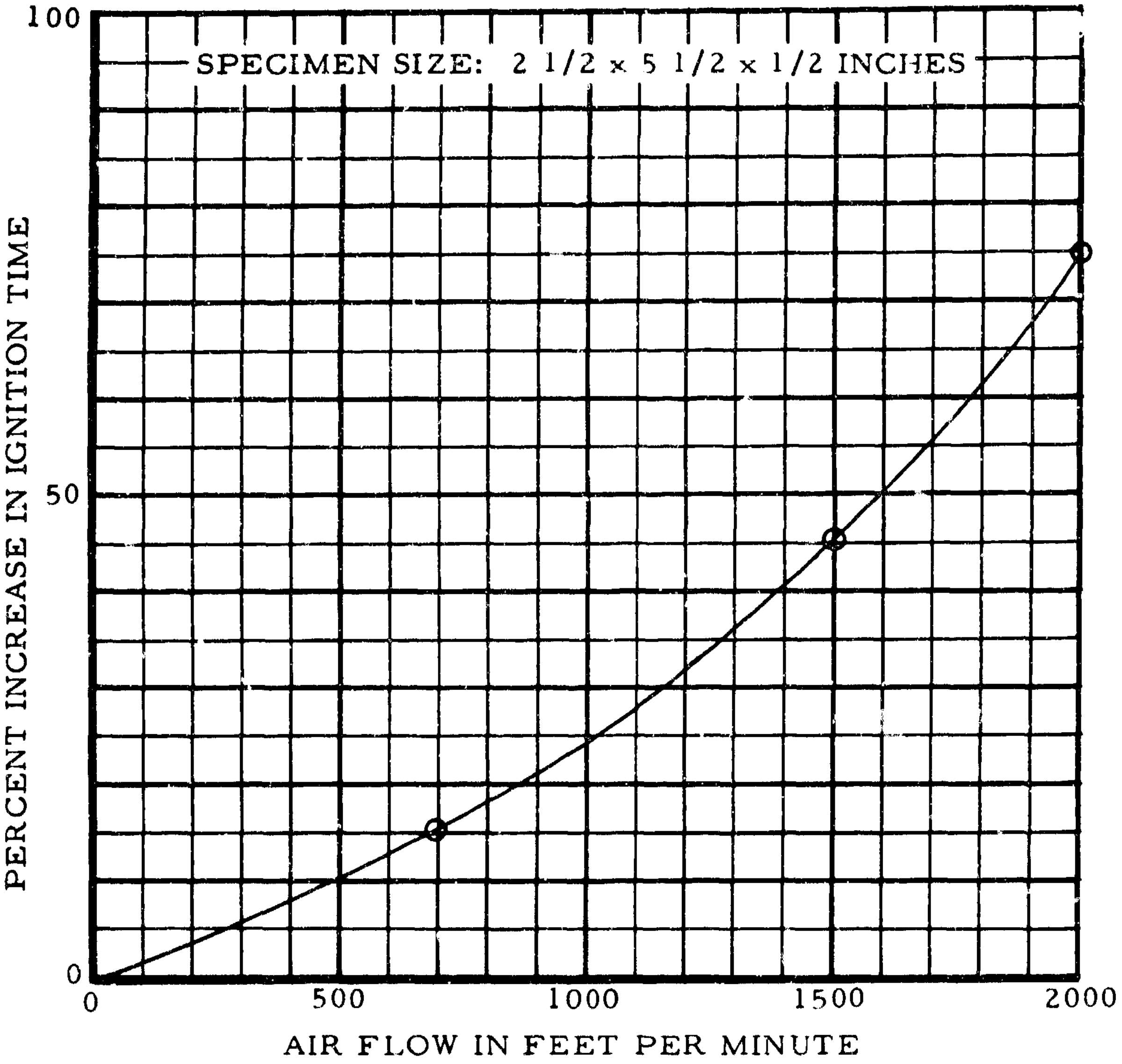


FIG. 18 PERCENT INCREASE IN IGNITION TIME DUE TO AIRFLOW (AVERAGE OF ALL MAGNESIUM ALLOYS)

