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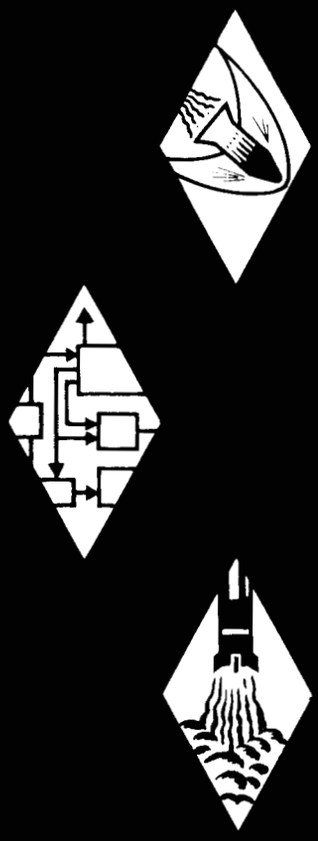

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EXPERIMENTAL RESULTS FOR THERMAL IGNITION OF HYDROGEN IN A SUPERSONIC VISCOUS FLOW

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TECHNICAL REPORT NO. 404

by James Dunn

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ABSTRACT

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This report contains results of a wind tunnel program to determine ignition characteristics of hydrogen vented from a supersonic or hypersonic launch vehicle. In the test program hydrogen gas was vented into the boundary layer of a two-dimensional Mach 3 flow with 6 psia static pressure and for a range of stagnation temperatures. The experimental results provide a correlation of the onset of combustion with the thermodynamic properties of the flow field and also ignition characteristics associated with surface irregularities or protuberances.

Author

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James Dunn

I. SUMMARY

Ignition characteristics, pressures and heat transfer have been measured in the hydrogen combustion region downstream of a slot injector exhausting into a Mach 3 flow with nominal static pressure of 6 psia and 10^7 Reynolds number. Three results from this work are listed below.

1. Flow conditions were chosen so that hydrogen dumped from a wall slot would not thermally ignite. A 15° wedge was placed in the flow downstream of the slot and hydrogen was ignited by the increased temperature on the downstream side of the oblique shock produced by the wedge. Thermal ignition occured if air at a temperature of 1900° R or higher could mix with hydrogen. Ignition delay times are consistent with estimates made with the one dimensional chemical kinetic calculations of Reference 3.

2. Pressure increase in the combustion zone indicate that the reaction was not complete in a distance longer than the theoretical reaction distance. This indicates that the reaction was probably diffusion controlled. Turbulent wall heat transfer rates in the reacting flow were observed to be 30% higher than would be predicted by using heat transfer equations developed for non-reacting flows and taking into account flow field changes associated with the reaction.

3. A series of tests was made with small two dimensional disturbances on the splitter plate upstream of the slot exhaust. Hot gas in the wake of these protuberances ignited hydrogen from the slot in the distances of less than one inch. The disturbance height was less than the boundary layer thickness and the leading edge was cylindrical. This result illustrates that a local disturbance can be a trigger for combustion provided it is blunt enough to produce high temperature air that can mix with hydrogen.

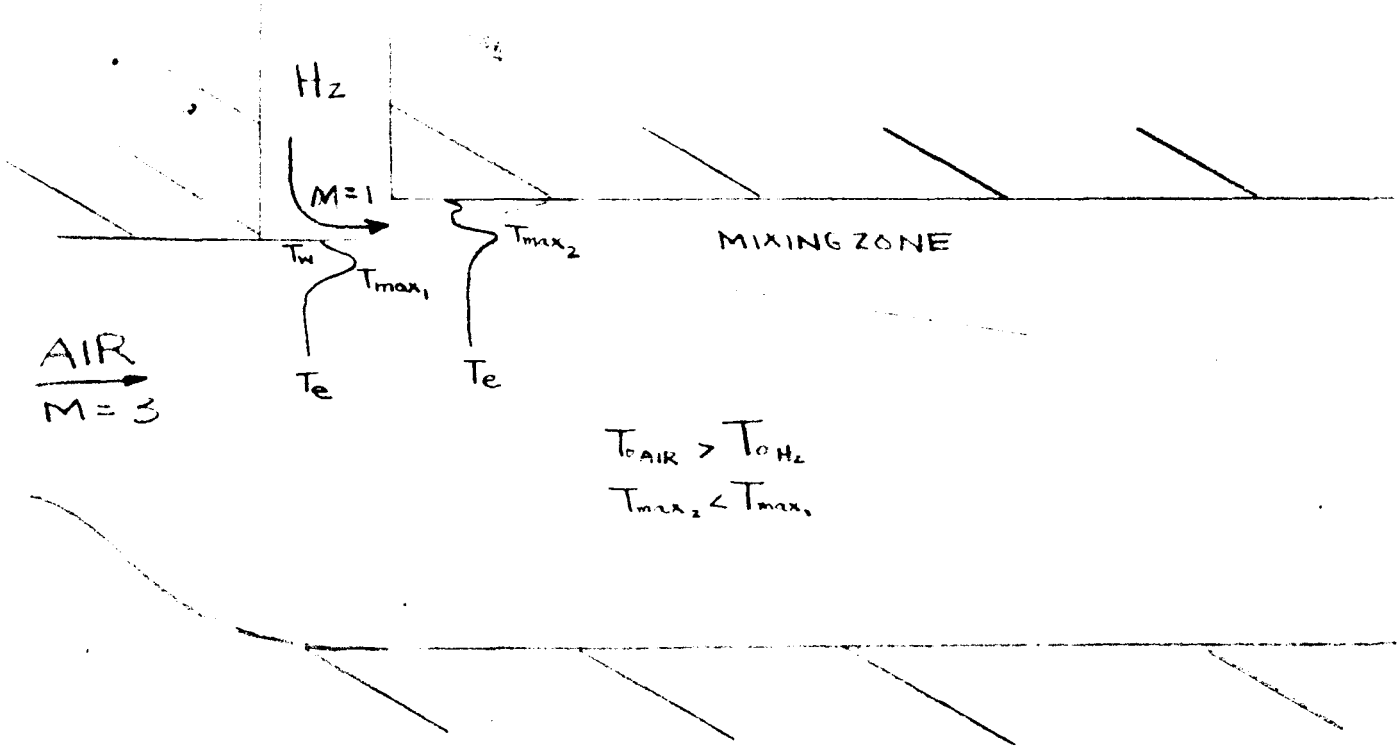


FIGURE 1

Schematic Representation of Temperature Profiles for Slot Mixing In Vicinity of Splitter Plate

II. INTRODUCTION

During the launch phase of a class of boost vehicles, hydrogen gas is vented from one of the upper stages into the airstream. Combustion of the hydrogen can ensue depending on the conditions of flow and on the venting configuration. If combustion does occur, then significant changes in the heat transfer to the wall of the vehicle and aerodynamic force distributions on the vehicle may result. The analysis of the problem is quite complex as a result of the interaction between the finite rate chemical effects and the shear flow-free stream interactions.

Various aspects of the problem have been considered analytically under the present program, References 1-8. This report presents the results of an experimental study of conditions for ignition of hydrogen in a turbulent boundary layer with particular reference to the effects of small protuberances in the flow. These tests do not simulate the low density conditions of hypersonic launch vehicle flight because of the large igntion delay and combustion distances which apply, but rather attempt to gather information at a more convenient scaling pressure which can be used to correlate with concurrent theoretical studies.

Three significant parameters that determine conditions for thermal ignition of hydrogen dumped from a wall slot are stagnation temperature, local Mach number and wall temperature inasmuch as these quantities set the maximum temperature in the splitter plate boundary layer (Figure I), that mixes with hydrogen ejected from the slot. In addition to these three parameters, static pressure of the flow affects ignition delay and reaction times of the combustion reaction. The effect of these four quantities on thermal ignition of hydrogen in supersonic flow is reported in References 1, 9, 10 and

11. In these references a temperature for supersonic autoignition of a slot flow is quoted for two different free stream pressures. Reference 9 also contains a significant similitude study for the turbulent mixing of two parallel streams with different densitites and velocities.

A conceptual model for autoignition of hydrogen dumped from a wall slot parallel to the external flow is that ignition occurs by hydrogen from the slot mixing with hot gas in the free shear layer that developed from the external splitter plate boundary layer. Provided, of course, the heat content of the wake is large enough to ignite the hydrogen. Ignition for this type of flow is thus controlled largely by the temperature of the gas in the wake that mixes with hydrogen from the slot. A measure of the wake temperature is the maximum temperature of the splitter plate boundary layer at the hydrogen exhaust. The maximum temperature in a boundary layer can be calculated by Croccos particular energy integral, and is $T_{max}=T_w+1/4\,\frac{(T_o-T_w)^2}{T_o-T_e}$ The wall (splitter plate) temperature plays an important part in setting the conditions for ignition, especially at low Mach numbers.

The scaling laws for the mixing of two parallel turbulent compressible flows has been reported in Reference 10 with the important result that the spread of the mixing zone depends on the ratio $\frac{(\rho u)_j}{(\rho u)_e}$, and is independent of free stream velocity per se. Thus ignition characteristics can be studied at an arbitrary free stream velocity and the parameters to simulate are the temperature in the splitter plate wake, the ratio $\frac{(\rho u)_j}{(\rho u)_e}$ and the static pressure of the flow. The ignition delay and energy release times for the combustion of hydrogen with air are pressure dependent as shown by the chemical kinetics calculations of Reference 11.

In References 9 and 10 supersonic flow ignition temperatures are reported for hydrogen air reaction at pressures of 15 psia and 6 psia. These tests were performed for two values of the parameter $\frac{(\rho u)_j}{(\rho u)_e}$. Turbulent mixing data for a range of $\frac{(\rho u)_j}{(\rho u)_e}$ (without combustion) will be the subject of a forthcoming GASL report. Also given in Reference 10 are heat transfer rates with and without combustion.

III. DESCRIPTION OF APPARATUS

1. Wind Tunnel Test Section

The tests were conducted in a combustion heated blow-down wind tunnel that exhausts to the atmosphere. The test section was two dimensional with a contoured half nozzle and exit size of 1-3/4 x 3-1/2 inches. The test section is shown schematically in Figure 1 and in more detail in Figure 2. The test section had four windows for taking luminosity photographs, shadowgraphs or motion pictures. Static pressures were measured along the top, bottom and side walls. Heat transfer rates were measured on the top wall with thermocouple gauges. Pitot pressures were measured at the tunnel exit to ascertain that the flow was supersonic after combustion and total temperature profiles were measured ahead of the flame zone to establish the homogeneity of the flow. A typical test duration for this program was fifteen seconds.

2. Combustion Heater

The GASL combustion heater burns a mixture of hydrogen and oxygen in air to produce products of combustion with an oxygen mass fraction equal to the oxygen content of uncontaminated air. This mixture of H_2O, N_2 and O_2 is called vitiated air and typical mass fractions (2500°R) would be 0.23 oxygen, 0.10 water and 0.67 nitrogen as compared to uncontaminated air with 0.23 oxygen and 0.77 nitrogen. In the expanded flow of the test section the water and nitrogen will be essentially inert dilutents and it is believed will have no significant effect on the chemistry of the problem considered in this report.

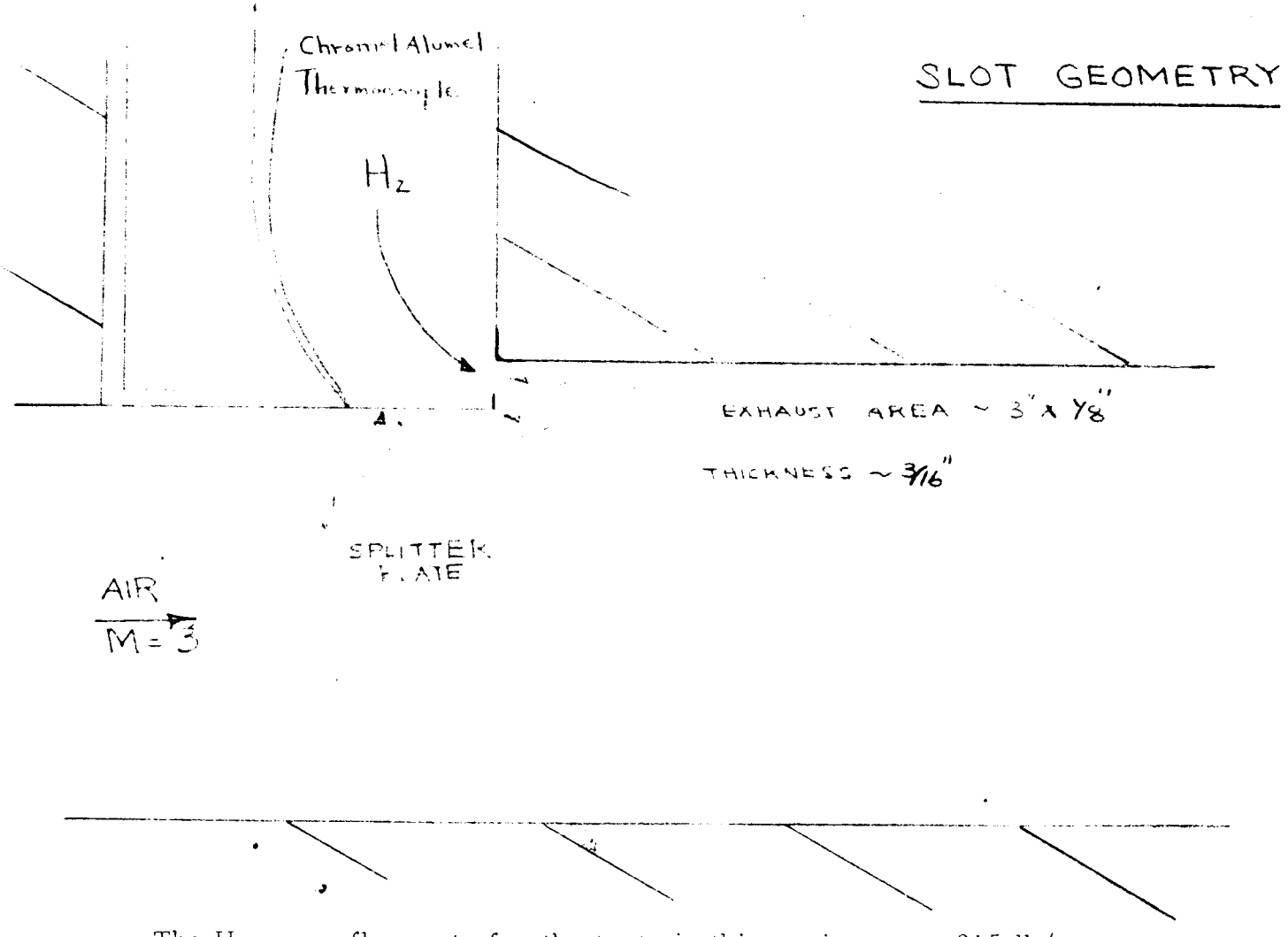
The portions of hydrogen and oxygen added to the air stream are calculated to produce a specific temperature of the products and the chemical composition discussed above. The oxygen and hydrogen are introduced into the air in preset quantities and the flow rates are controlled by commercial regulators. Air for the burner is compressed and stored in a bank of tanks at pressures up to 2000 psi. The combustion gases are stored in manifolds of commercial gas bottles. The flow rates of oxygen, air and hydrogen are monitored with venturis and the pressures are measured with transducers.

Hydrogen and oxygen are injected into a plenum chamber through a multi-holed ring injector to promote thorough mixing with the air flow. The mixture is ignited with a 15,000 volt spark and the products of combustion are confined in a 7" diameter steel tube that is 5' long. The pressure of the products is measured in the subsonic flow ahead of the throat and the total temperature is measured with two platinum-rhodium thermocouples. The vitiated air passes from the combustion tube through the two-dimensional throat and then into the test section. Figure 3 shows a cross-sectional view of the combustion chamber.

3. Hydrogen Wall Slot

Hydrogen was dumped into the test section through a wall slot as shown in Figure 1. The wall slot was located in the fully expanded section of the wind tunnel, and was 3" wide by 1/8" high. The nozzle plenum pressure was set at 12 psia nominal to match static pressure of the slot flow with static pressure of the free stream. For all tests the total temperature of the hydrogen was approximately 530°R. The plate that forms the boundary between the air flow and hydrogen flow is called the splitter plate in this report. The splitter plate used in these tests was approximately 3/16" thick

and had a fast response chromel-alumel thermocouple heliarced to the surface. The detailed shape of the slot is shown in the cross sectional sketch below.



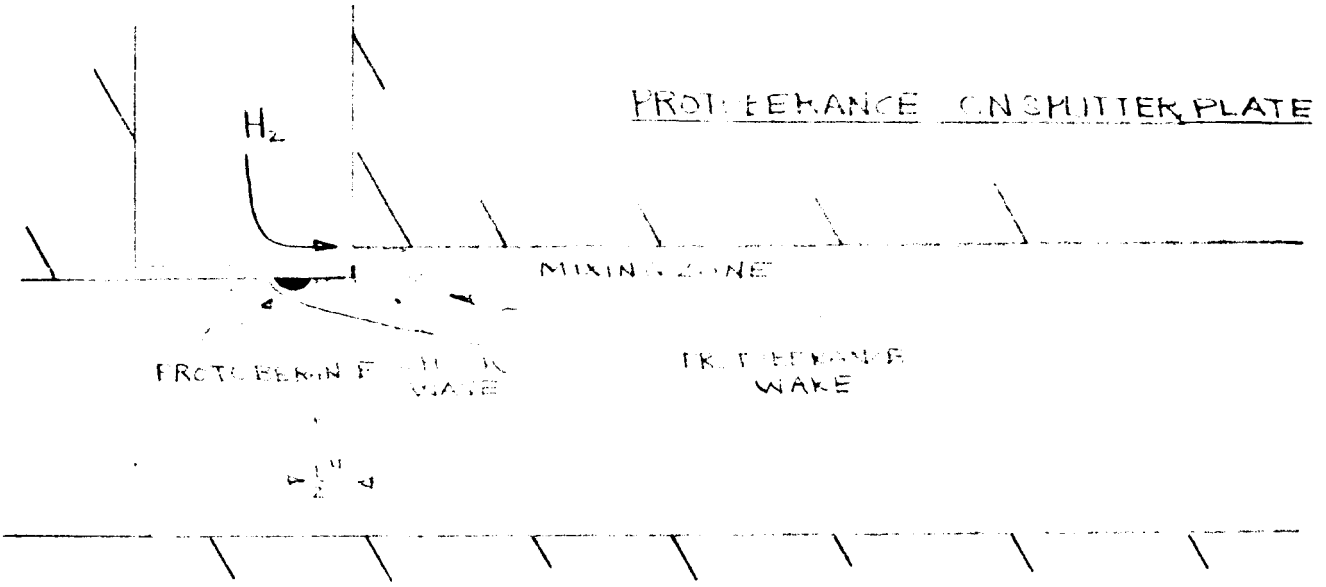
The H_2 mass flow rate for the tests in this series was .015 lb/sec or an equivalence ratio of 0.2.

4. Wedge for Combustion Studies

A 15° half angle wedge was placed on the top wall of test section for the series of wedge burning tests. Recall that the top wall of the tunnel is straight and the hydrogen slot is on this wall whereas the bottom wall is contoured to obtain the Mach 3 flow. The wedge was located 9-1/4" downstream of the slot exit or 74 slot heights downstream. The wedge was 0.45" high by 2-1/4" wide and fillers were used to streamline the corners and thereby reduce the disturbance in the corner. The wedge did not span the test section because the area reduction of a 3-1/2" wide wedge was large enough to choke the wind tunnel. The wedge was made symmetrical in the streamwise direction rather than as a plateau to prevent thermal choking of the tunnel due to heat release in the combustion zone. A plateau type wedge was built and used for one test series but the tunnel choked after combustion. Pressure ports were built into the upstream and downstream side of the wedge.

5. Disturbances on Splitter Plate

A half-cylindrical stainless steel rod was welded to the splitter plate to assess the effect of local protuberances on ignition characteristics. Two different size rods were used, one with a 1/16" radius and the second with a 3/16" radius. The rod length was 3-1/2" (test section width) and each was heliarced to the splitter plate on the air side. The rod radii were chosen to be less than the boundary layer thickness which was roughly 1/4". The rods were axially located one half inch upstream of the hydrogen slot exhaust. The following sketch shows the protuberance location:



6. Instrumentation

a) Pressure

Pressures were measured with strain gauge and variable reluctance transducers. The outputs were recorded on high speed oscillographs which ordinarily were operated at 4 " per second. Transducers were calibrated daily. A Scanni-valve was used to multiplex a number of the static pressures on the wall.

b) Temperature

Temperatures were measured with either platinum-rhodium or chromel-alumel thermocouples. The outputs were recorded on an oscillograph or alternately on a mechanical recorder.

c) Heat Transfer

Transient heat transfer rates were obtained by measuring the surface temperature rise of a semi-infinite slab. The measured surface temperature was converted to time varying heat flux by a straight forward numerical integration of the heat-transfer equation. The details of the solution

are covered adequately in References 12 and 13. The heat transfer gauge is shown in Figure 5.

d) Pitot Tube and Total Temperature Rakes

A three prong total pressure rake was used at the tunnel exit to ascertain that the flow was supersonic after combustion occurred. The rake was pulsed into the flow by an air cylinder and remained in the flow for 1/3 second, nominal.

A four prong stagnation temperature rake was installed below the test section and could be inserted in the flow for durations of 1/4 second or more. Platinum-rhodium thermocouples were used to measure vertical distributions of total temperature and thereby ascertain that no sizable temperature gradients existed in the flow field.

IV. DISCUSSION OF RESULTS

The principal work reported here is the condition for autoignition when hydrogen from a wall slot flows through an oblique shock wave such as would be produced by a launch vehicle transition section. The tests were performed for temperature conditions (To, Te, Tw) such that the splitter plate wake was not hot enough to ignite hydrogen from the slot. The tests were made in the Mach 3, two-dimensional wind tunnel described in Section II. A 15° wedge was placed on the upper wall of the wind tunnel and hydrogen was dumped from the slot which was located 74 slot heights upstream of the wedge. One test was made with stagnation temperature low enough so that the hydrogen did not burn either on the splitter plate or on the wedge. Two tests were made with a stagnation temperature high enough that the hydrogen ignited when it crossed the shock.

The temperature conditions for the tests are listed in Table 1.

TABLE 1

Number	Stagnation Temp $^{\circ}R$	Splitter Plate temp. at time of H_2 injection $^{\circ}R$	Cal. Max. Temp. in splitter Plate boundary layer* $^{\circ}R$	Temp. of Col. 2 after pass. thru Shock $^{\circ}R$	Results
61	2600	1200	1500	1900	Ignited on Wedge
62	2700	1150	1500	1900	" " "
65	2200	1050	1250	1600	No Ignition

* $\gamma = 1.33$

Note that hydrogen from the slot did not ignite when mixed with air from the splitter plate boundary layer at a calculated temperature of 1500°R or less. Also given in Table 1 is a calculated temperature increase on the downstream side of the oblique shock wave.

If the hot gas from the splitter plate boundary layer had crossed the shock wave without mixing with hydrogen or cooler air, then a maximum gas temperature of 1900°R downstream of the shock would have ignited the hydrogen as indicated in Column 5 of Table 1. The concept of supersonic autoignition occurring if hydrogen is mixed with air at a certain temperature is, of course, a gross oversimplification since ignition and flame propagation are controlled by the complete heat balance for the reacting gas. In addition, the hydrogen was heated by the hot upper wall. Nevertheless to an engineering approximation, it would appear from these results that if hydrogen from a wall slot is mixed with air at a temperature some place between 1600°R and 1900°R that autoignition can be expected (p=6 psia). This result is in agreement with the widely used value of 1800°R for autoignition of hydrogen-air mixtures.

A. Pressure and Heat Transfer Results

Figures 9, 10 and 11 show static pressures measured in the test section for the 3 runs in Table 1. Figures 9 and 9a show the top and bottom wall static pressures for run 65. (No Ignition). Note that no pressure rise was measured ahead of the wedge, which indicates that the boundary layer did not separate. If the empirical separation data in Reference 7 is employed the plateau pressure for wedge type separation would be 15 psi, which was not observed. Additionally, the separation correlations of Reference 6 indicate that for air flow at Mach 3 and 10^7 Reynolds number a $\Delta P/q$ of 0.35 is

required to separate the turbulent boundary layer approaching a wedge. The 15^{o} wedge pressure coefficient is 0.29 at Mach 3, which further suggests that the boundary layer did not separate in the corner. The difference in pressure level between the measurements before slot injection and after injection were due to a slight drift in tunnel stagnation pressure. The low pressure region on the bottom wall downstream of the slot before injection is caused by the expansion fan originating at the splitter plate lip. Downstream of the wedge the oblique shock wave reflects from the bottom wall and hits the top wall again, causing a high pressure region on the top wall.

Figure 6a through 6e show Run 65 - heat transfer rates on the top wall. The duration of hydrogen injection is indicated on each figure. The location of the gauges is indicated in Figure 9 in relation to the slot and wedge. Figure 6 also contains the calculated flat plate heat transfer rate.

$$q = \frac{.0296}{Pr^{2/3}} \frac{(\rho_e u_e)(h_r - h_w)}{(R_{e_x})^{.2}} \left[\left(\frac{\rho_e}{\rho^*} \right)^{.8} \left(\frac{\mu^*}{\mu_e} \right)^{.2} \right] \quad (1)$$

This is the turbulent heat transfer rate calculated by Reynold's analogy using the constant-property Blasius incompressible skin friction relation and Eckert's reference enthalpy factor for compressibility. (Reference 16). Agreement between calculated and measured heat flux is within 12% before hydrogen injection except for gauge 3. The discrepancy for gauge 3 is felt to be an experimental error, rather than low heat flux in a separated region on the basis of the pressure measurements and previous discussion. The steady decrease of heat flux before injection was caused by the rising surface temperature. For instance, the wall temperature rose from $900^{o}R$

to 1100°R for gauge 1 in the time interval of five to nine seconds. Gauges 1 and 2 show the decrease in heat flux when the cold (To=540°R) hydrogen is injected into the test section. Gauge 3 does not change during hydrogen injection indicating that the hydrogen was at least partially mixed with the air at this location, i.e., 66 slot heights downstream. Gauges 4 and 5 were downstream of the wedge and yielded no significant information for the no-burning test. The tail-off at the end of each heat flux trace represents the tunnel shut down. No attempt was made to explain the 12% difference between measured and calculated heat flux since the measurements were made primarily to compare heat transfer with and without combustion and 12% may be considered reasonable engineering agreement.

Figure 10 and 10a give pressure distributions for Run 61, in which the hydrogen burned downstream of the wedge. Note that the pressure level behind the wedge increased from seven psia to 14 psia, due to the heat release in this region. The distance from the onset of combustion to the end of the tunnel was about ten inches and combustion was not complete in this distance as indicated by comparing the observed pressure rise with a one dimensional estimate. Despite this fact, a simple one-dimensional calculation of changes in flow properties can be made using the measured static pressures, as an indication of the heat release. The dynamic and thermodynamic properties obtained from the one-dimensional calculation can then be used with the flat plate turbulent heat transfer equation to calculate a new heat flux, ignoring any combustion-induced changes in the mechanism of heat transfer. This type of calculation was made for Run 61. Table 2 contains a summary of these results.

TABLE 2

Heat Flux Calculation for Runs 61 & 62 (All heat flux in $\frac{BTU}{ft^2 sec}$)

Run No.	Gauge No.	$\dot{q}$ theor no. comb.	$\dot{q}$ theor with comb.	$\frac{\dot{q}\ comb.}{\dot{q}\ no\ comb.}$ theor.	$\dot{q}$ meas. no. comb.	$\dot{q}$ meas. with comb.	$\frac{\dot{q}\ comb.}{\dot{q}\ no\ comb.}$ meas.	Ratio $\frac{meas.}{calcu.}$
I	II	III	IV	IV ÷ III	VI	VII	VII ÷ VI	IX
61	5	43	70	1.63	38	77	2.0	1.23
61	6	40	76	1.91	43	100	2.3	1.21
62	5	45	69	1.54	48	83	1.7	1.10
62	6	47	74	1.56	55	110	2.0	1.29

The individual curves of heat transfer rates for Run 61 are given in Figure 7a-7f. No qualitative differences from the no burning test are evident except for gauges 5 and 6 which are in the combustion region downstream of the wedge. Increases in heat transfer rates of 2.0 and 2.3 are observed for gauges 5 and 6. These ratios are not felt to be representative of heat transfer increases that would occur in the external flow on a vehicle since these results are for flow in a constant area channel; however, a different type of calculation can be made for an external application. It appears from the calculation and results in Table 2 that turbulent heat transfer in the combustion region can be calculated to within 30% by using the flow properties evaluated in the burning gas and the heat flux equation developed from non-reacting data. To calculate the heat flux in an external flow with hydrogen combustion the flow field with combustion would have to be calculated and then Equation (1) would be used to

estimate the heat transfer rate and subsequently increased by a factor of 1.3. Figure 12 is a luminosity photograph taken during the burning portion of test 61. This picture indicates that the flame zone starts immediately behind the wedge apex and that hydrogen was still concentrated on the top wall after the compression and subsequent re-expansion around the wedge. Also given in Figure 12 is a schematic aid for interpreting the luminosity photo.

Run 62 was an additional test with combustion on the downstream side of the wedge. The pressure distributions for this run are given in Figure 11 and 11a. No qualitative differences exist between the pressures in this run and run 61 which was previously discussed. Figures 8a to 8e show heat transfer rates for test 61. Once again, the wall cooling is observed near the slot exit and heat transfer increases occur in the combustion region behind the wedge. Gauges 5 and 6 indicate gross heat flux increases of 1.7 and 2.0 during combustion. These ratios are compared to the calculated ratios in Table 2. The agreement of the theoretical with experimental ratios of heat flux with combustion to heat flux without combustion is once again within 30% .

B. Ignition Delay Time

In previous work at GASL (Ref. 11) curve fits to calculations for ignition delay and reactions times were developed for the combustion of hydrogen in air. It is difficult to interpret experimental data in terms of theoretically defined igrition delay times; however, in Ref. 11 a measure of experimental ignition delay time was taken as the length at which visible radiation was first observed on a long exposure photograph divided by a characteristic flow velocity. In this sense Figure 12 can be used to estimate a distance from the beginning of the observed flame back to the shock wave and a characteristic velocity can be taken as the inviscid air velocity on the wedge. This calculation

gives $\tau_{ID} = \frac{1.6 \text{ inches}}{4200 \text{ fps } 12 \text{ inch/ft.}} = 32\ \mu \text{ sec.}$ If the empirical relation

$\tau_{ID} = \frac{8 \times 10^{-3}}{p} \exp \frac{9600}{T}$ is used to calculate an ignition delay time, then

$\tau_{ID} = 57\ \mu$ sec. This was calculated using the measured pressure on the wedge and the "unmixed" maximum splitter plate boundary layer temperature downstream of the shock wave. This is considered a reasonable agreement between theory and experiment. It is not possible to compare theoretical reaction times from Reference 11 with any characteristic distance of the flow because the flow was not reaction rate controlled. That is, the hydrogen did not completely burn in the 10 inches from the wedge to the tunnel exit whereas the theoretical reaction distance is $L_R = u_\infty \tau_R = 4900 \text{ fps } \frac{105}{p^{1.7}} \exp \frac{-1.12T}{1000} = 5$

This is the distance in which the reaction would have reached equilibrium if the hydrogen and air had been premixed when ignition occurred, which of course, is not indicated by the theoretical calculation of reaction time.

A rough measure of how much of the hydrogen had reacted at the tunnel exit can be obtained from the static pressure rise downstream of the wedge. The static pressure rise of approximately 2.0 (Run 61) yields a one-dimensional simple To change of about 1.24. Using the tunnel mass flow rate of 2.6 lb/sec this yields a heat release of 500 BTU as compared to a heat of $Q = \dot{m} \Delta H = (.015 \text{ lb/sec.})(55000 \text{ BTU/lb}) = 800$ BTU for complete combustion. These calculations were made to demonstrate that the measured heat transfer rates were taken in a diffusion controlled reacting flow and that no conclusions can be made from this data about heat flux for downstream on a vehicle after the reaction has reached equilibrium.

A total pressure survey was made at the tunnel exit to be sure that combustion was not choking the tunnel. Figure 15 shows the Mach number

distribution calculated from this run. Note that the Mach number is lower at the top where hydrogen is burning than in the non-reacting gas at the bottom wall. An additional run was made with a total temperature rake to check the temperature distribution in the test section. Figure 17 is the measured profile 2 inches downstream of the slot exhaust. The test section measured temperatures are 150° lower than the 2900°R measured in the subsonic plenum chamber but no recovery factor was applied to the probes in the supersonic test section. The profiles show that the vitiated air entering the nozzle was mixed enough to provide a uniform temperature distribution.

C. Ignition by Two-Dimensional Disturbance on Splitter Plate Lip

A series of tests was made with a disturbance on the free stream side of the splitter plate as shown in the sketch on Page 9. The purpose of this test series was to determine if hydrogen can be ignited by a local disturbance that serves as a source of hot gas. Recall from the description in Section II that the disturbance was half of a circular cylinder and spanned the test section. One cylinder was 1/16" high and the second was 3/16". Hydrogen from the slot was ignited within one inch of the exhaust by either rod. The tunnel was run at conditions (see Table 5 for To, Te, Tw) such that the slot hydrogen would not have burned any place in the tunnel if the disturbance had not been on the splitter plate. Note that the calculated maximum splitter plate boundary layer temperature was in all cases lower than 1600°R and that results in Section B indicate that hydrogen from the slot would not have been ignited for a temperature this low. Reference 10 also contains some pertinent data on this topic. Figure 13 is a luminosity photograph of hydrogen

combustion triggered by the two different disturbances. As an aid to interpreting these photographs the reader is referred again to the sketch on Page 9.

TABLE 3

Run No.	Disturbance	To ^{o}R	Tw ^{o}R	T_{max} ^{o}R	Results
88	3/16	2700	1350	1600	burned at splitter plate lip
90	3/16	2400	1250	1450	" " " "
91	1/16	2600	1350	1600	" " " "
93	1/16	2800	1150	1550	" " " "
95	1/16	2900	1050	1500	" " " "

The hydrogen ignition and short ignition delay distance (approximately one inch) is attributed to the high temperature in the viscous wake behind the blunt cylinder and perhaps also to enhanced mixing of the hydrogen and air in the presence of the large free shear region shed from the rod. Static pressures were measured on the tunnel wall downstream of the slot. This data is given in Figures 14 and 14a and is presented mainly to demonstrate conclusively that combustion occured in the presence of the disturbance. The boundary layer thickness on the splitter plate was estimated to be about one quarter inch at the location of the disturbance and the displacement thickness was about 0.1". Both disturbances were within the estimated boundary layer.

V. CONCLUSIONS

1. Slot flow autoignition of hydrogen in air can be expected if the maximum temperature of the splitter plate boundary layer is 1900°R or higher. The temperature for autoignition is probably below 1900°R but is definitely above 1600°R. This applies to a flow with static pressure of 6 psia and with a splitter plate thickness at least 1/8". The principal effect of static pressure will be to change the ignition delay and reaction times (lengths) as shown by Figures 17 and 18.

2. Thermal ignition of unburned hydrogen from a slot that is compressed by passing through a shock can be expected if the "unmixed" maximum splitter plate boundary layer temperature is raised to 1900°R by the shock. (The qualifying comments in Item 1 apply here also.) Alternatively, if the maximum temperature in a hydrogen air boundary layer is raised to 1900°R by passing through a shock thermal ignition can be expected.

3. A blunt disturbance ahead of the slot exhaust with a height equal to or greater than the boundary layer displacement thickness can generate enough hot gas to significantly alter the ignition characteristic of the slot flow. It is difficult to make a quantitative estimate of the temperature conditions for which a proturberance will ignite the slot hydrogen. However, if a maximum temperature can be assigned to the protuberance wake at the slot exhaust then 1900°R could tentatively be taken as an ignition temperature (at 6 psia).

4. The theoretical ignition delay curve of Reference 11 (also Figure 17) appears to be in reasonable quantitative agreement with results from these tests and previous GASL work.

5. Heat transfer increases of 1.7 to 2.3 were measured during combustion in a constant area channel. Turbulent wall heat transfer rates in the reacting flow were observed to be 30% higher than would be predicted by using heat transfer relations developed for non-reacting flow and using flow properties of the burning gas.

VI. APPLICATION TO FLIGHT CONDITIONS

A sample calculation for thermal ignition of hydrogen dumped from a wall slot was made for the typical launch vehicle trajectory shown in Figure 19. Figure 20 shows the results of this calculation and indicates that (based on the results of this program) thermal ignition can be expected at altitudes above 130,000 feet. For ignition delay and reaction lengths Figure 17 and 18 can be used along with the local velocity of the flow. Ignition delay lengths may of course be longer than the booster at high altitudes as has been previously reported in Reference 1.

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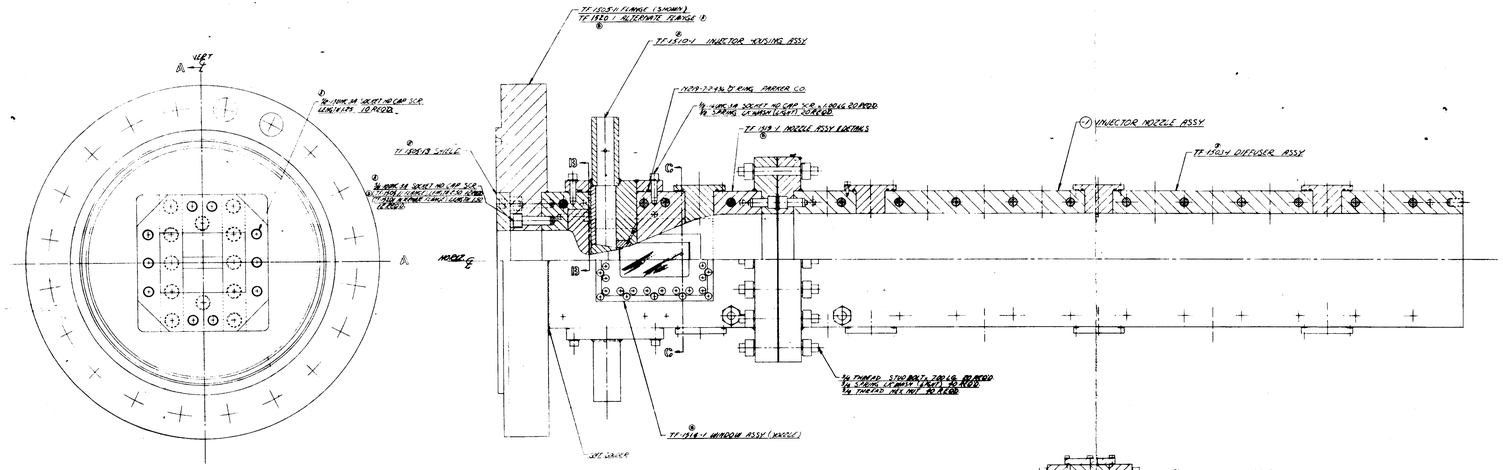

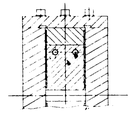

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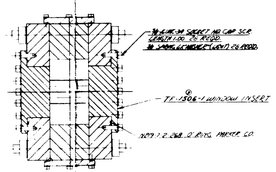

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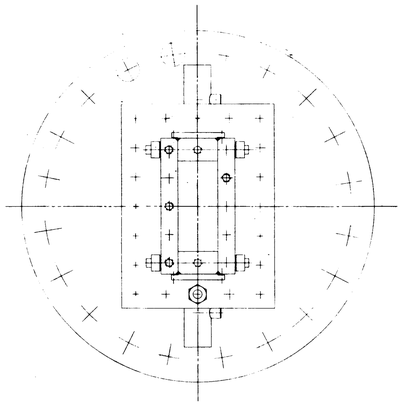
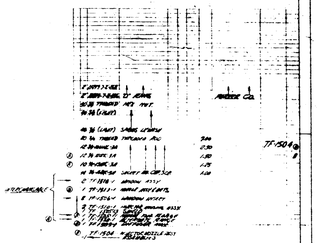
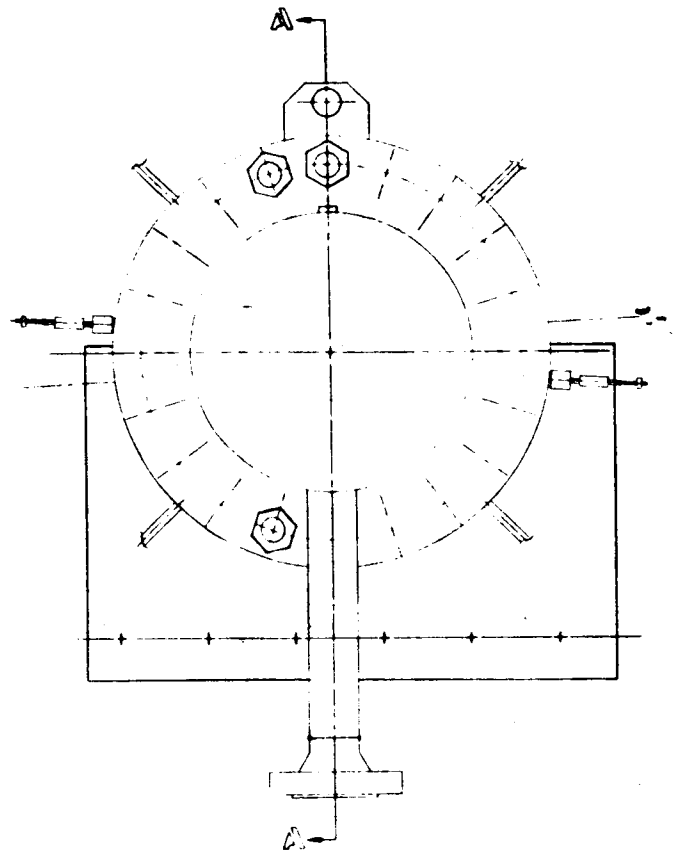
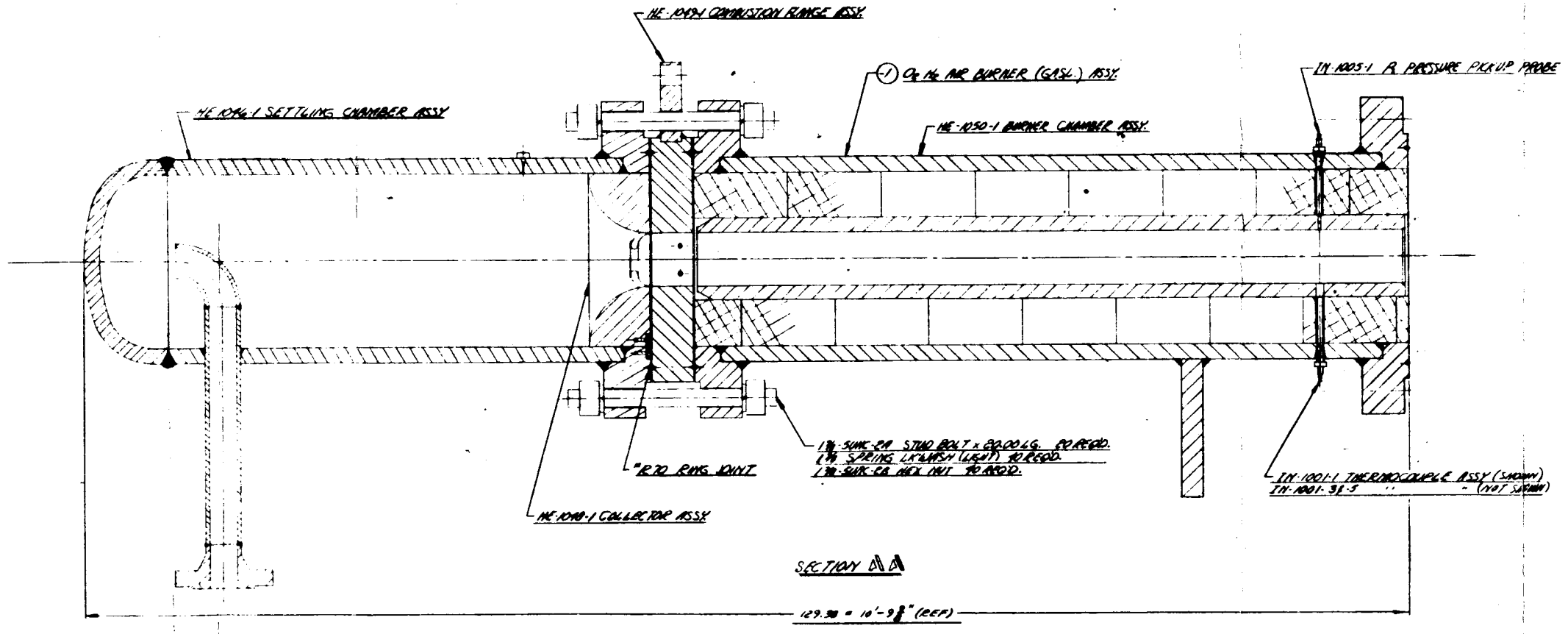