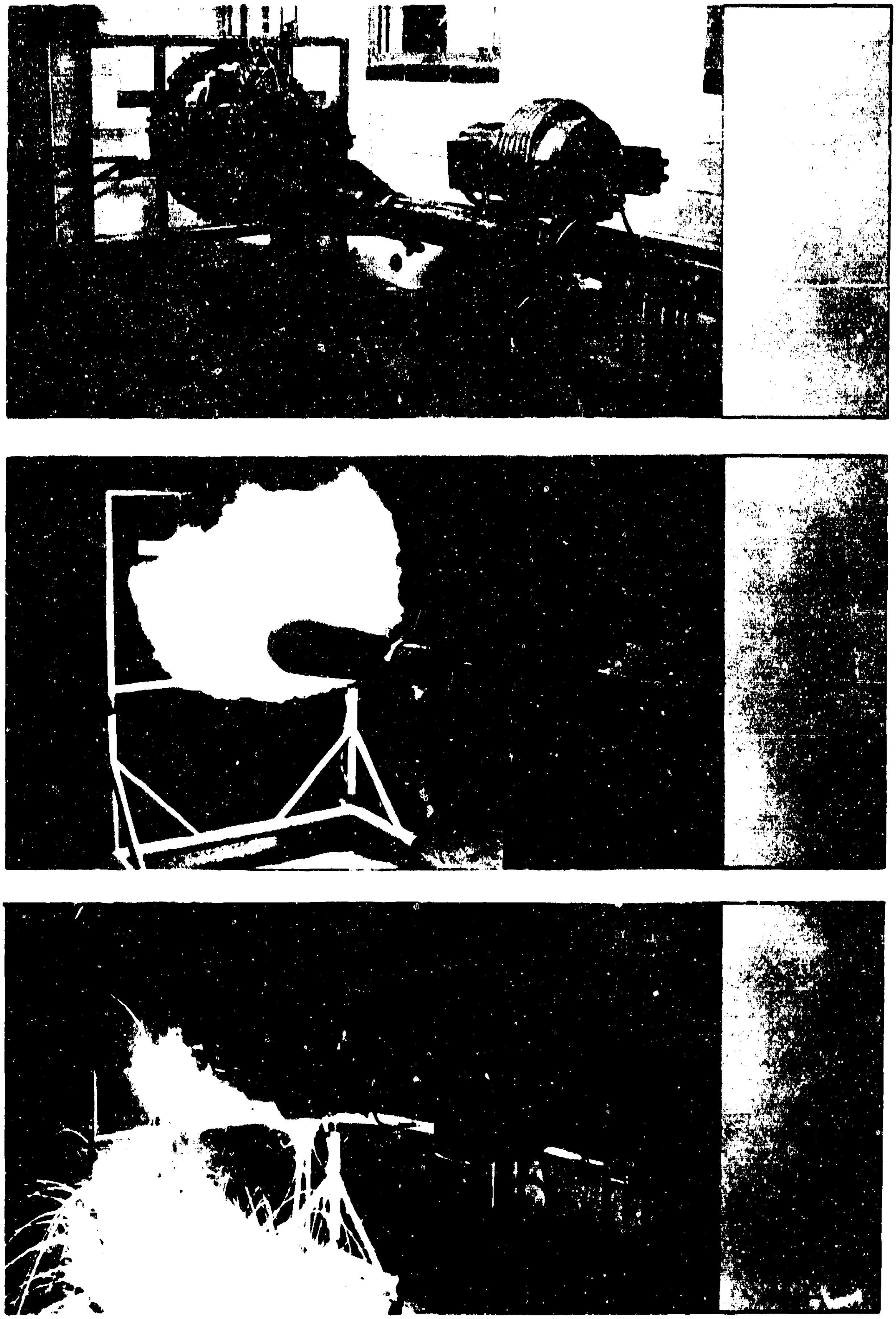


FIG. 19 IGNITION TEST SEQUENCE FOR 81 1/4-POUND MAGNESIUM CASTING

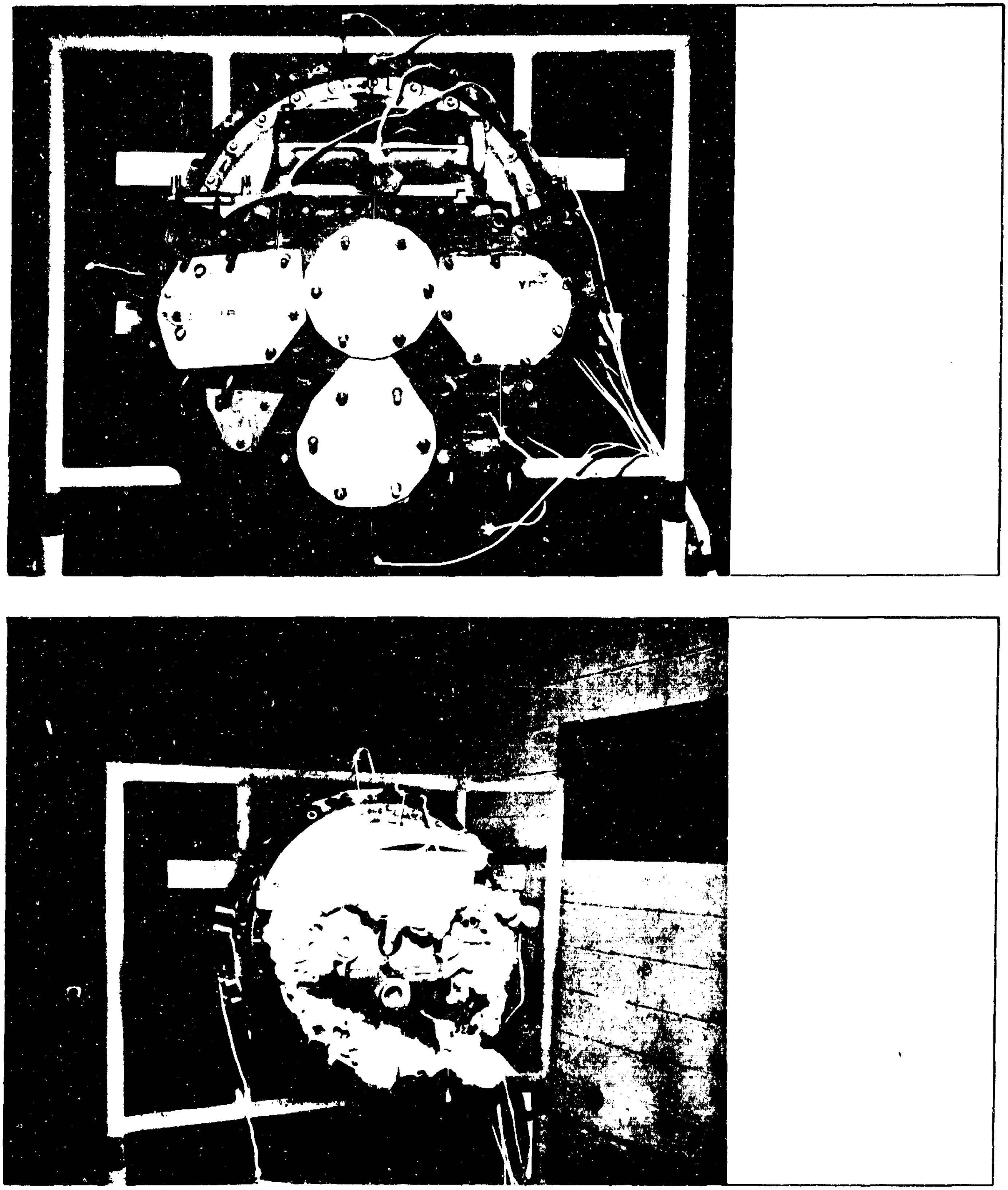


FIG. 20 RESULT OF IGNITION TEST FOR 81 1/4-POUND MAGNESIUM CASTING

TABLE I

COMPOSITION OF ALLOYS USED IN LABORATORY TESTS

Analysis (Percent)

Alloy No.	(1) Mn	(2) Al	(3) Zn	(4) Cu	(5) Ni	(6) Si	(7) Fe	(8) Mg	Other	(9) Zr
AZ61A	.26	6.0	.78	.02	under .005	under .04	under .005	bal.	.3	
AZ31B	.37	2.8	.68	.015	under .005	under .04	under .005	bal.	.3	
AZ80A	.35	9.0	.35	.03	under .005	under .065	under .005	bal.	.3	
ZK60A	.10		5.6					bal.		.58

(1) Mn - Manganese
(2) Al - Aluminum
(3) Zn - Zinc
(4) Cu - Copper
(5) Ni - Nickel
(6) Si - Silicon
(7) Fe - Iron
(8) Mg - Magnesium
(9) Zr - Zirconium

TABLE II

ENGINE CASTING IGNITION TESTS

Name	Weight (lb.)	Engine	Time To Ignition (min.)	Fire Out (min.)	Burn Rate (Percentage)
1. Rear Accessory Case	23	R-1830	2	6	15
*2. (As Unit)	81.25		2	36	33
Rear Accessory Case	81.25	R-2000			
Intermediate Rear Case		R-1830			
Blower Case		R-1830			
3. (As Unit)	91.25		4	54	74
Rear Accessory Case		R-2800			
Intermediate Rear Case		R-2800			

*These castings for the R-2000 and R-1830 engine are similar; hence the castings could be fitted together for this test.