FIGURE 2




A
A


HE-1094-1 COMBUSTION RANGE ASSY.
CR-16 AIR BARRIER (GAS) ASSY.
TH-1005-1 R. PRESSURE PICK-UP PROBE
HE-1094-1 SETTLING CHAMBER ASSY.
HE-1050-1 BURNER CHAMBER ASSY.
*R20 RING JOINT
HE-1094-1 COLLECTOR ASSY.
SECTION AA
129.38 = 10'-9 3/8" (REF)

CR-16 AIR BARRIER (GAS) ASSY.
HE-1095

WEDGE
FOR HYDROGEN BURNING TEST

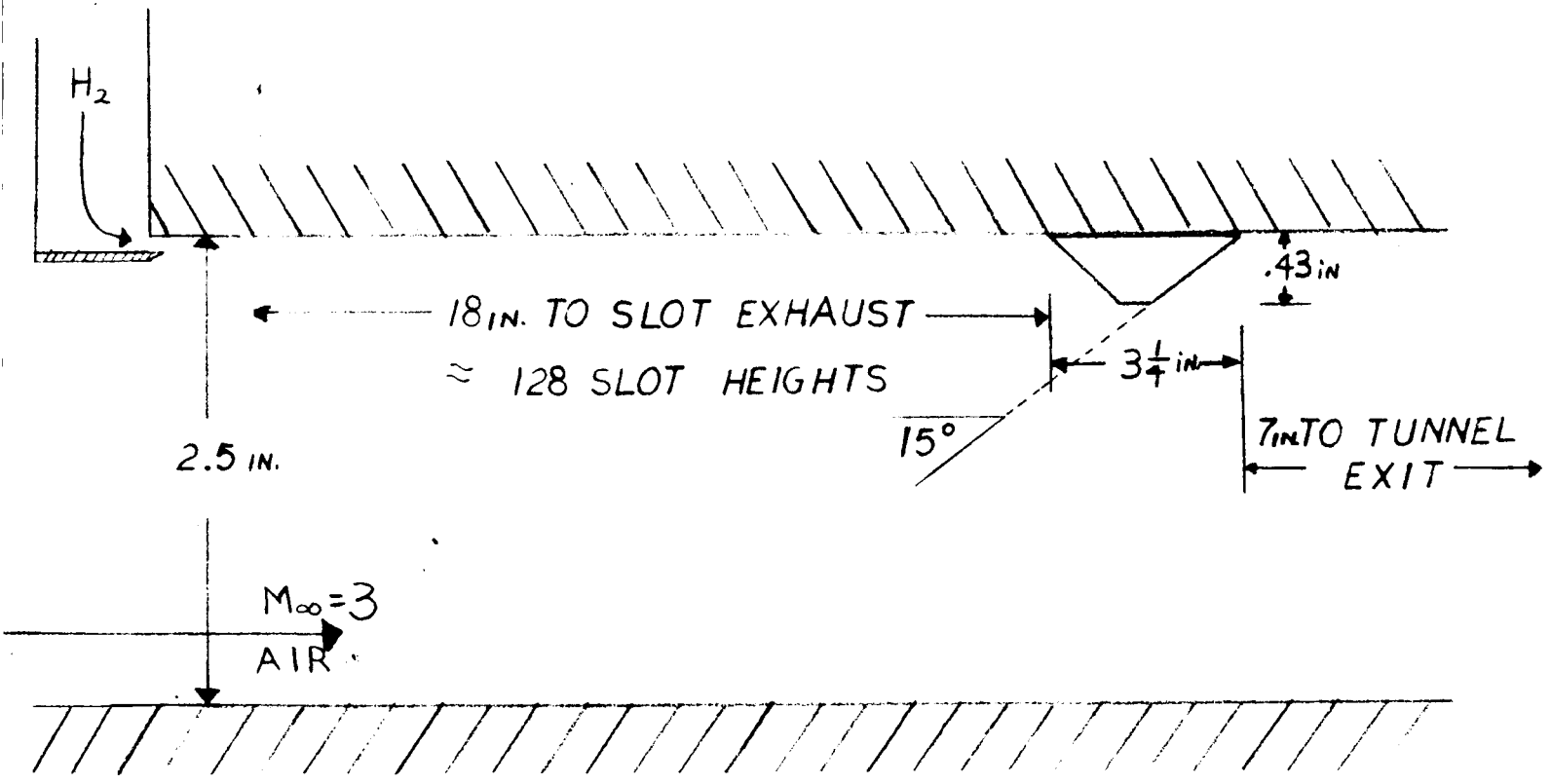


FIGURE 4

GASL HEAT TRANSFER GAUGE

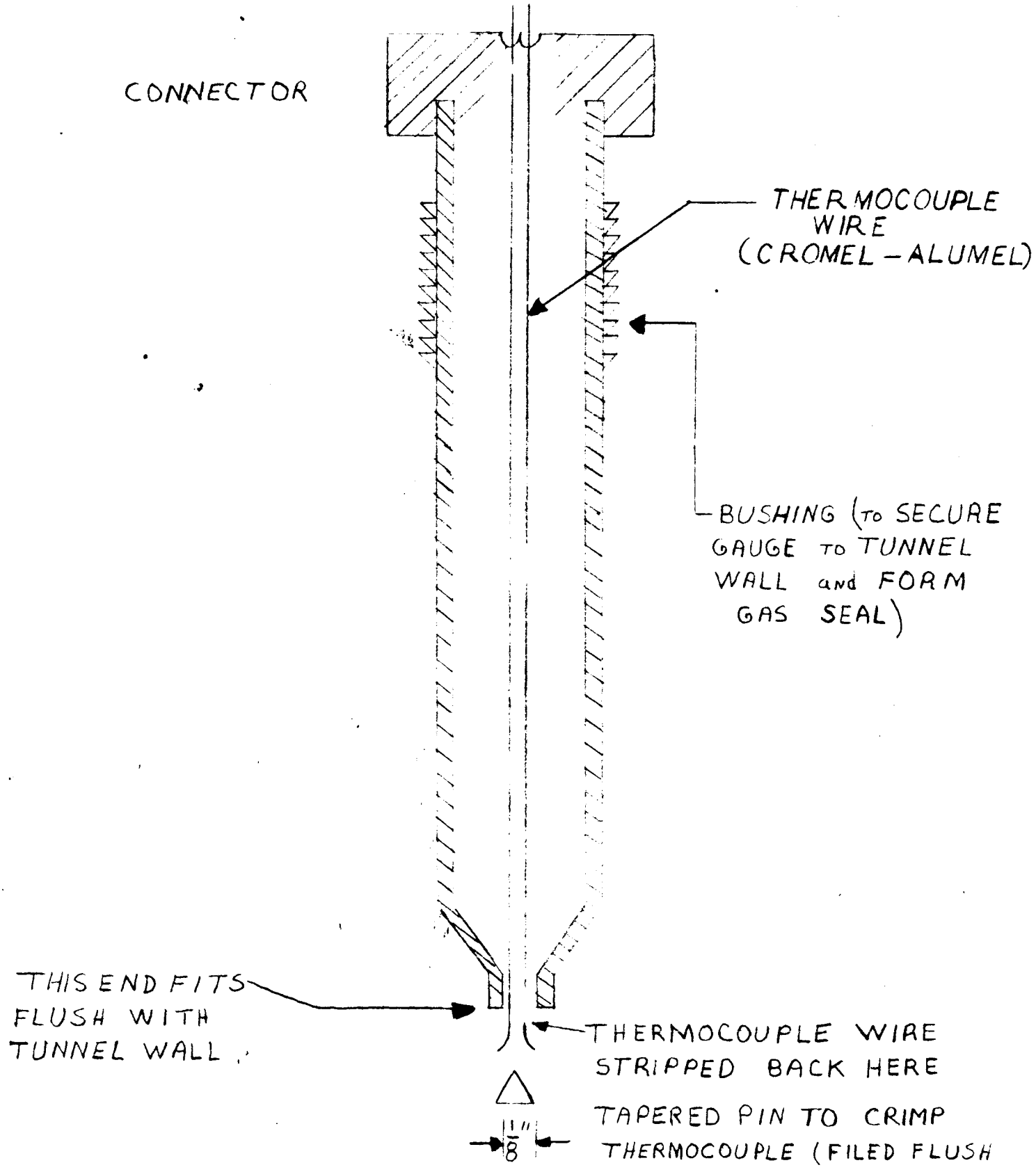


FIGURE 5

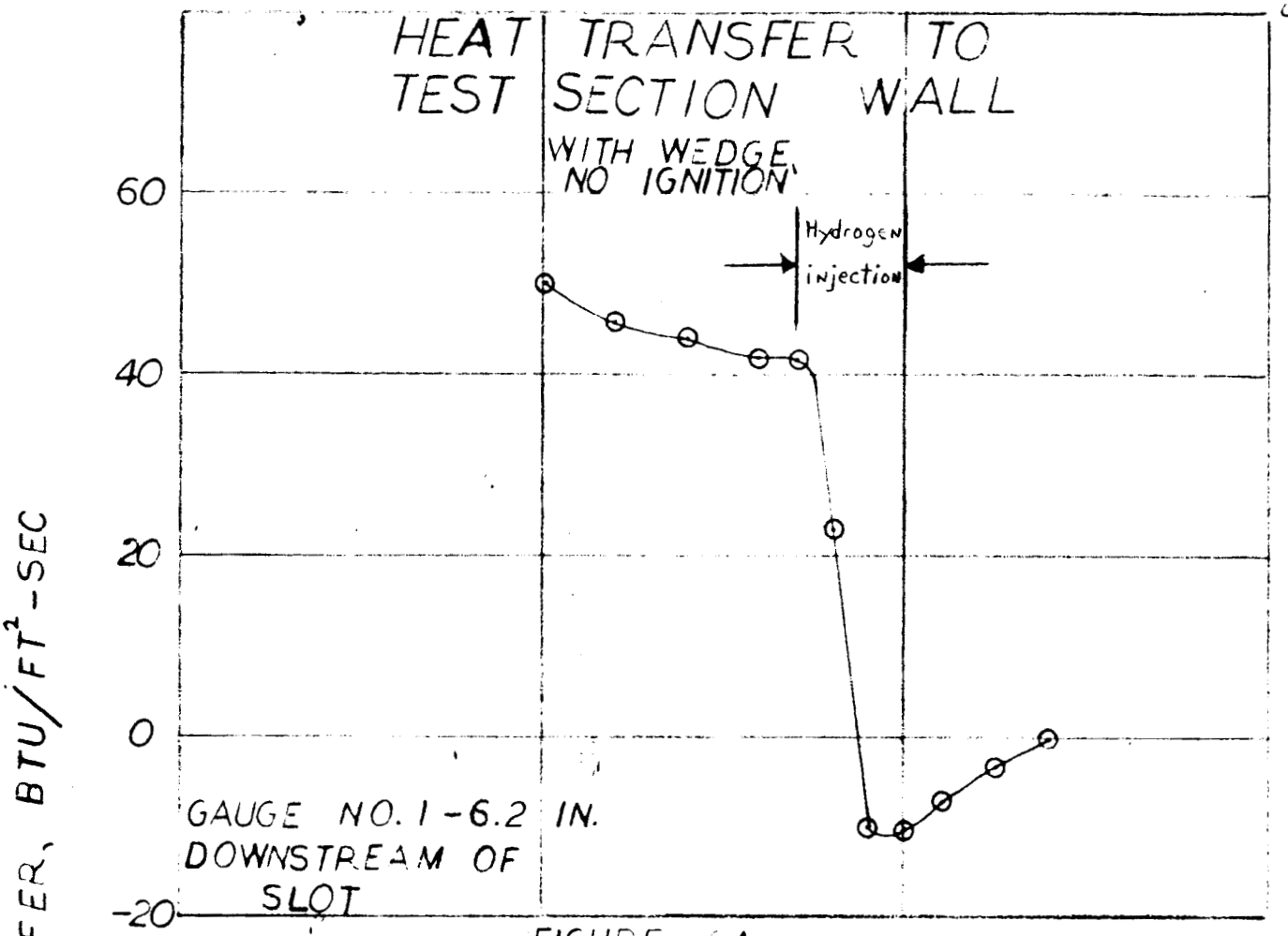


FIGURE 6A

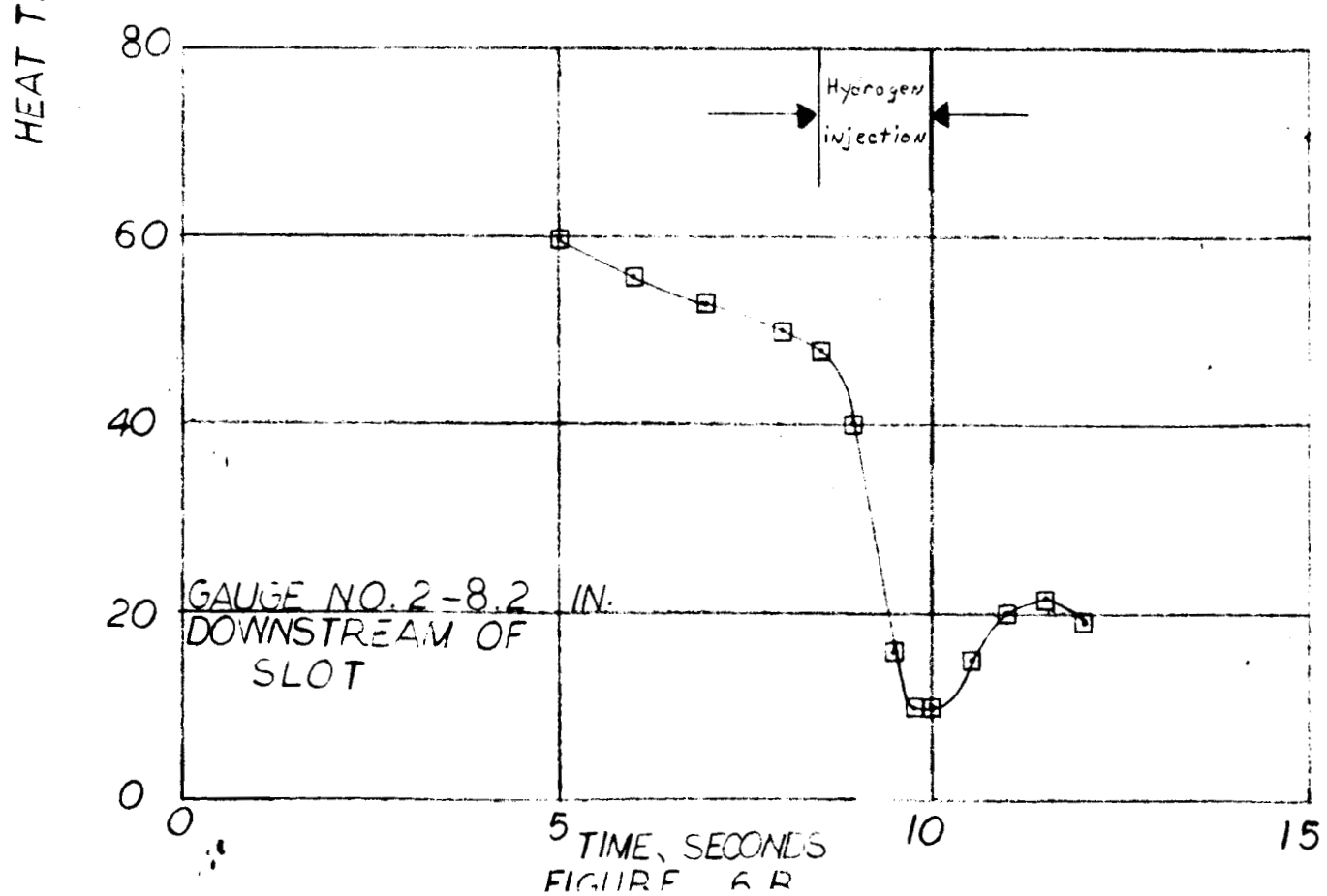


FIGURE 6B

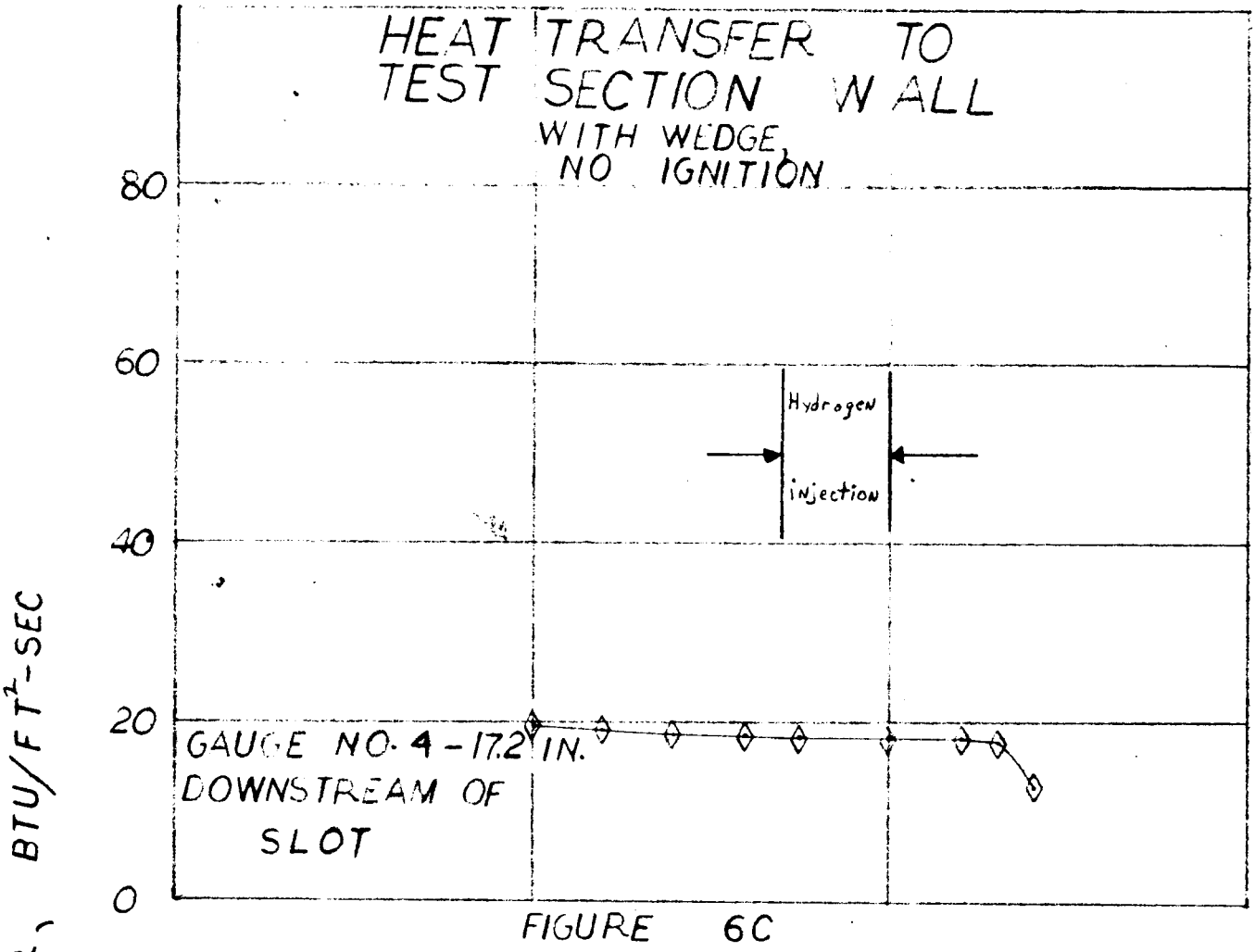


FIGURE 6C

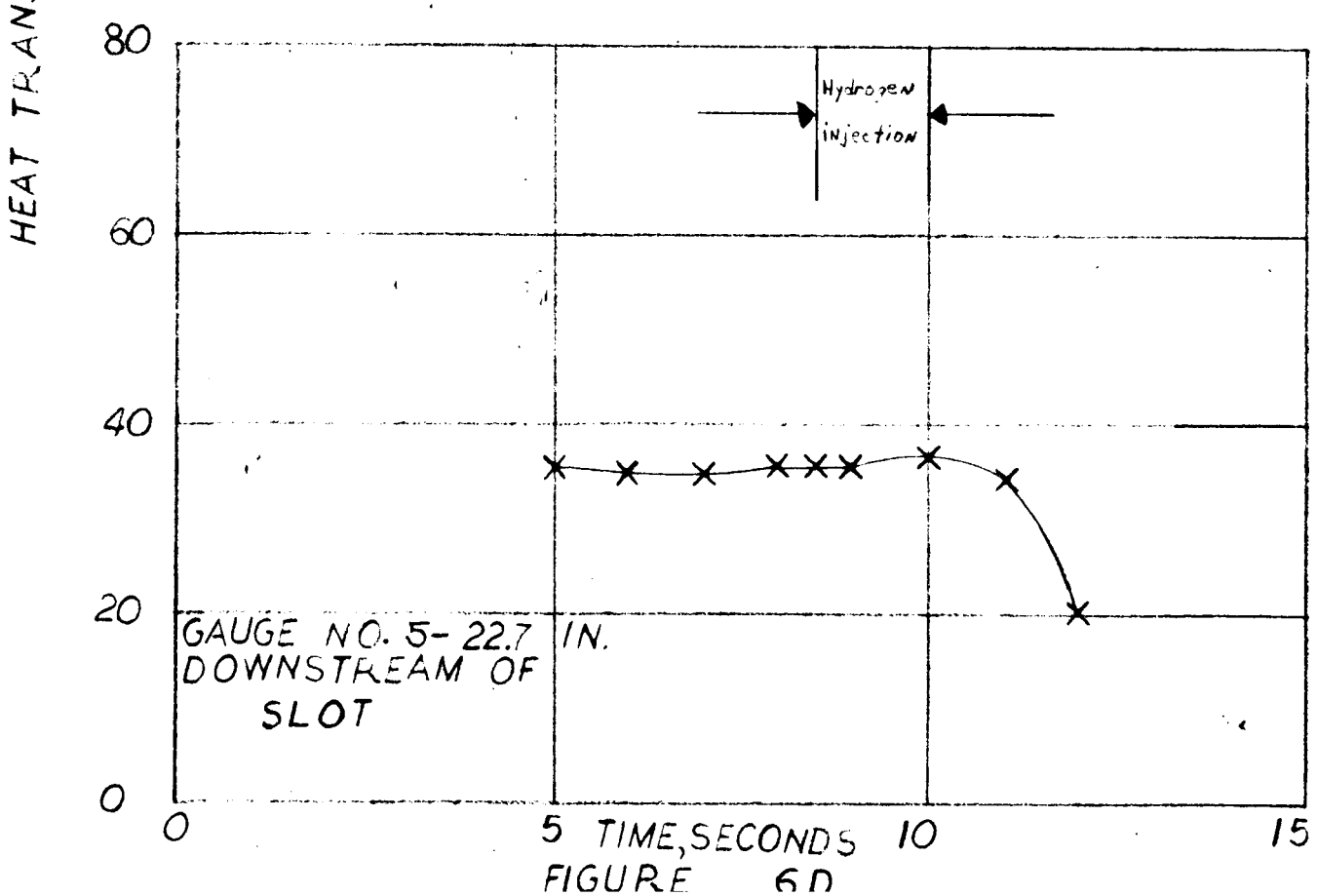
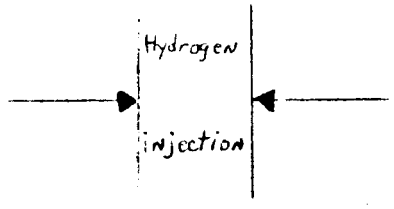


FIGURE 6D

HEAT TRANSFER TO TEST SECTION WALL WITH WEDGE, NO IGNITION



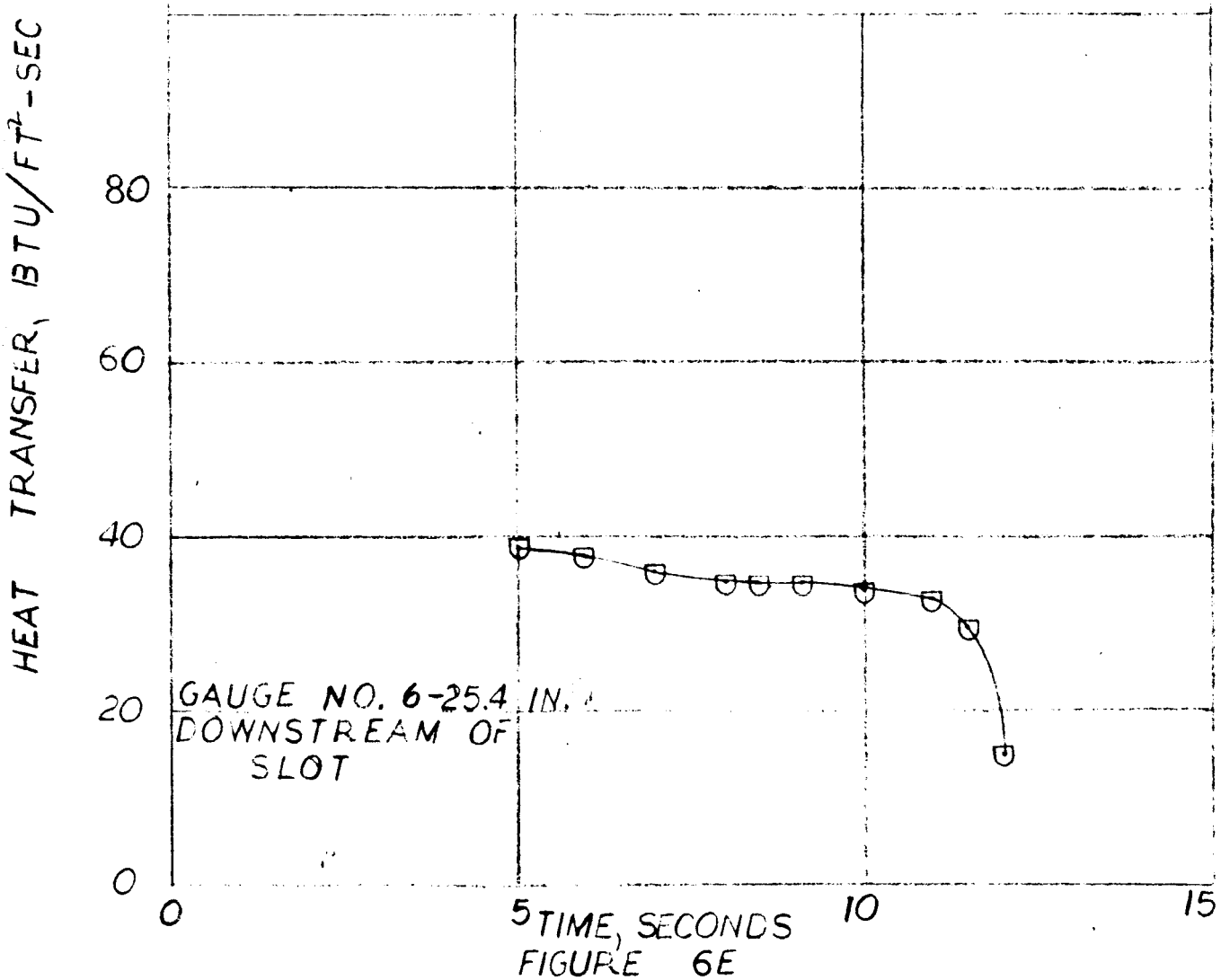


FIGURE 6E

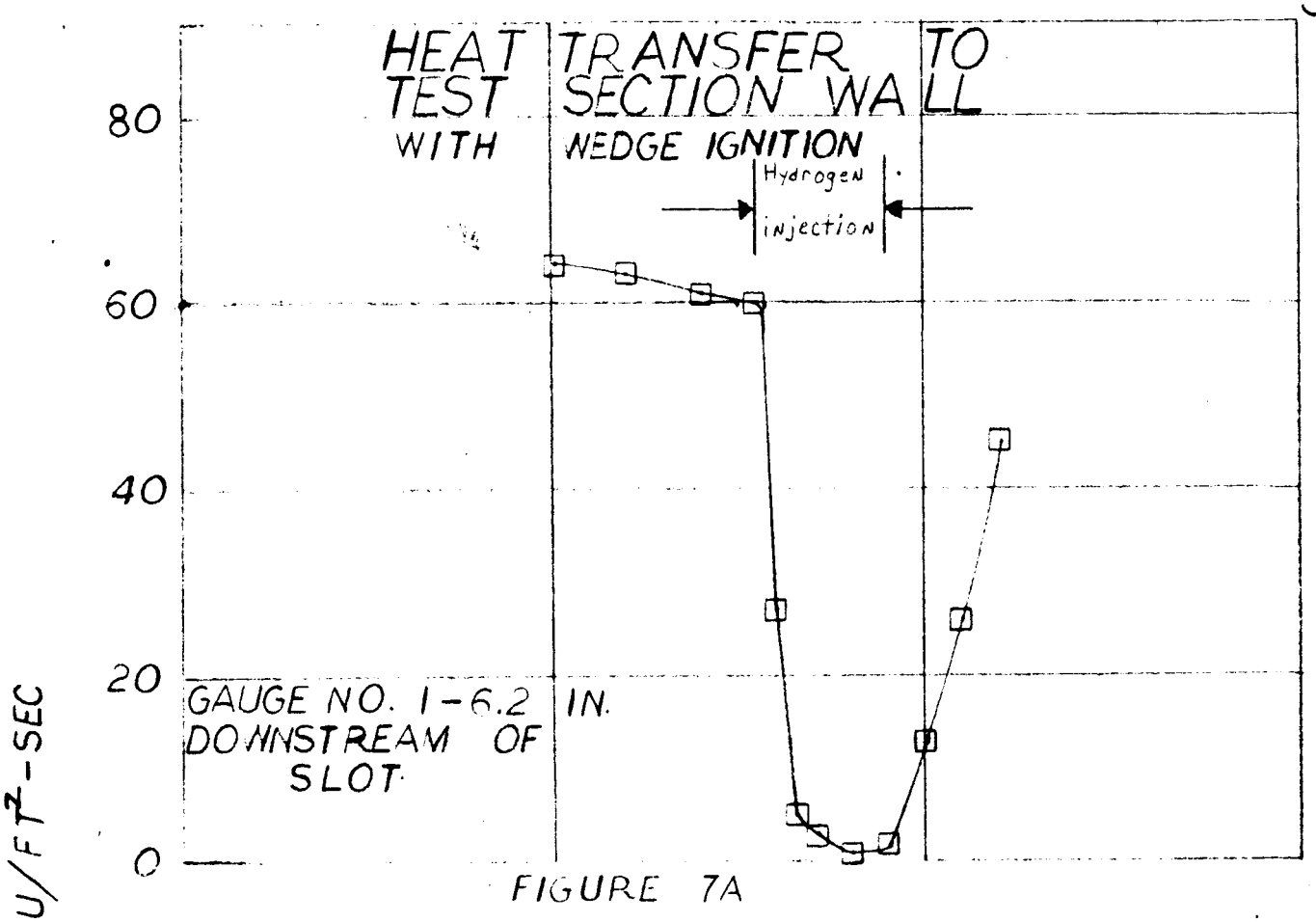


FIGURE 7A

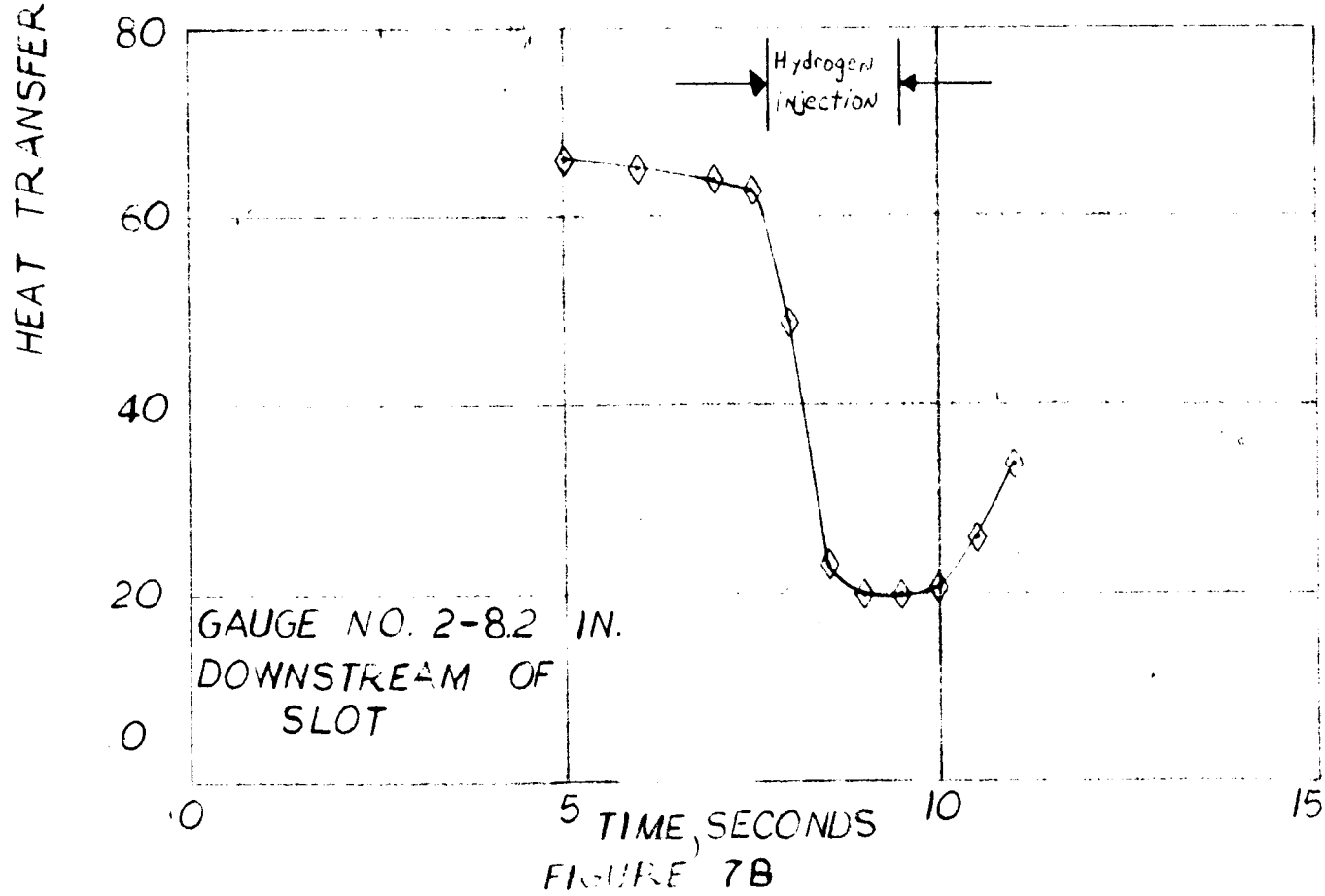


FIGURE 7B

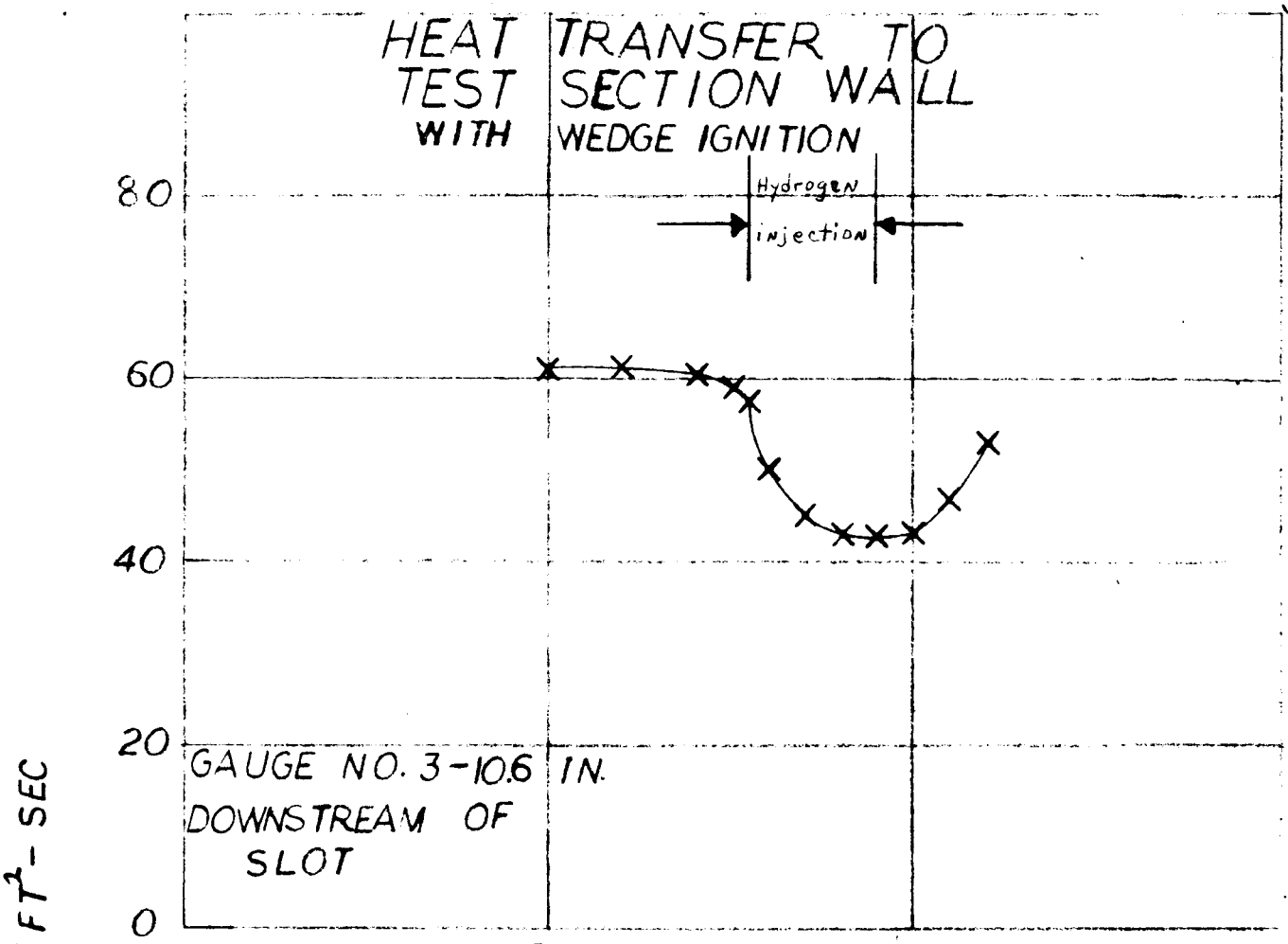


FIGURE 7C

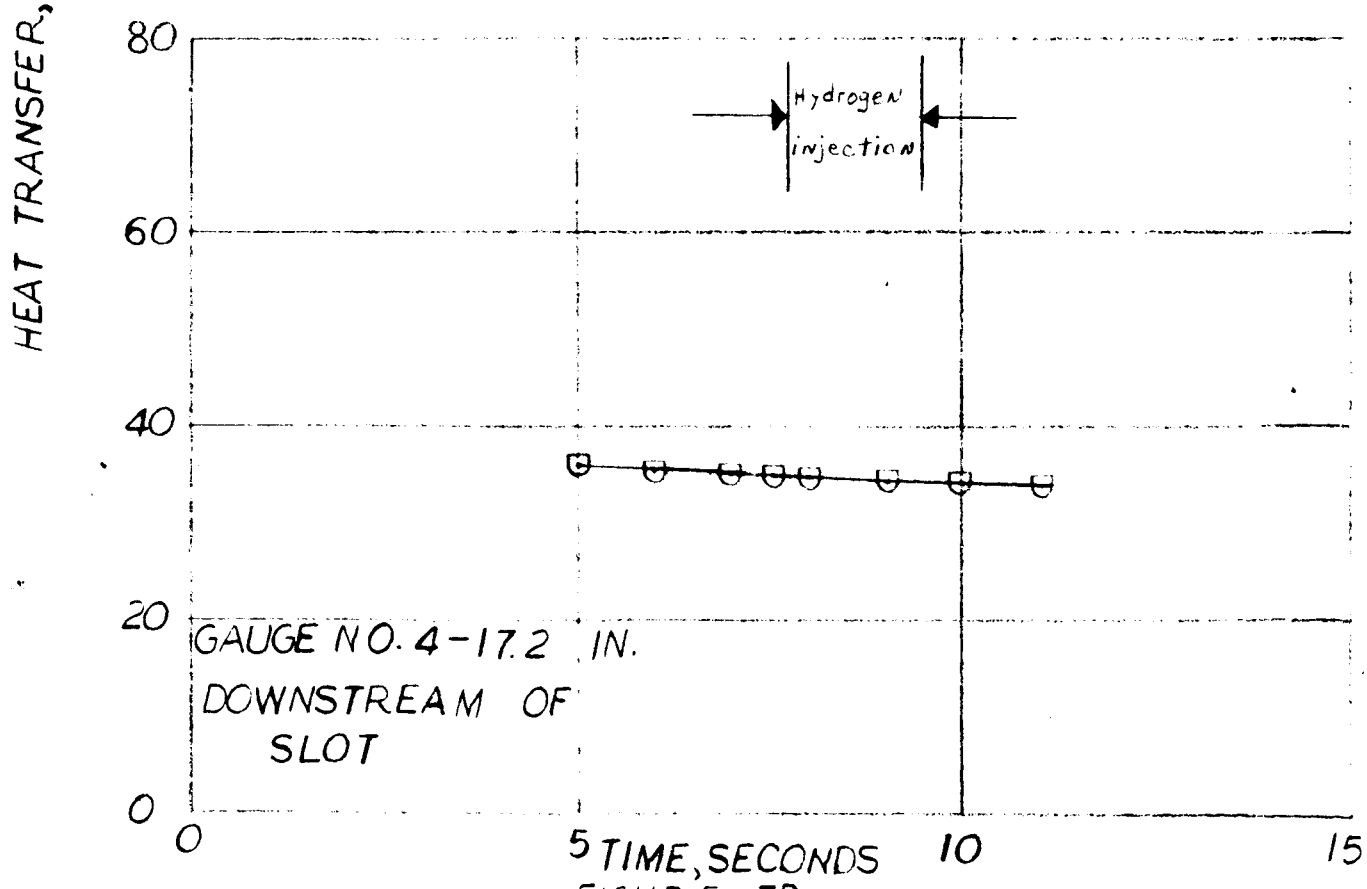


FIGURE 7D

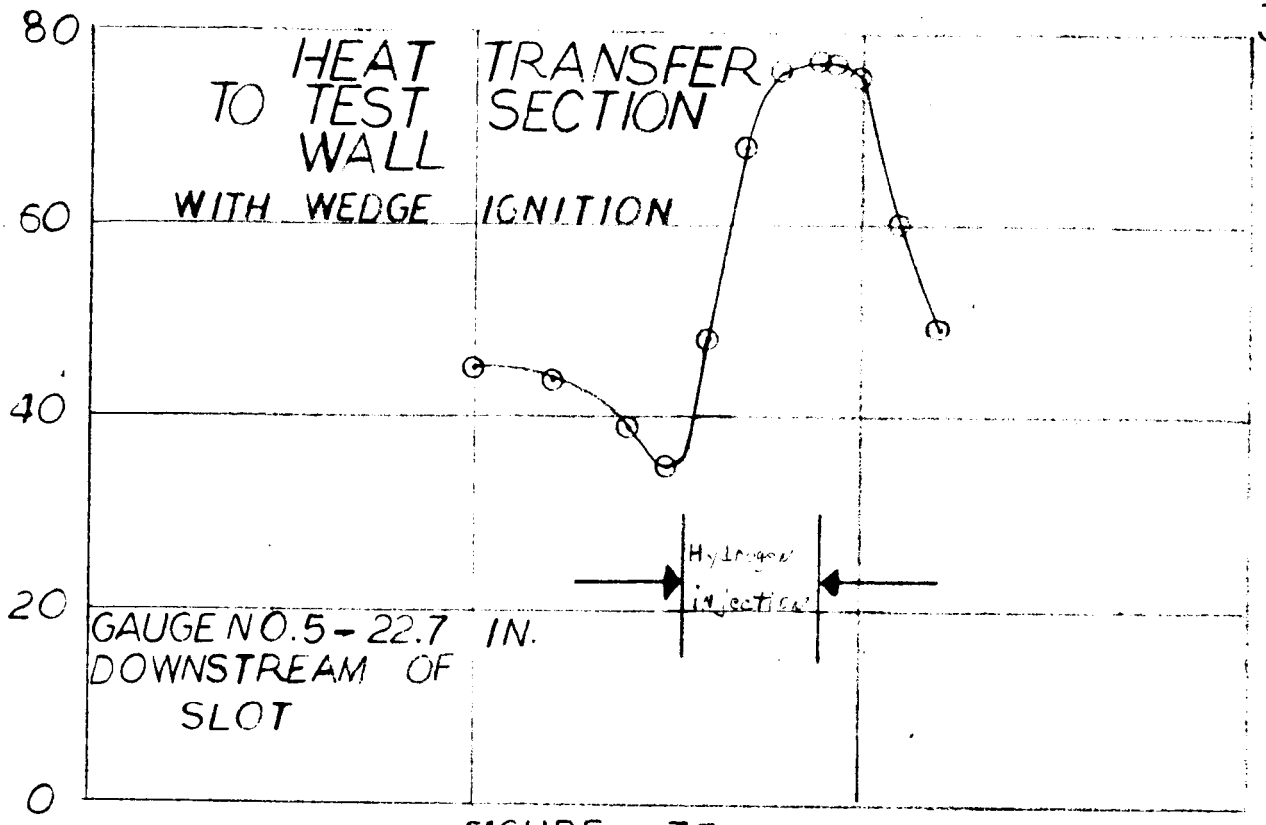
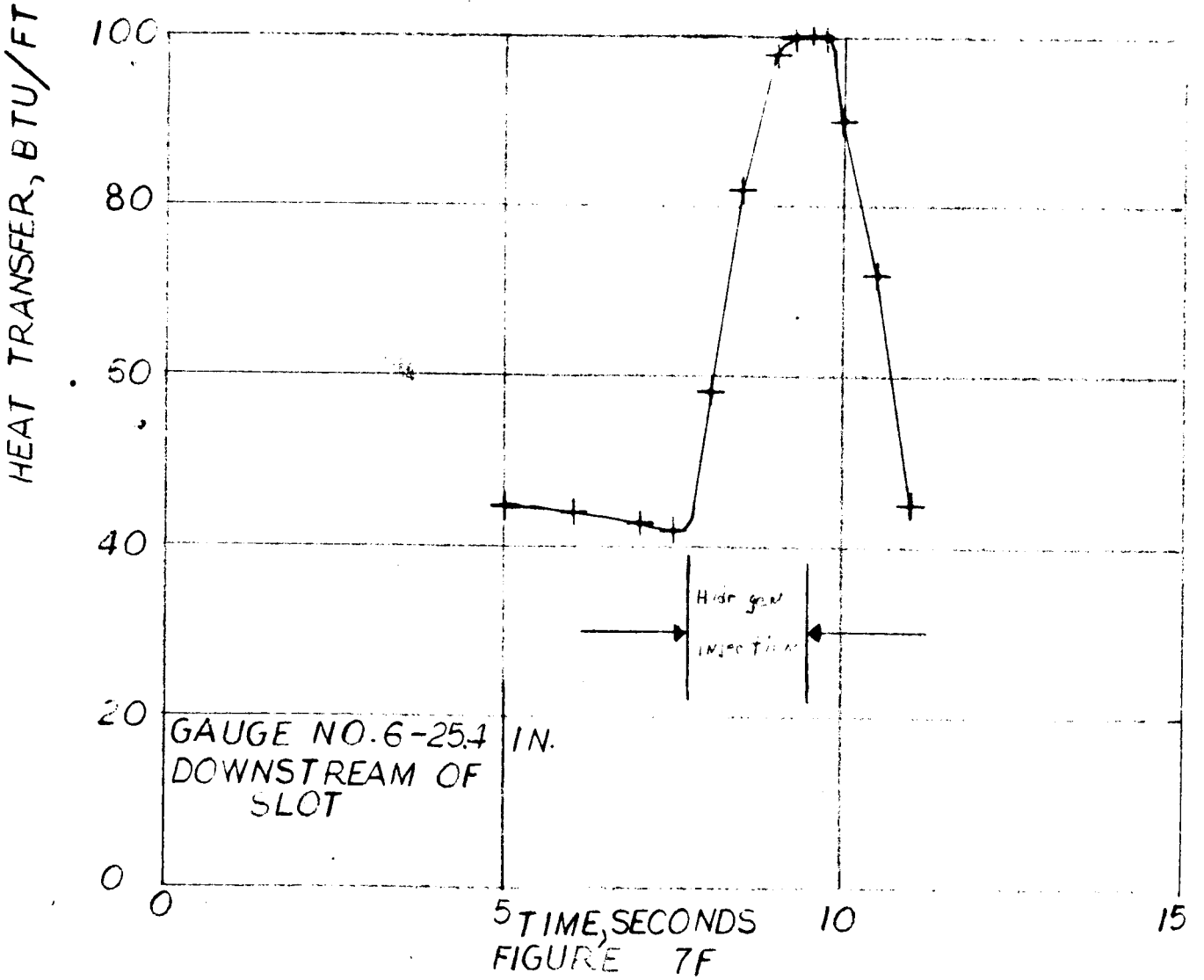


FIGURE 7E



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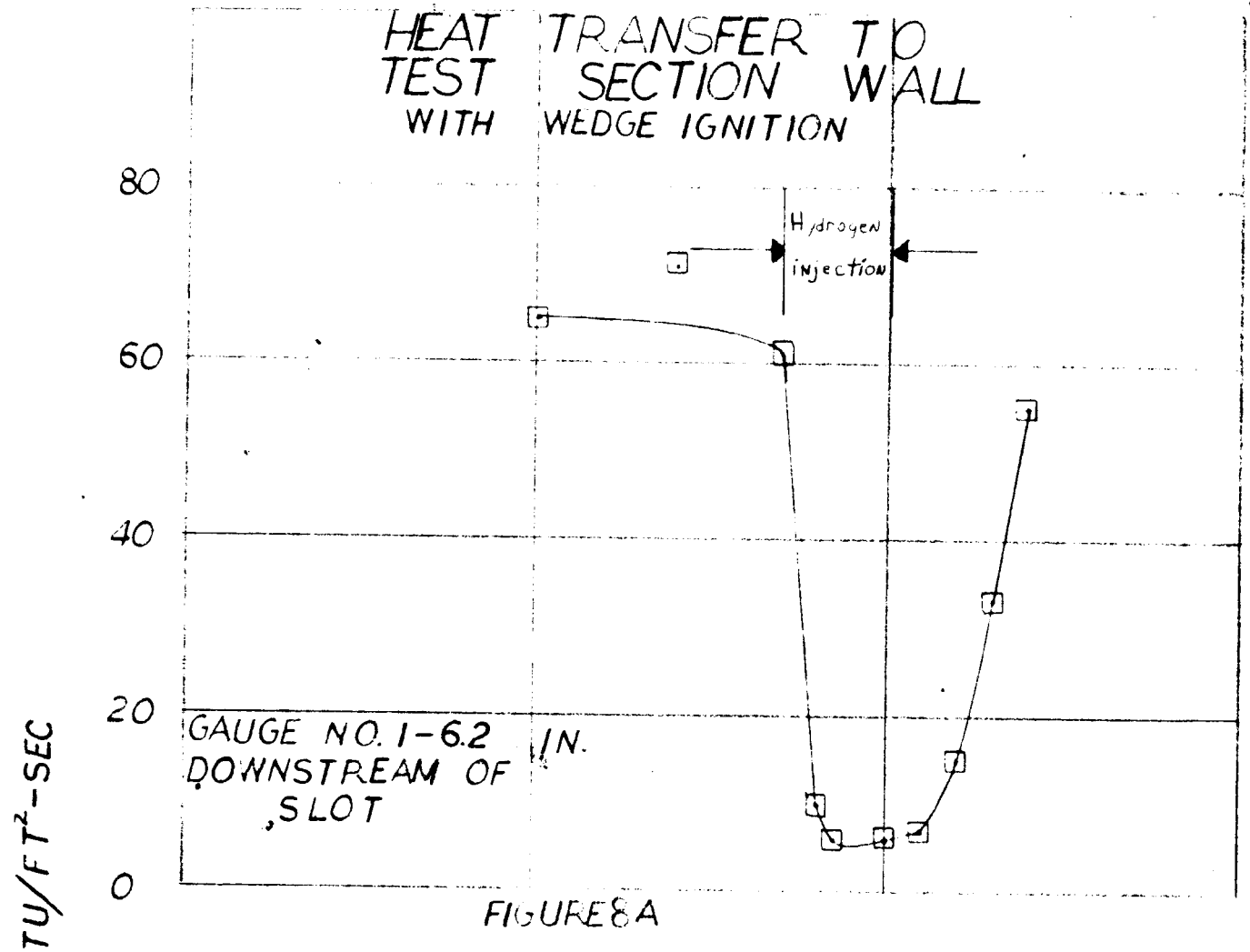


FIGURE 8A

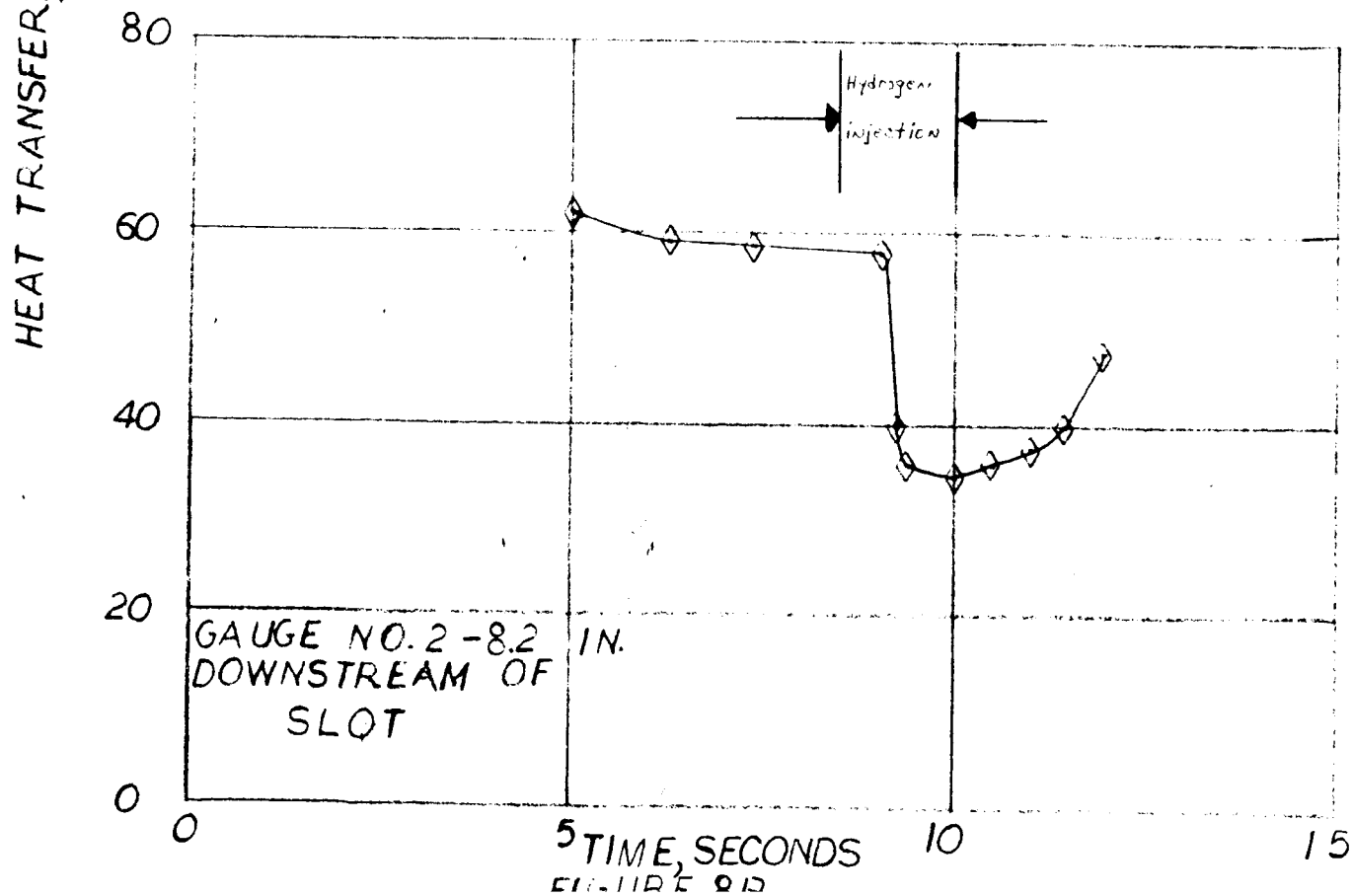


FIGURE 8B

HEAT TRANSFER TO TEST SECTION WALL WITH WEDGE IGNITION

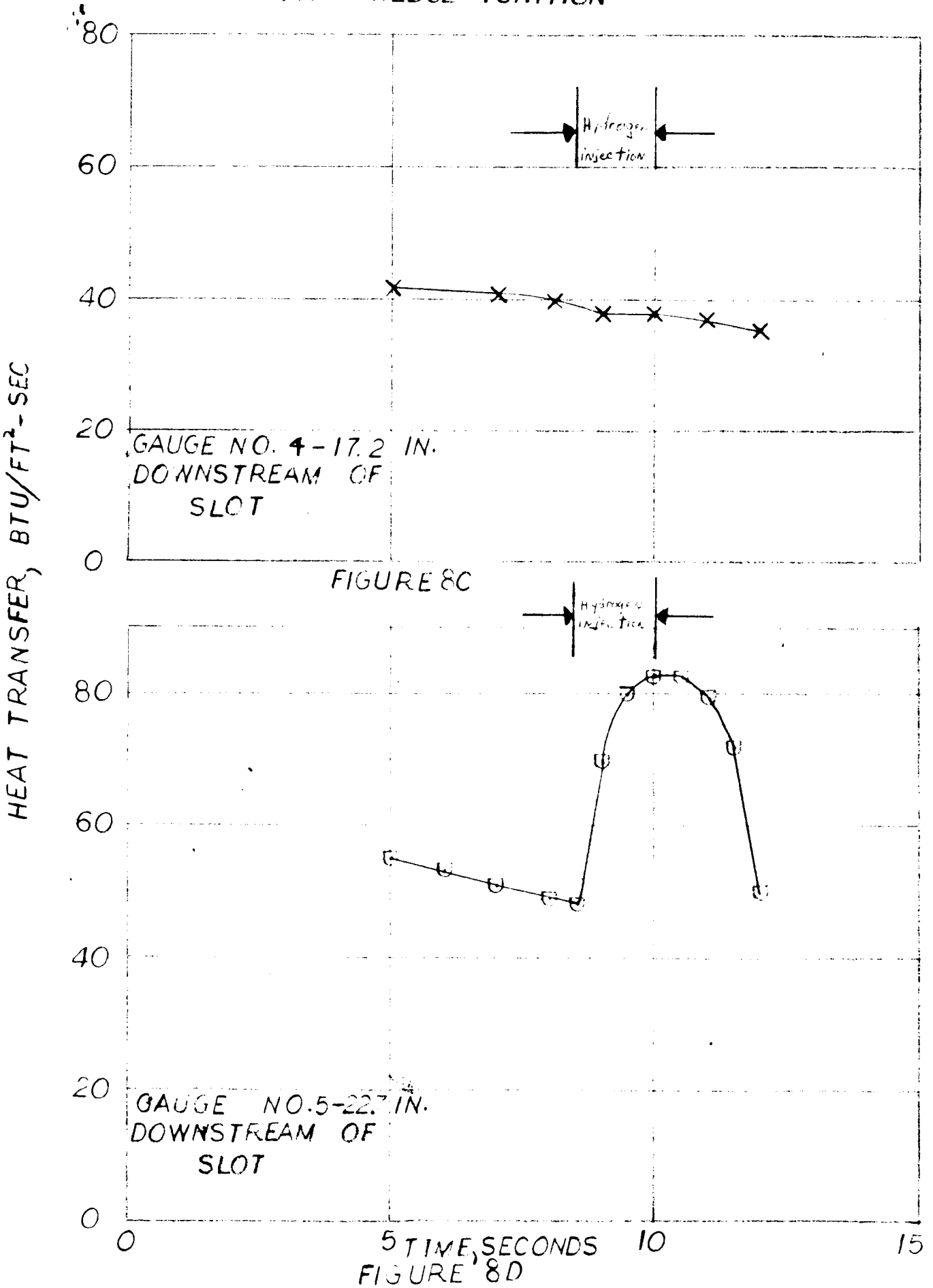
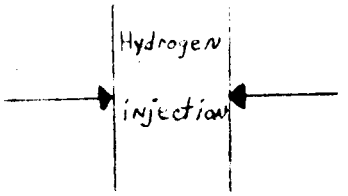


FIGURE 8C

FIGURE 8D

HEAT TRANSFER TO TEST SECTION WALL WITH WEDGE IGNITION



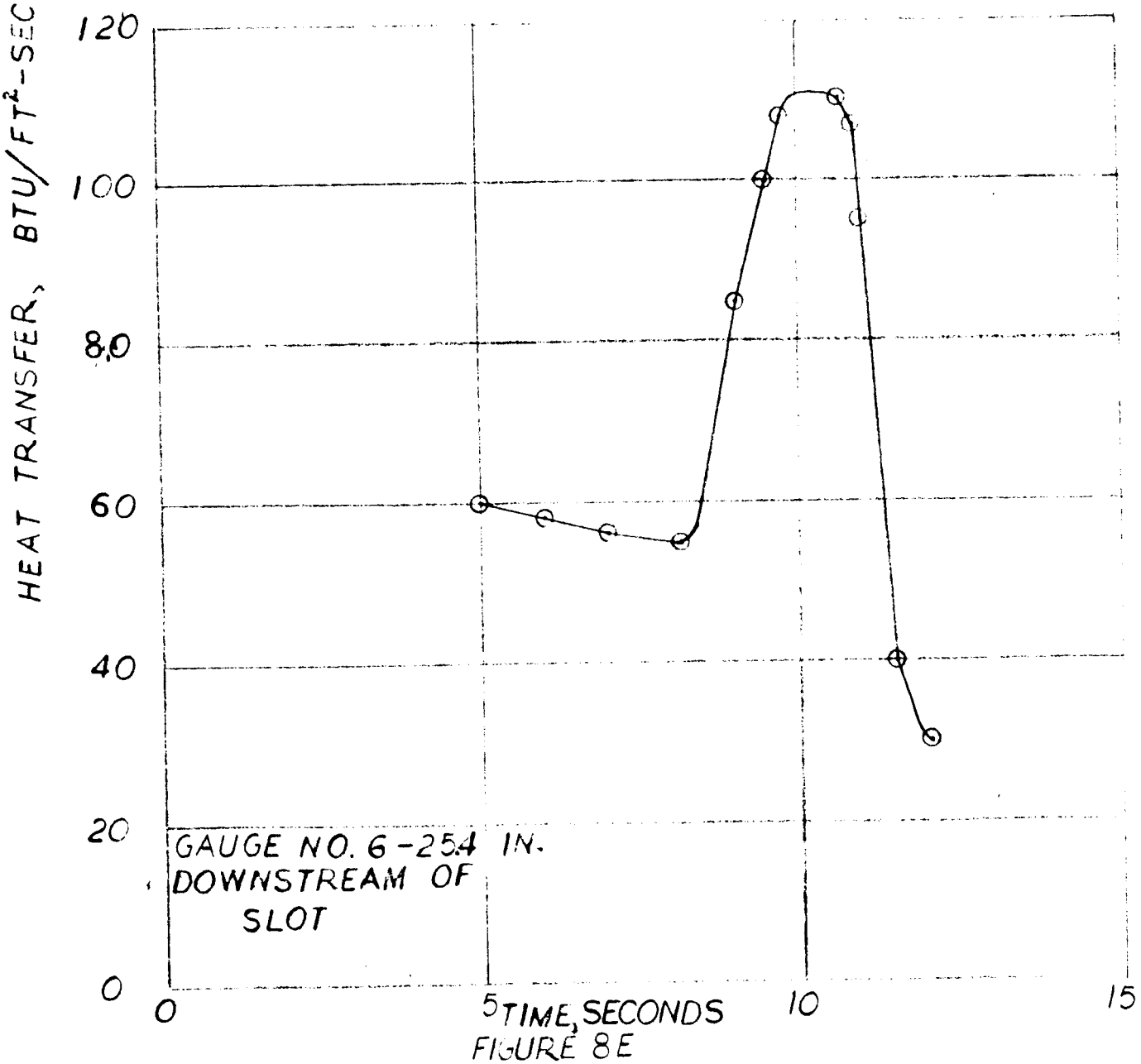
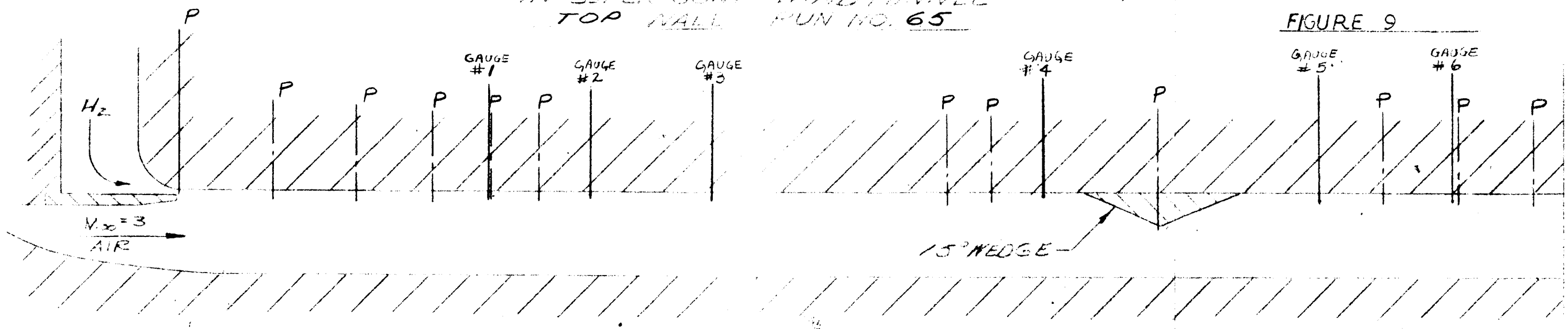
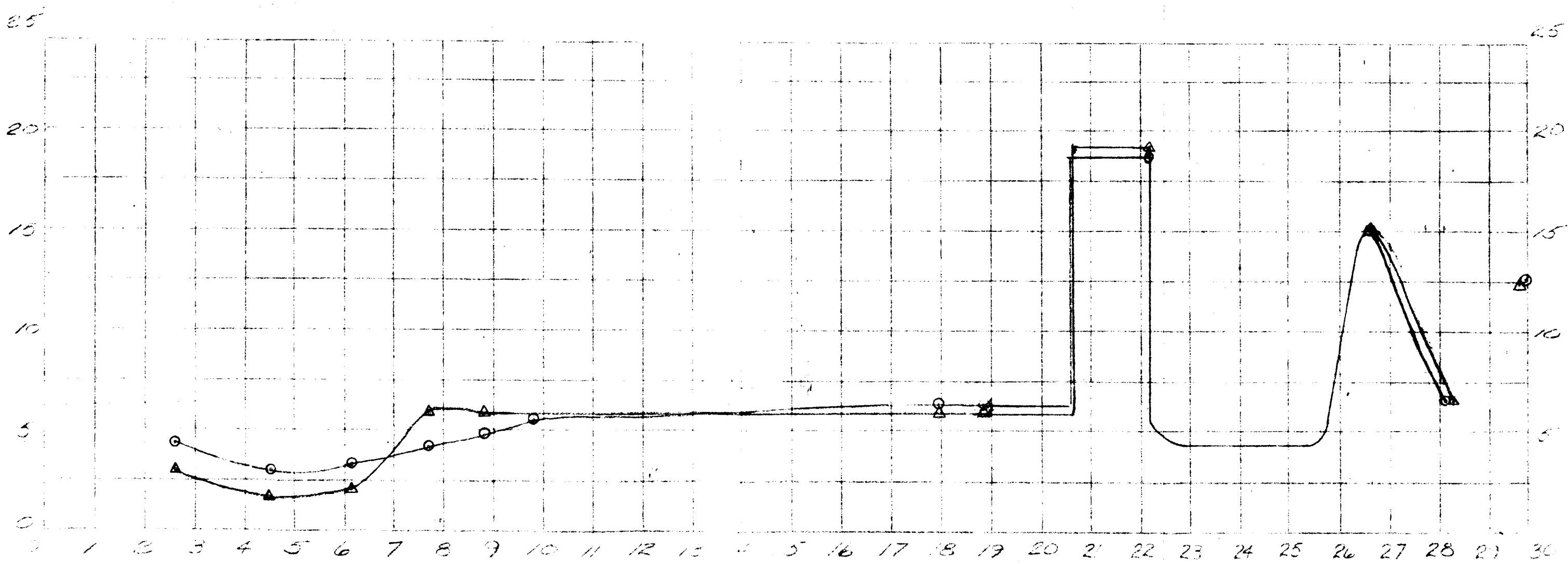


FIGURE 8E

PRESSURE DISTRIBUTION
IN SUPERSONIC BLOWDOWN TUNNEL
TOP WALL RUN NO. 65

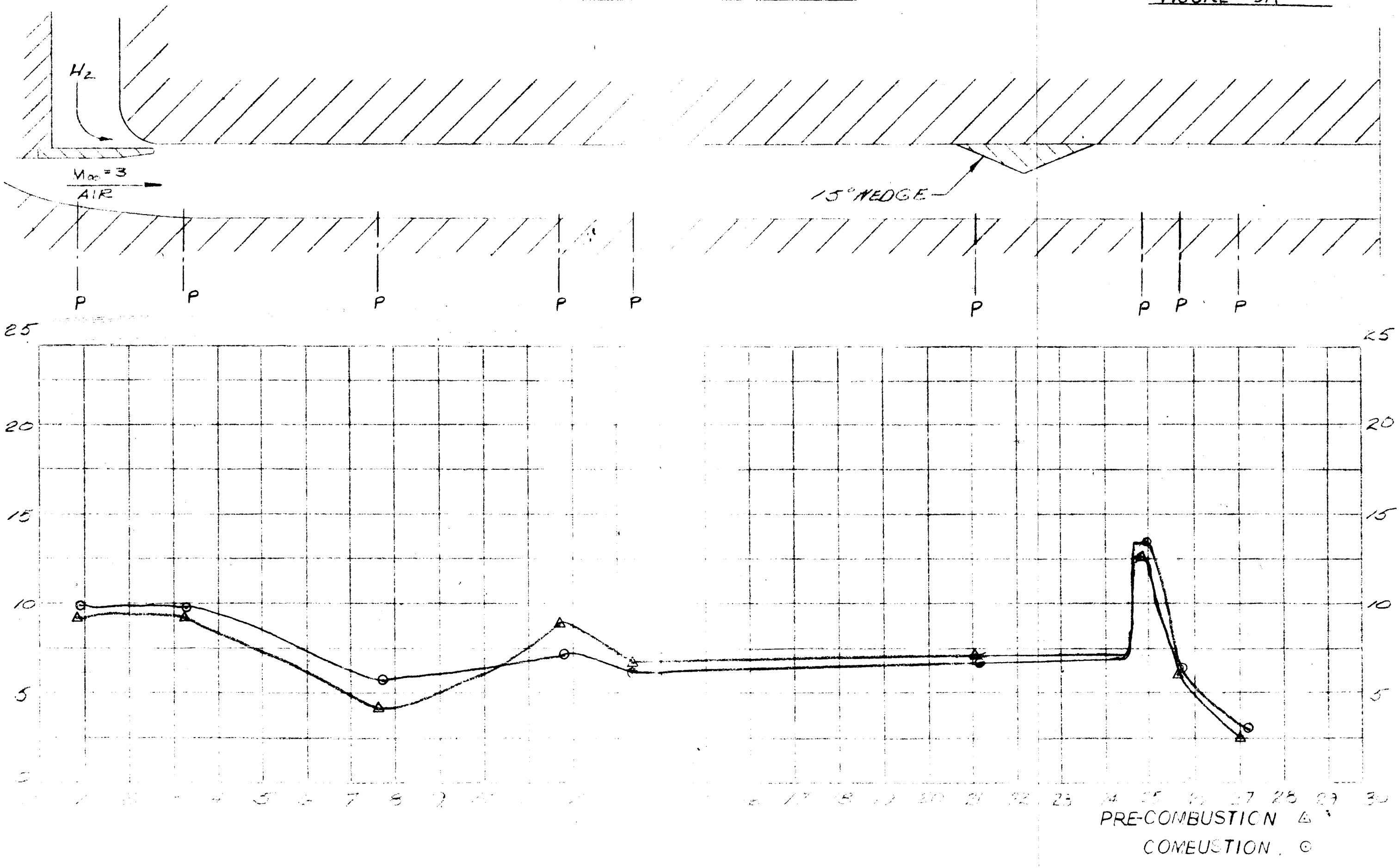
FIGURE 9





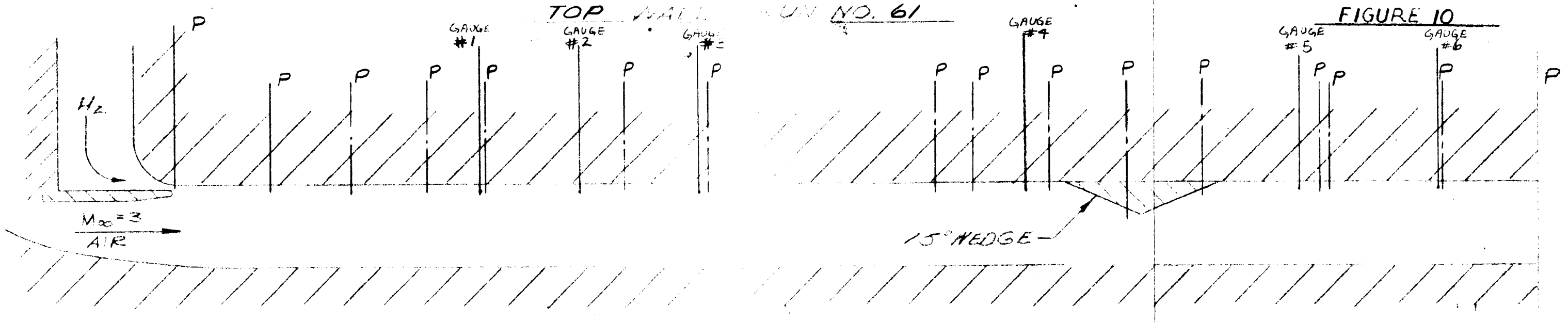
PRESSURE DISTRIBUTION
IN SUPER SONIC WIND TUNNEL
BOTTOM WALL RUN NO. 65

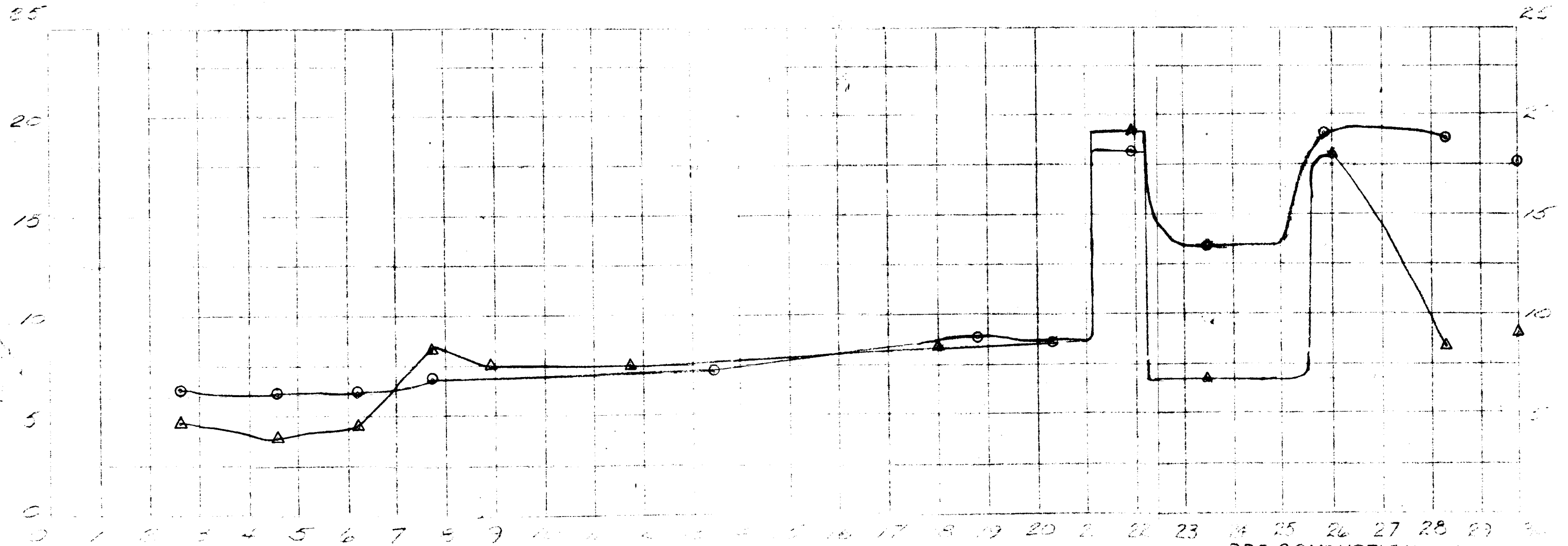
FIGURE 9A



PRESSURE ... IBUTION
IN SUPER... ...NOTUNNEL
TOP WALL ... RUN NO. 61

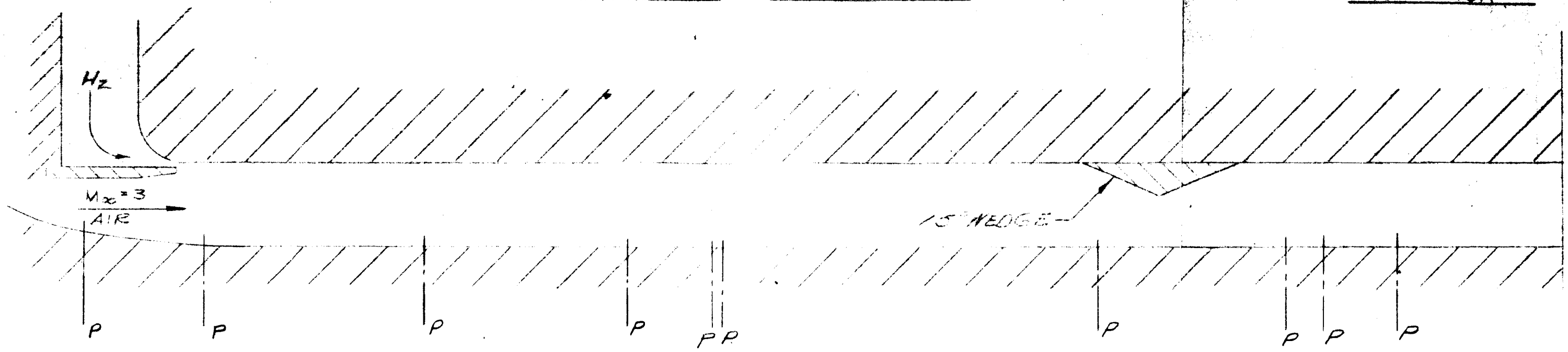
FIGURE 10

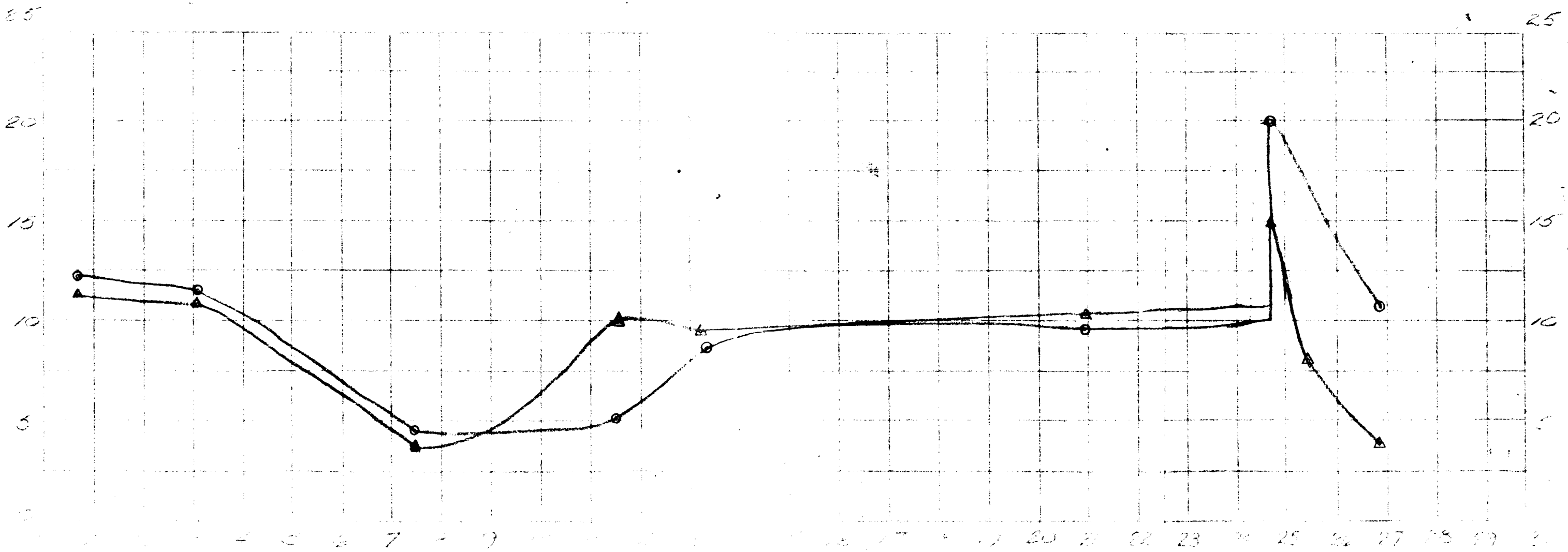




PRESSURE DISTRIBUTION IN SUPER SONIC WIND TUNNEL
BOTTOMWALL RUN NO. 61

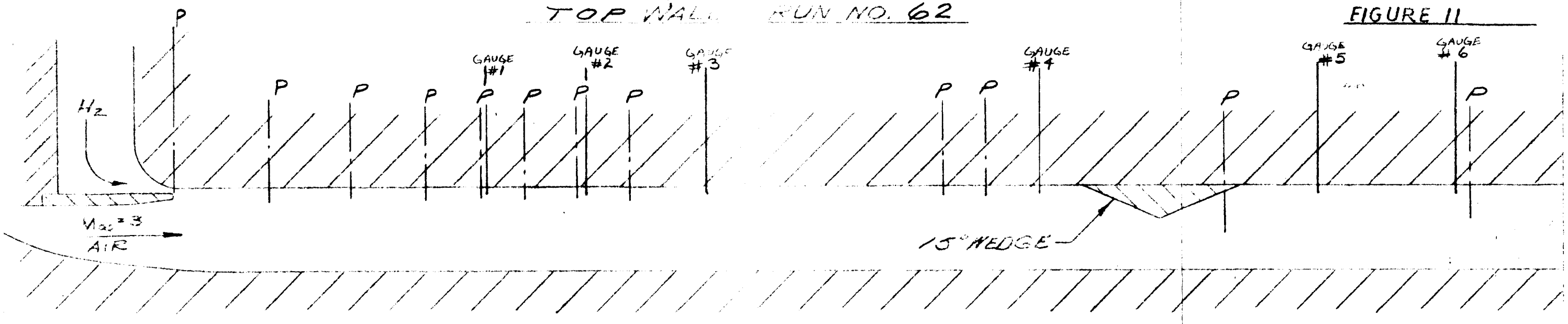
FIGURE 10A

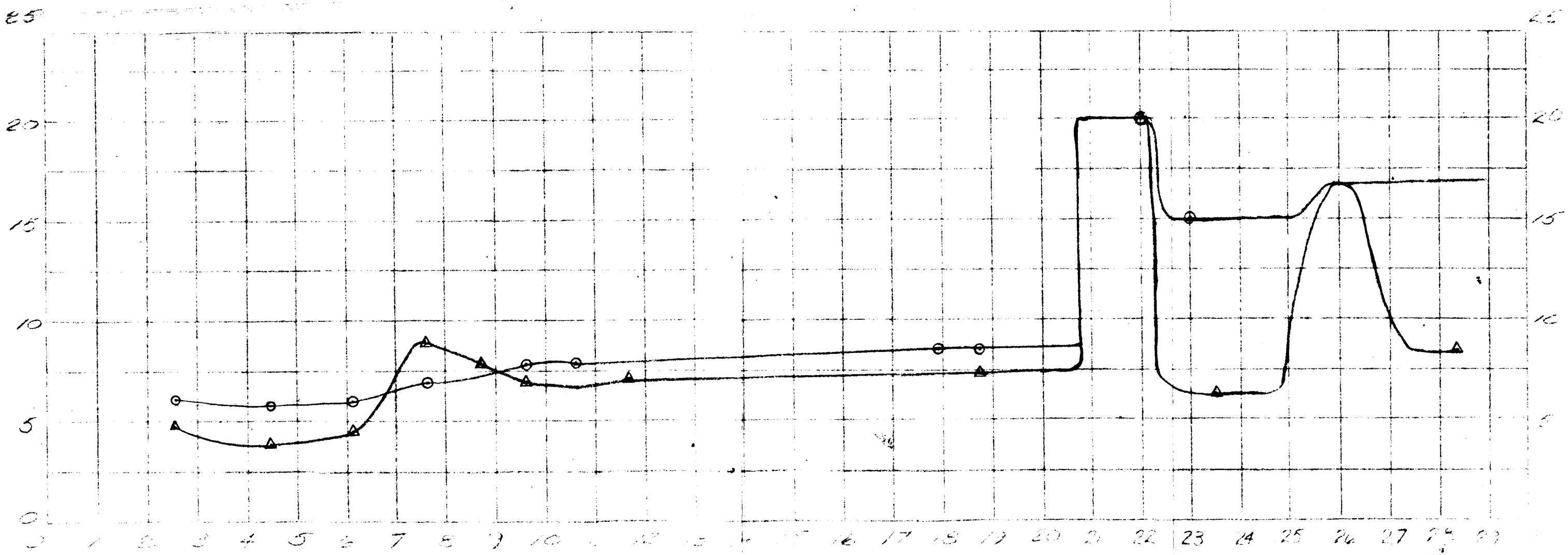




PRESSURE DISTRIBUTION
IN SUPERSONIC WIND TUNNEL
TOP WALL RUN NO. 62

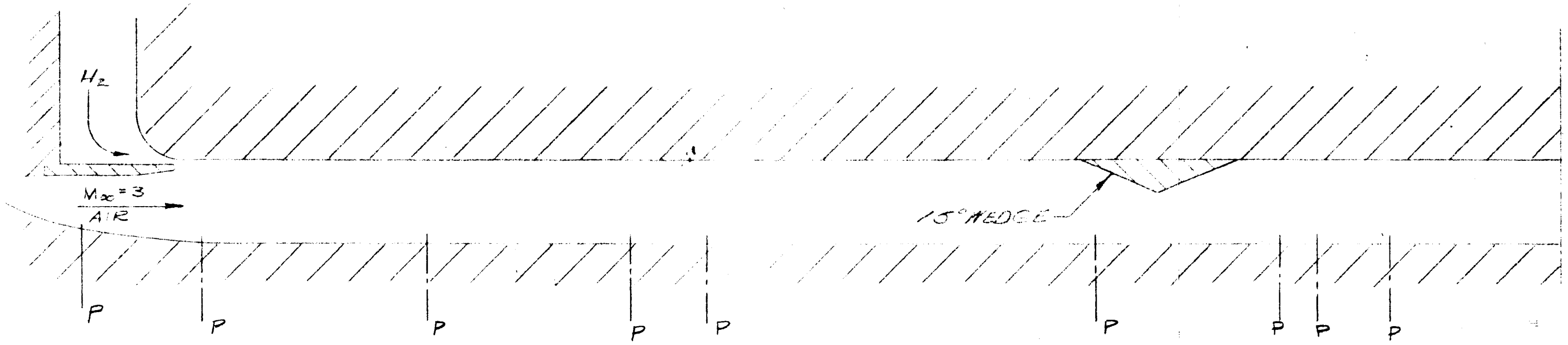
FIGURE 11

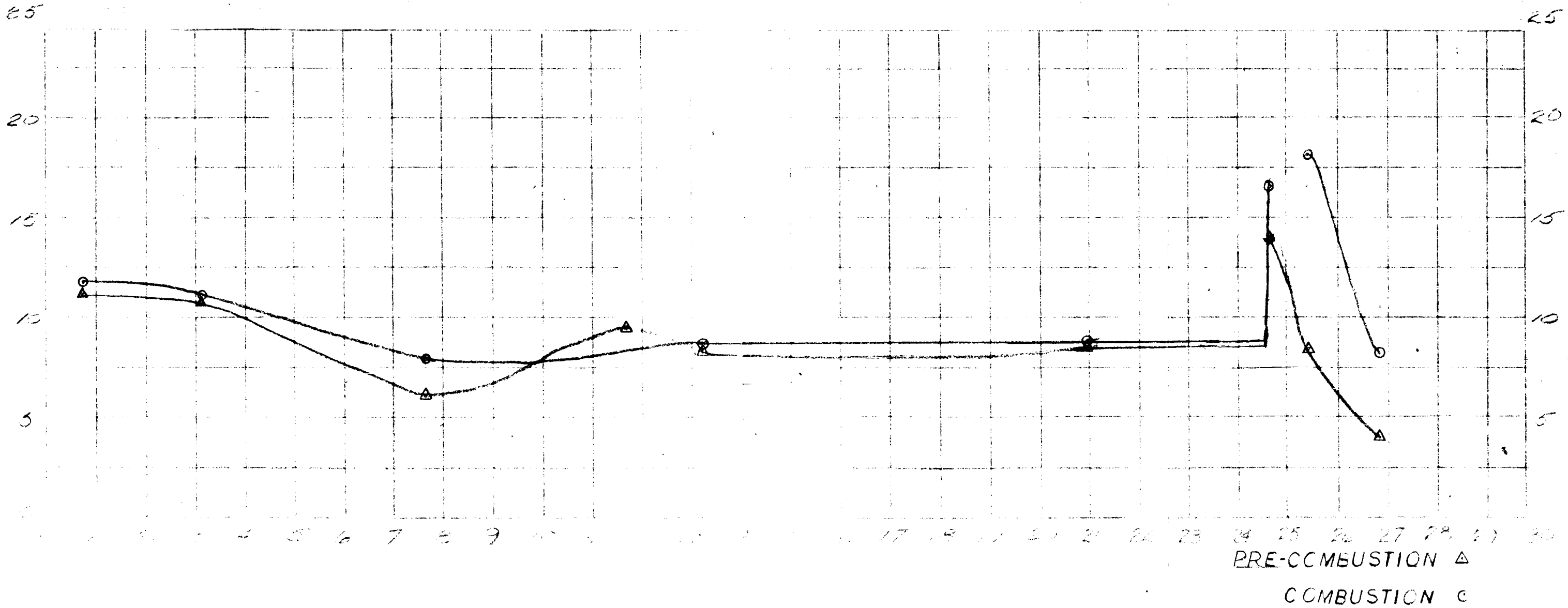




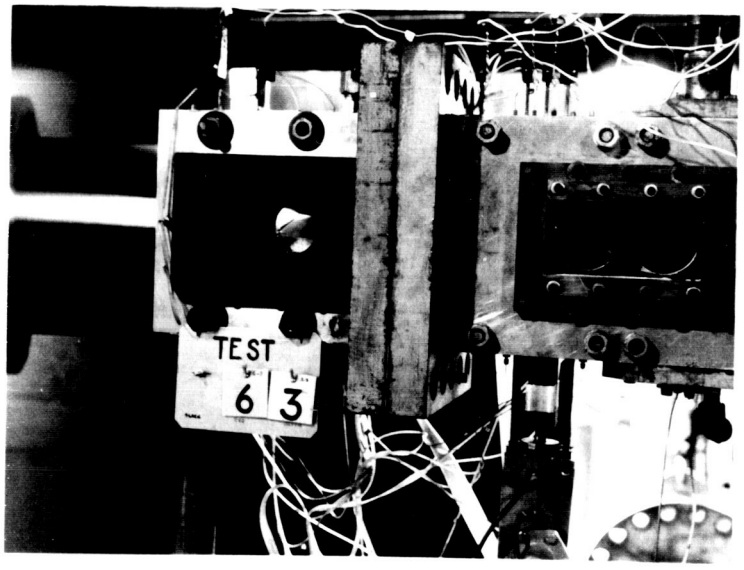
PRESSURE DISTRIBUTION
IN SUPER SONIC WIND TUNNEL
BOTTOM WALL RUN NO. 62

FIGURE IIA





LUMINOSITY PHOTOGRAPH OF IGNITION ON WEDGE



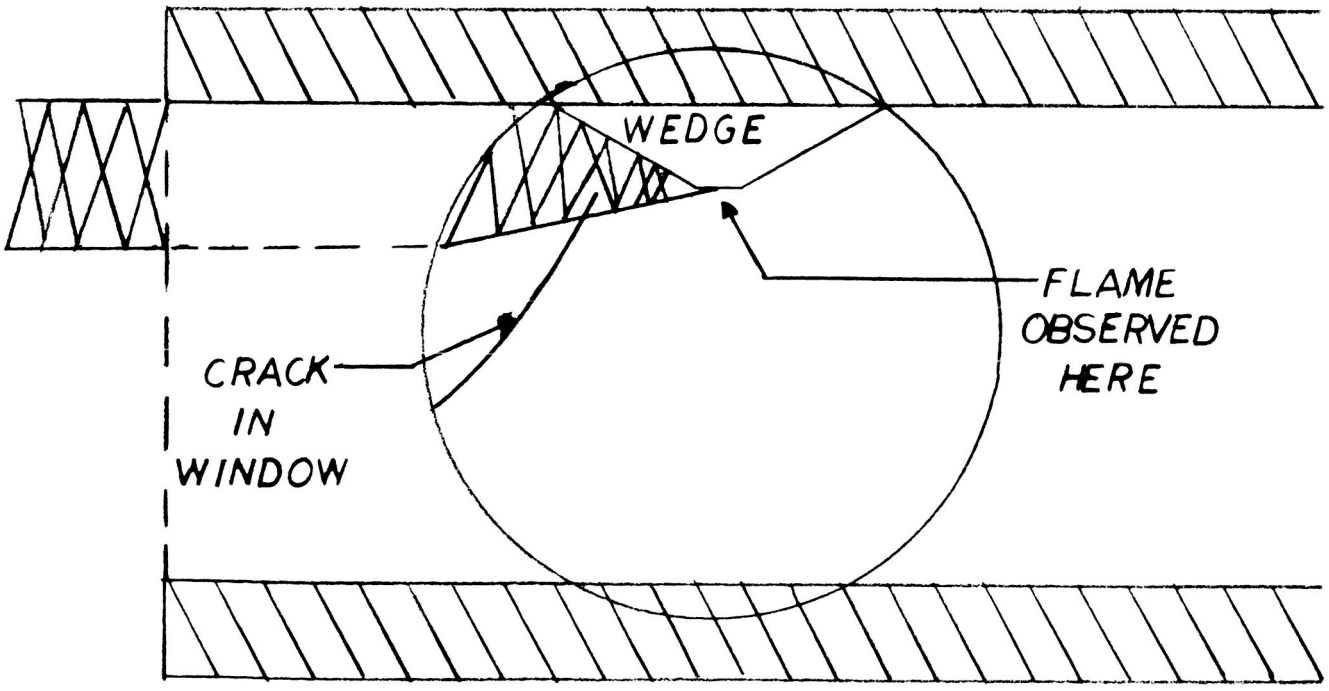
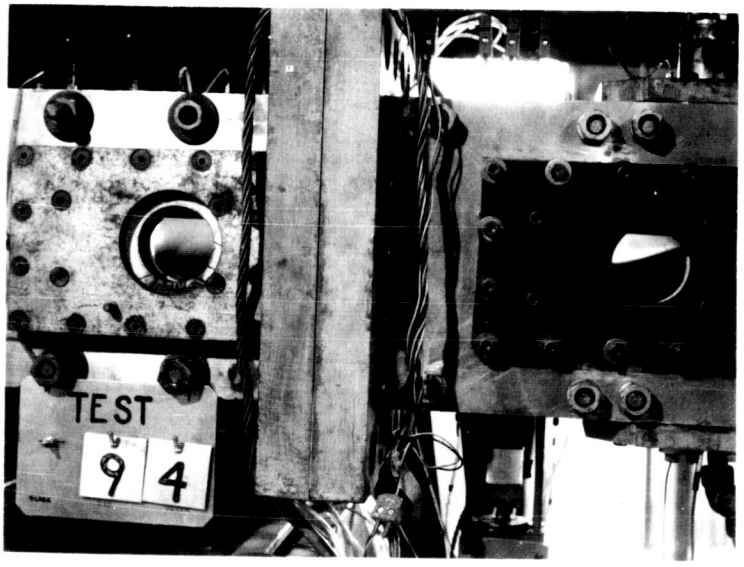
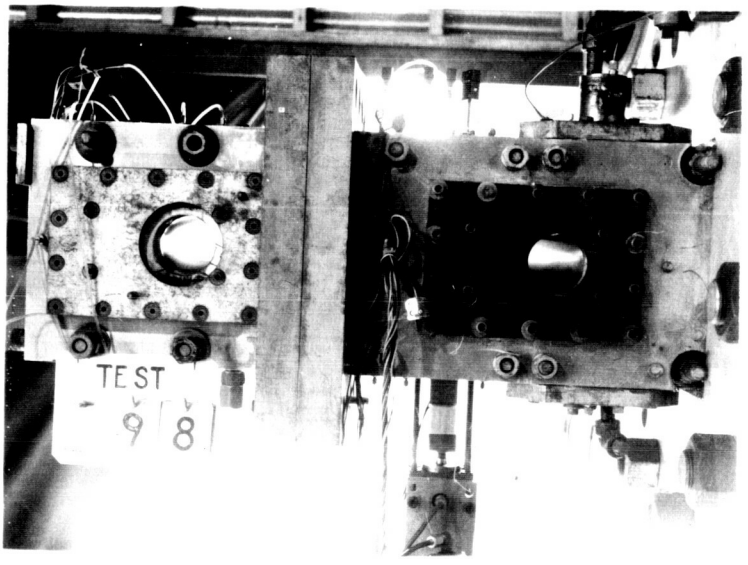


FIGURE 12

LUMINOSITY PHOTOGRAPH OF BURNING TRIGGERED BY DISTURBANCE





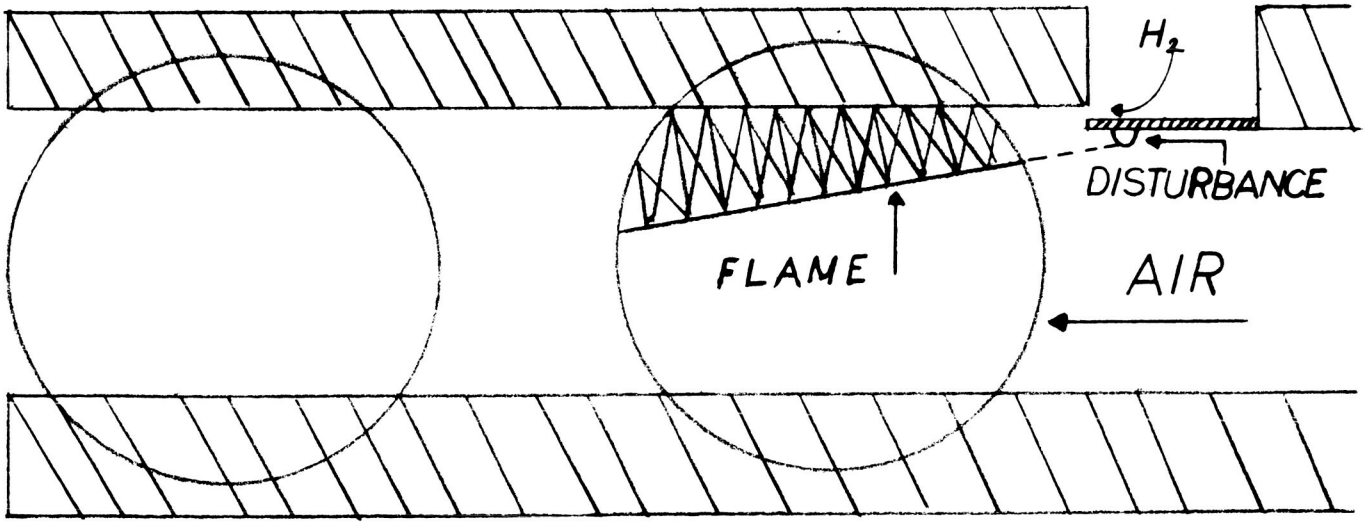
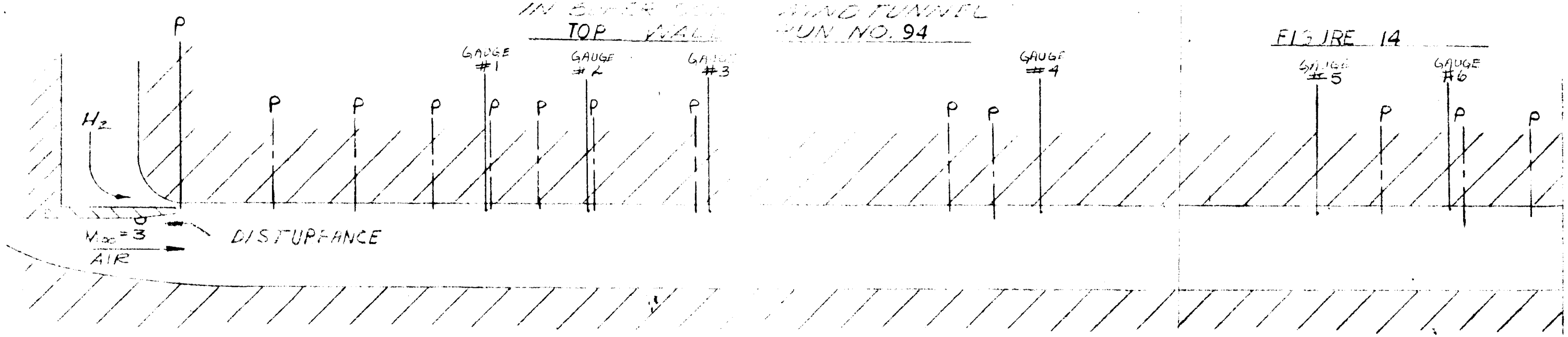


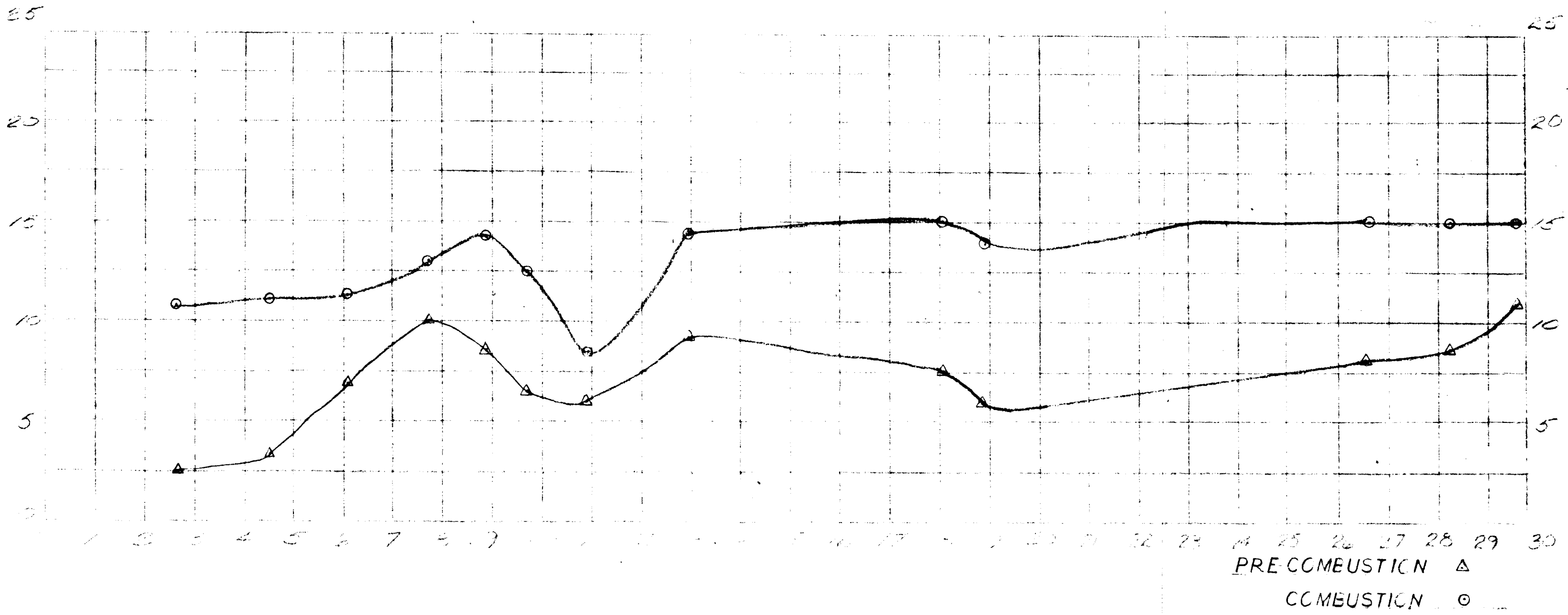
FIGURE 13

PRESSURE [illegible] IN SUPER [illegible] TOP WALL

[illegible] WIND TUNNEL RUN NO. 94

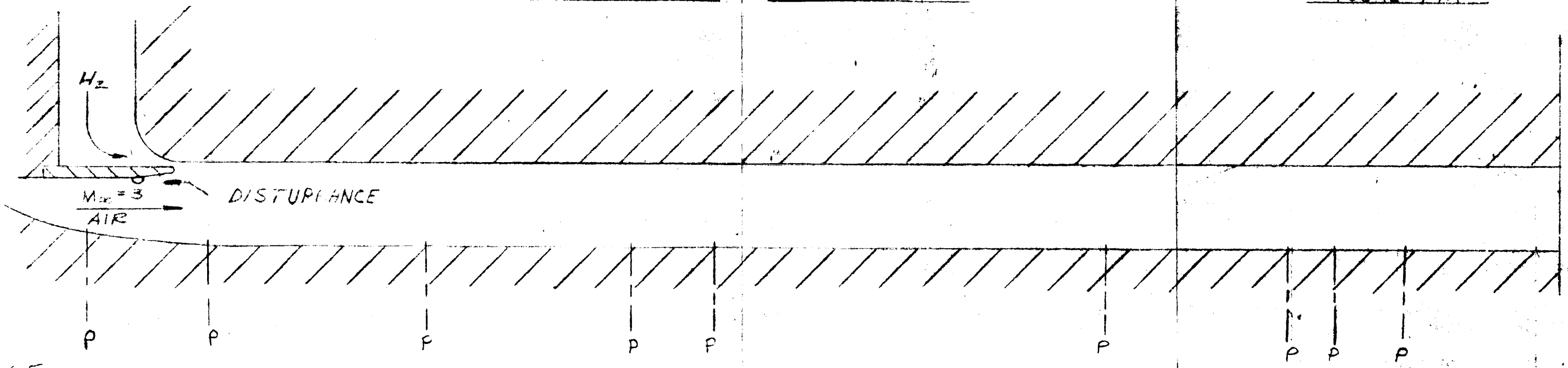
FIGURE 14





PRESSURE DISTRIBUTION IN SUPER SONIC WIND TUNNEL
BOTTOM WALL RUN NO. 94

FIGURE 14A



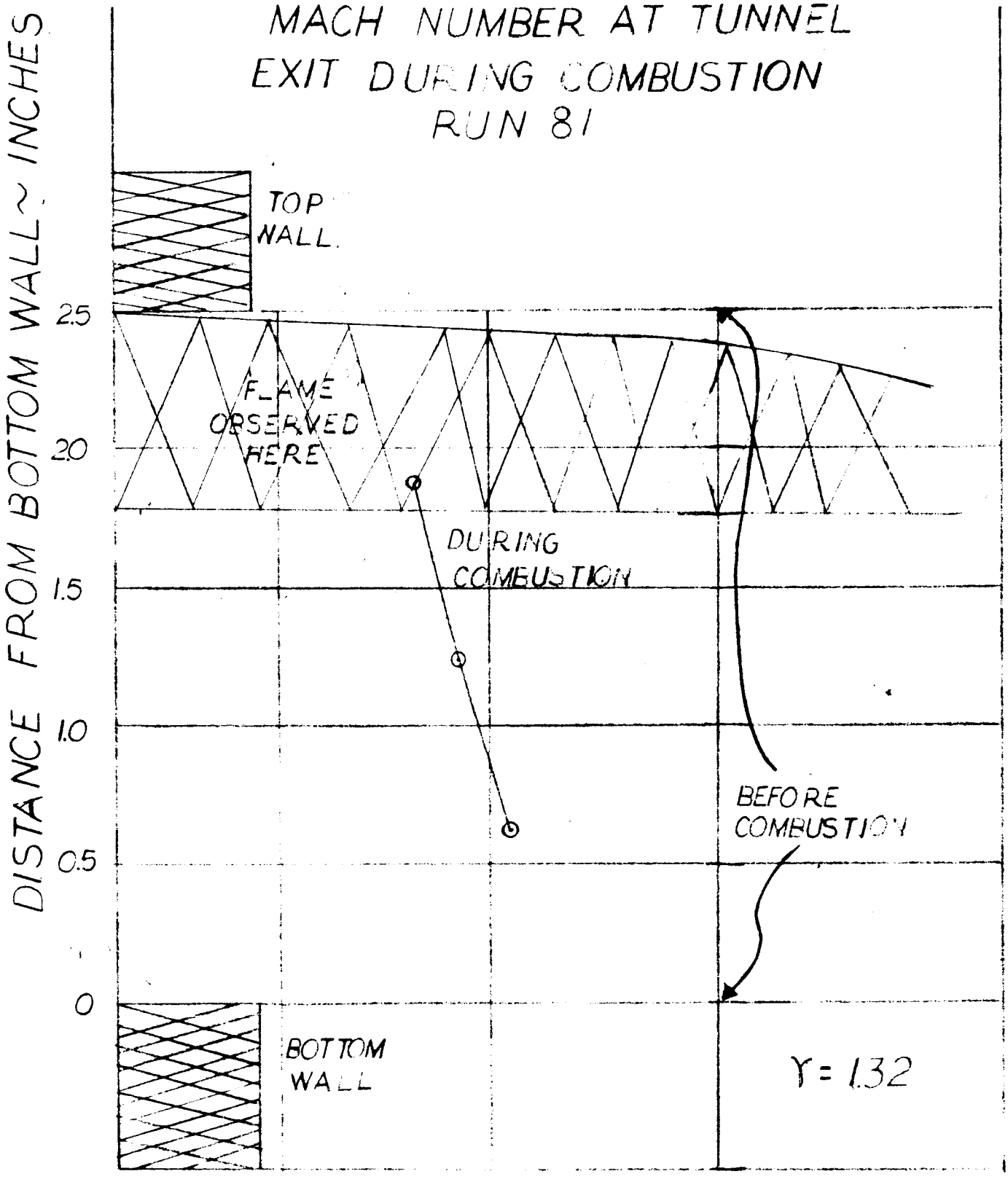

MACH NUMBER AT TUNNEL EXIT DURING COMBUSTION
RUN 81
TOP WALL
FLAME OBSERVED HERE
DURING COMBUSTION
BEFORE COMBUSTION
BOTTOM WALL
γ = 1.32
DISTANCE FROM BOTTOM WALL ~ INCHES
2.5
2.0
1.5
1.0
0.5
0
1.0
2.0
3.0
MACH NUMBER

FIGURE 15

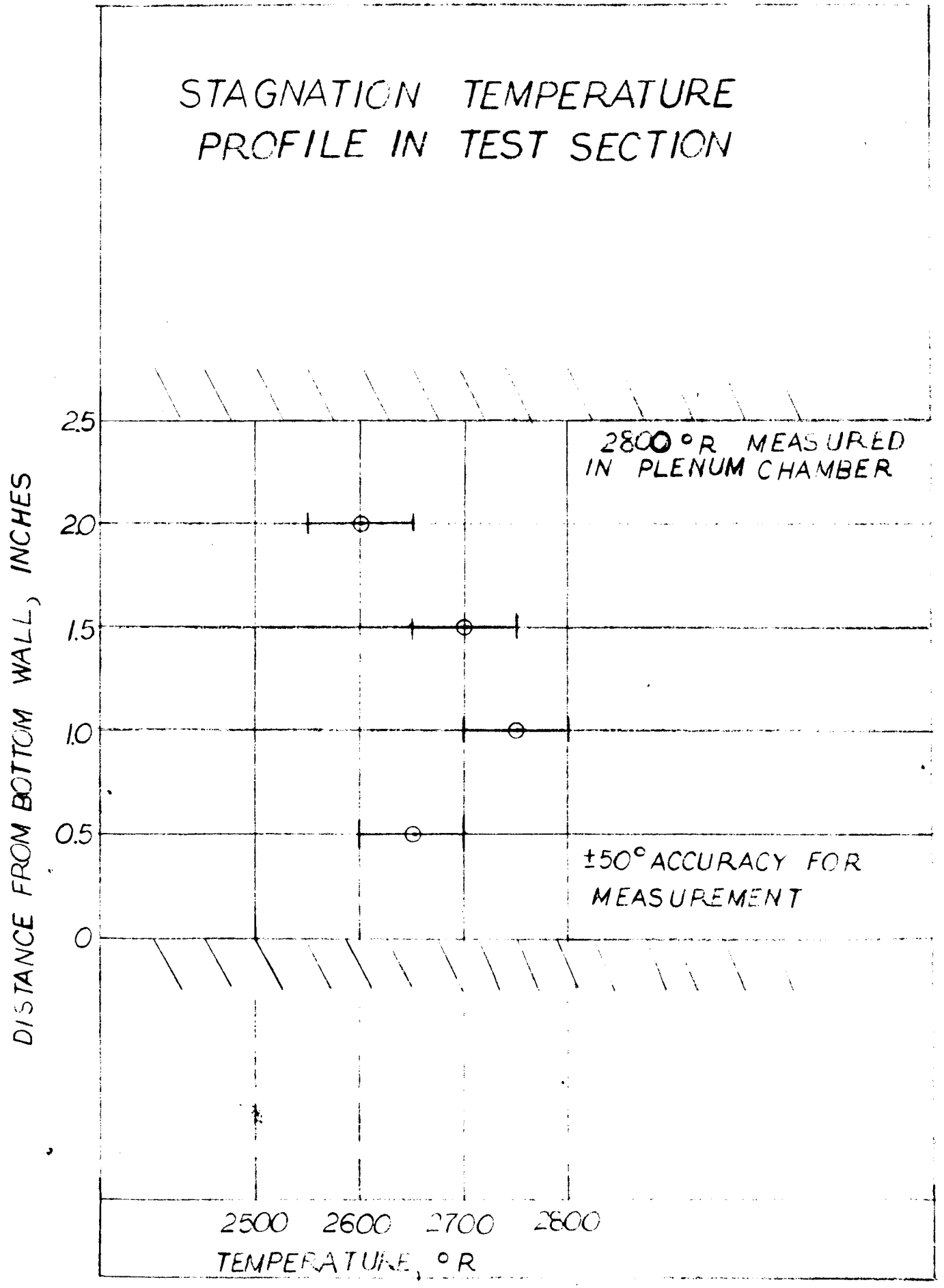

STAGNATION TEMPERATURE
PROFILE IN TEST SECTION
2800 °R MEASURED
IN PLENUM CHAMBER
±50° ACCURACY FOR
MEASUREMENT
DISTANCE FROM BOTTOM WALL, INCHES
2.5
2.0
1.5
1.0
0.5
0
2500
2600
2700
2800
TEMPERATURE, °R

FIGURE 16

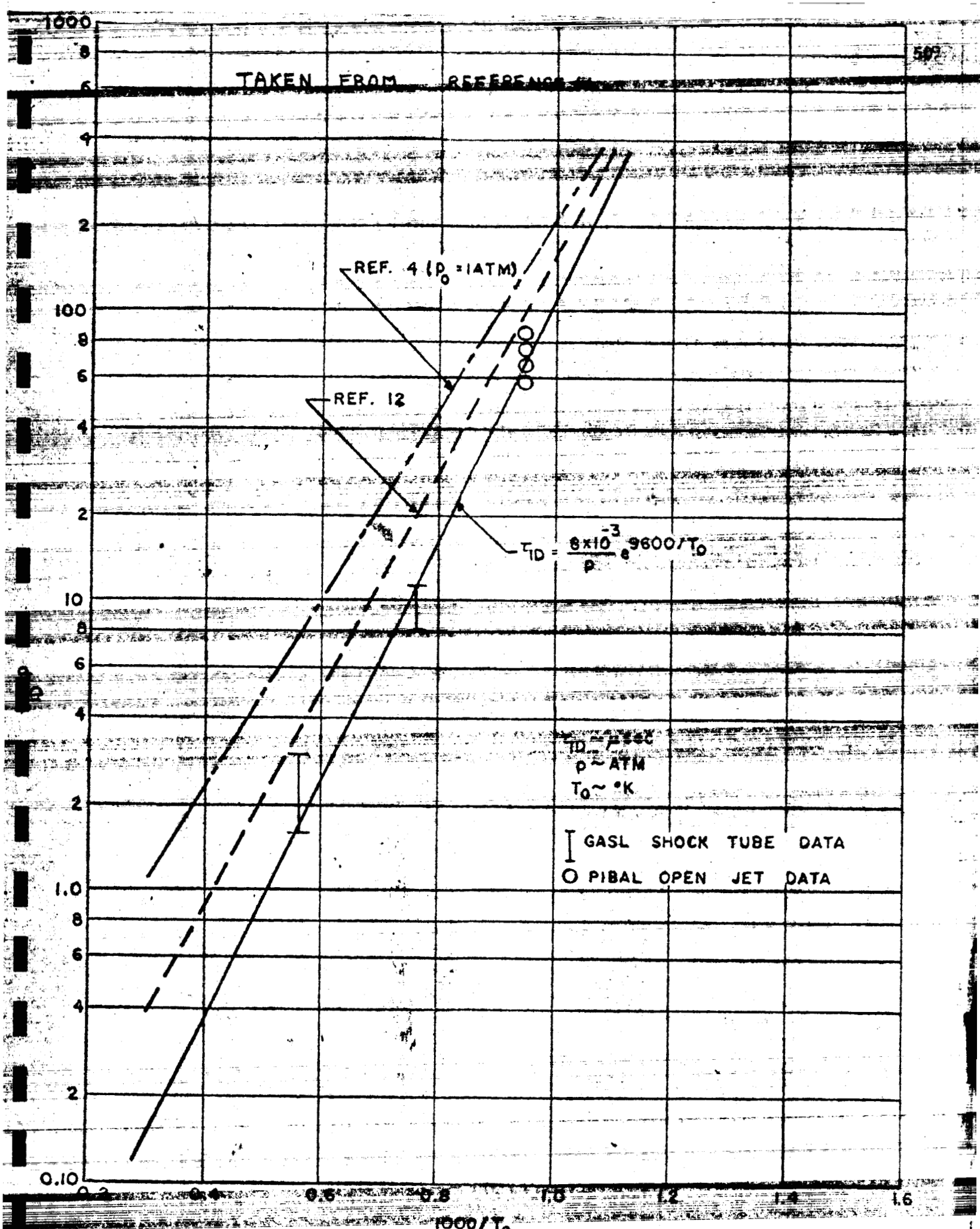


FIG. 17 CORRELATION OF IGNITION DELAY TIME NUMERICAL RESULTS

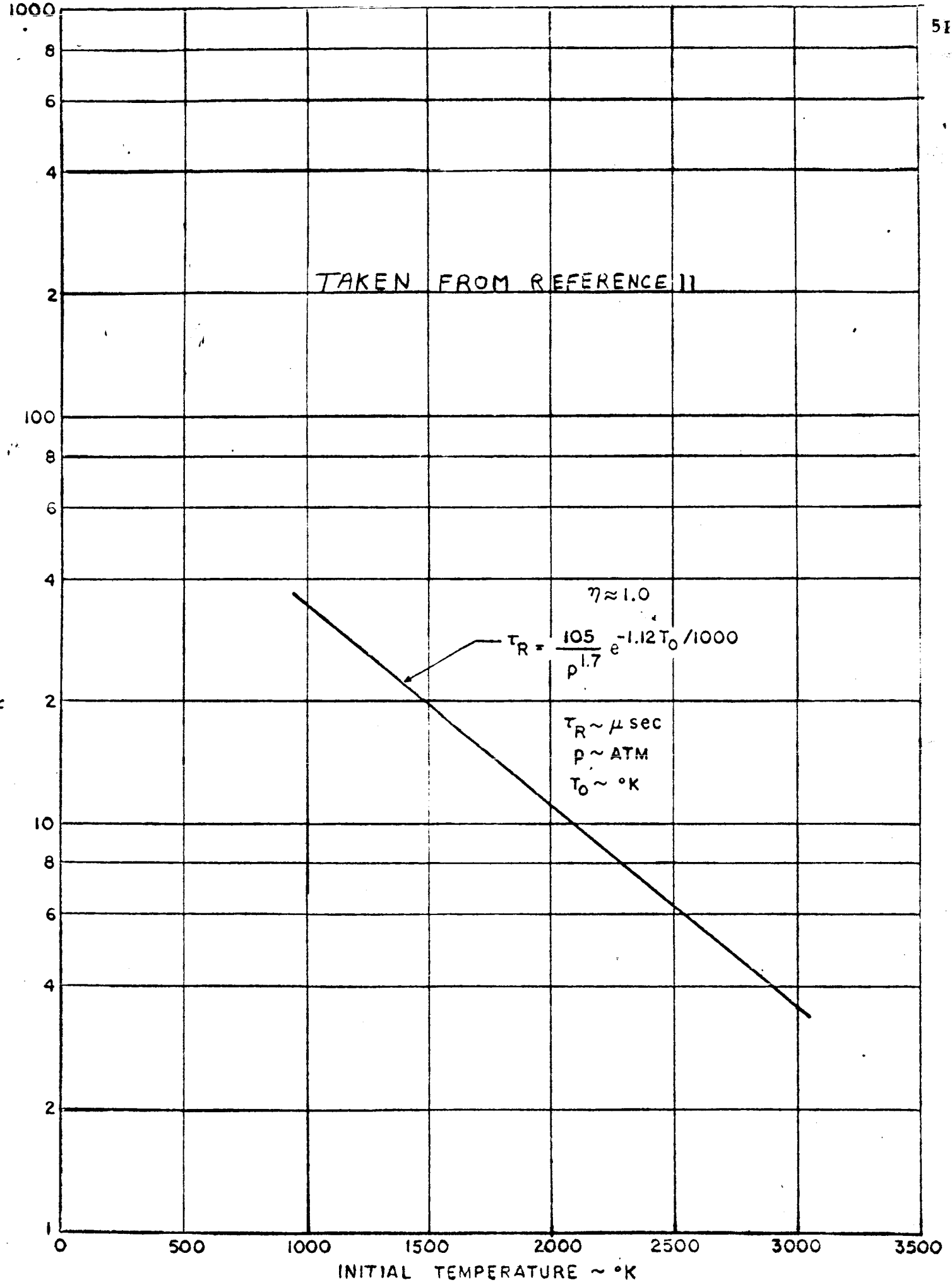


FIG. 18 CORRELATION OF REACTION TIME NUMERICAL RESULTS

TYPICAL LAUNCH VEHICLE TRAJECTORY

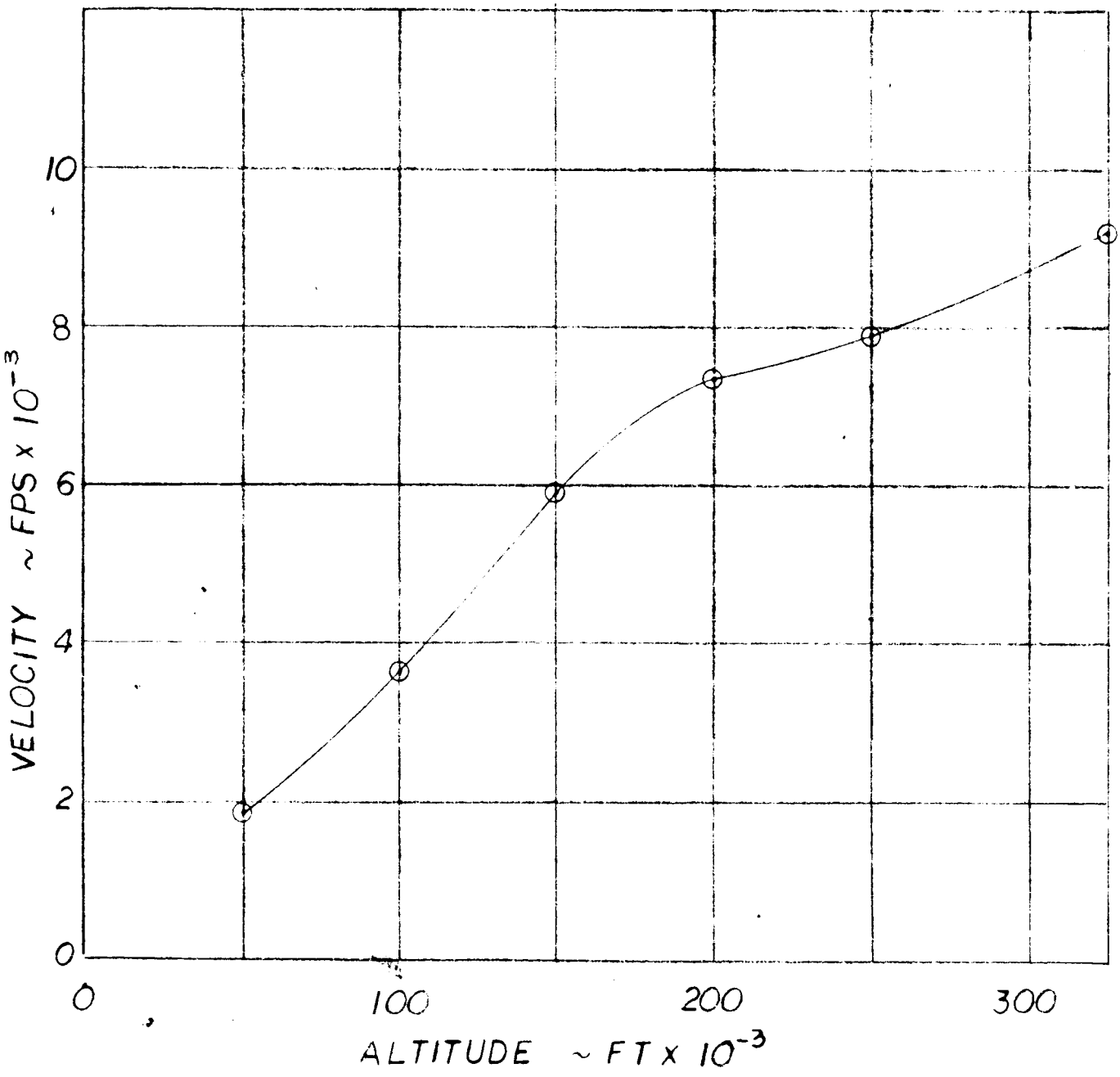
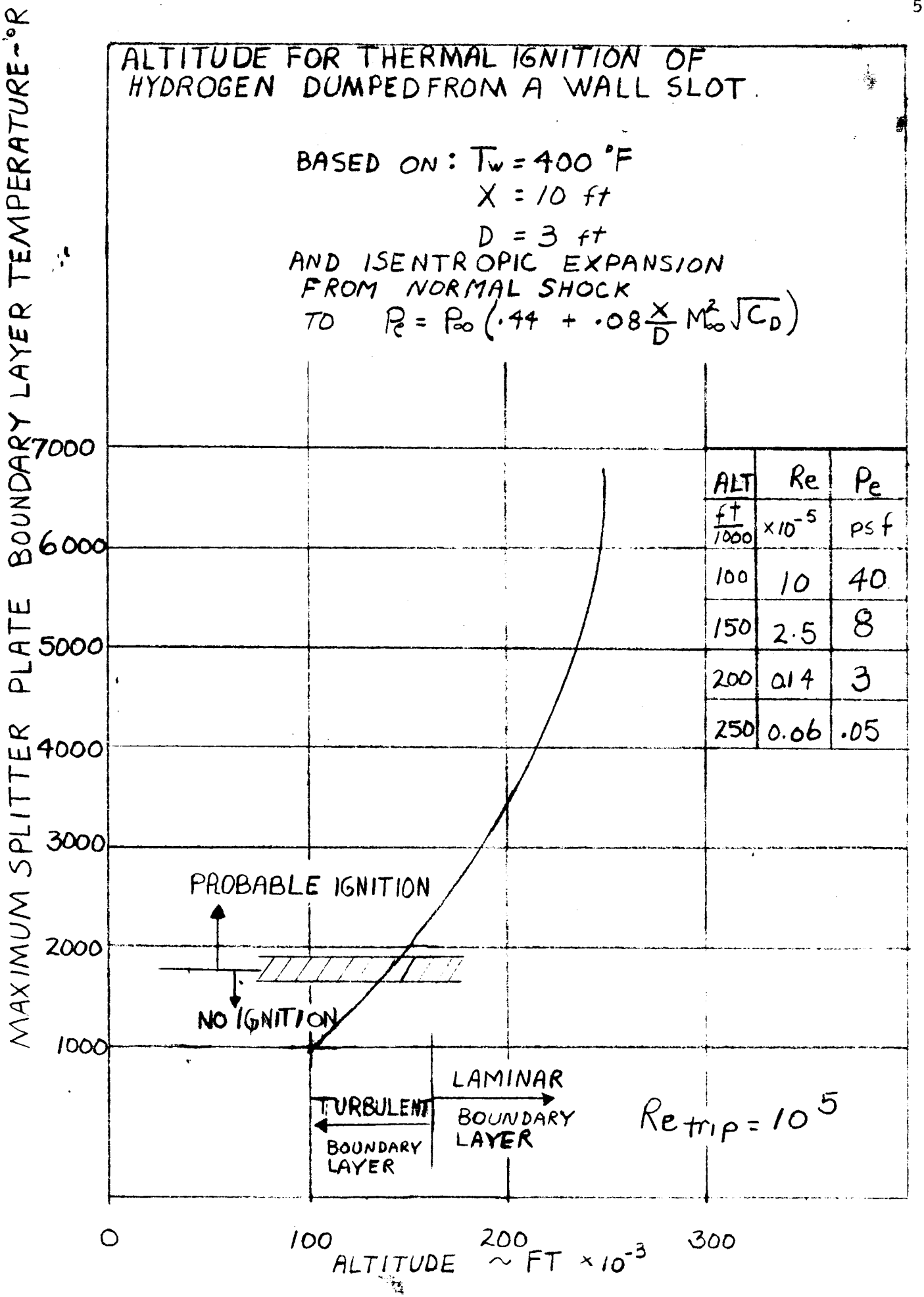


FIGURE 19



ALT $\frac{ft}{1000}$	Re $\times 10^{-5}$	P_e psf
100	10	40
150	2.5	8
200	0.14	3
250	0.06	.05

FIGURE 20