THE COMBUSTION OF NORMAL BUTANE-AIR MIXTURES IN UNCONSOLIDATED POROUS MEDIA

By

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Symbol

H	heat rate, Btu/hr
T	temperature, °F
u	volumetric velocity, standard cubic feet per hour per square foot

Subscripts

A	air
C	combustion, H_C
E	exhaust gas
l	loss, H_l
W	combustion tube wall, T_W

CHAPTER I

INTRODUCTION

The spiraling cost of finding and producing crude petroleum has created within the petroleum industry an interest in methods which might prove profitable in the recovery of hydrocarbons from reservoirs containing highly viscous crude oils. Recent interest in this problem has been centered around thermal recovery methods, in particular, in situ combustion.

The general aspects of in situ combustion are that a sufficient quantity of air is supplied to the oil reservoir through an injection well to permit the combustion of the heavy fractions of the highly viscous crude oil while the lighter fractions are driven toward a producing well by a combination air, steam, and thermal drive. Thermal recovery by the in situ combustion process may be accomplished by initiating the combustion zone at the injection well and allowing it to progress toward the production well which is referred to as forward combustion, or combustion may be initiated at the production well and be permitted to burn toward the injection well, which is known as reverse combustion.

The purpose of this study was to determine, if possible, some of the factors which influence the establishment and movement of a combustion zone within a porous medium by the use of a system which was less complex than might be encountered under actual field conditions. The system used was a two-inch cylindrical sand pack, composed of an unconsolidated, graded sand, in which mixtures of pure normal butane and air were burned at low pressures. The problem under study was a reverse combustion process. However, it differed from in situ combustion in that all of the fuel was supplied with the air. Originally, the combustion of methane-air mixtures in a semi-adiabatic system was proposed. However, attempts to accomplish this objective were unsuccessful for reasons that will be discussed later.

CHAPTER II

PREVIOUS INVESTIGATIONS

A large quantity of literature has been published on combustion, but there was little concern about the principles of combustion as applied to combustion in porous media until 1952 when the Sinclair Oil Company and Magnolia Petroleum Company began independent field tests of oil recovery by this process. Since that time most of the major petroleum research laboratories have conducted laboratory and field experiments to determine the applicability of this process to oil recovery. However, little work has been published in the form of basic research, and no published results have been found on the combustion of gases in a porous medium, although it is known that several laboratories have conducted experiments of this nature.

The only references that were found on reverse in situ combustion were recently released by the Gulf Research and Development Company. Reed, et al, (1) made experimental runs of this process in tar sands contained in an adiabatic tube, employing a unique wall temperature control system. They concluded that for reverse combustion in tar sands the average peak temperature was a function of air flux and was insensitive to heat loss. An increase of air flux from 10 to 130 scf/hr-ft^2 increased the peak temperature from 500 to 1070°F. They stated that combustion zone velocity varied almost linearly with air flux and was decreased by heat loss. The zone velocity increased from 1.8 to 7.6 ft./day for an air flux increase from 10 to 130 scf/hr-ft.^{2}. They also found that increasing the initial temperature decreased the peak temperature and increased the combustion zone velocity.

Warren, et al (2) have theoretically investigated the reverse in situ combustion process by means of an idealized theoretical model which was described by two non-linear equations involving heat and mass transfer which were coupled with a concentration-dependent reaction rate function. They concluded that the process could be mechanistically described by simple physical models whose behavior equations could be solved formally, and that the general equations which they derived could be solved numerically within the error limits of the experimental data. They also found that the theoretically predicted peak temperature-air flux relationship and temperature distribution agreed reasonably well with experimental data.

Martin, et al (3) have presented the results of an in situ combustion experiment in a semi-adiabatic, unconsolidated sand pack using a forward combustion process which utilized 10.9 to 34.2°API gravity crude oils. They investigated the air-fuel requirements, rates of advance, combustion temperatures, and coke and fluid distributions.

It was concluded that heat must be liberated by combustion at a rate equal to the net rate of heat loss in order to maintain isothermal combustion. They found this to be the heating rate required to maintain a 600°F combustion zone temperature. This heating rate determines the minimum air flux which was found to be less than 9.0 scf/hr-ft^2, and which in turn determines the minimum rate of advance which was

0.7 ft/day. They found that combustion temperatures ranged from 625 to 1000°F, and rates of advance ranged from 0.7 to 12.5 ft/day over an exit flux range of 8.9 to 250 scf/hr-ft^2. They concluded that the fuel requirements were largely fixed by the heat capacity of the porous matrix and heat losses from the zone.

McNiel and Nelson (4) give a review of the application of in situ combustion to actual field projects and include a very good bibliography of the currently available literature on this process. They report that combustion front temperatures in field projects range from 600°F to 1200°F.

Benham and Poettman (5) have derived an equation relating frontal velocity, air flux, oxygen utilization, residual fuel, hydrogen:carbon ratio, and the ratio of carbon dioxide to carbon monoxide, and they have compared it to the data determined by Martin, et al (3).

Kuhn and Koch (6) reported on one of the first in situ combustion field projects in 1953. They told of preliminary laboratory experiments with 1600°F peak combustion temperatures and 27 ft/day frontal advance rates at an air flux of 324 scf/hr-ft in a sand pack containing 9.6°API gravity crude oil.

Khitrin and Solovyeva (7) have experimented with homogeneous-heterogeneous combustion of carbon monoxide and they state that combustion can be carried out practically in a small grain bed of highly active catalyst, and that this surface, catalytic, or flameless combustion may lead to a significant increase in the intensity of combustion of a gas. This increase in combustion intensity is a result of the shorter combustion zone that occurs in surface combustion. They say that the length of the combustion zone changes very little with changing flow rate; therefore, the volume rate of heat release increases almost linearly with increasing flow rate.

They give an equation characterizing the combustion efficiency of homogeneous-heterogeneous combustion in the presence of a large excess of oxygen as:

$$K = 1 - e^{-(k_v + S_i k)x/w}$$

K = a factor characterizing combustion efficiency

k_v = a reaction velocity constant for the volume reaction, seconds^{-1}

k = a reaction velocity constant for the surface reaction, cm/sec

S_i = the specific surface of the catalyst, cm^2/cm^3

x = the length in the direction of flow, cm

w = the filtration rate, cm/sec

In the case where heterogeneous combustion is dominant, this equation becomes $K = 1 - e^{-S_i kx/w}$. It is noted from this equation that the efficiency of combustion is a direct function of the surface area per unit volume, which is inversely proportional to particle diameter, the surface reaction velocity, and the length of the flow path, and is an inverse function of flow rate.

CHAPTER III

EQUIPMENT

The equipment for this study, which is shown in Plates I and II, was grouped upon an equipment rack with the exception of the multipoint temperature recorder which was mounted upon a portable stand. The rack was constructed of pre-punched steel angles which could be easily modified for future work. The variable transformers, pressure gauges, control valves, orifice meters, and manometers were mounted on a plywood instrument panel. The flow diagram is shown in Figure 1.

Combustion Tube. The original combustion tube, as shown in Plate III, was constructed of 0.032-inch wall thickness, 2.0-inch o.d., SAE 321 stainless steel tubing 24 inches in length. Eight immersion type thermocouples were then radially mounted through the tube wall to indicate the centerline temperature, while eight contact type thermocouples were constructed and attached to the tube wall to indicate the wall temperatures. The immersion type thermocouples used with this tube were Minneapolis-Honeywell Megopak Type J iron-constantan with insulated wires which were sheathed in a 1/16-inch o.d. stainless tube. The contact type thermocouples were made by fusing together the ends of 24 gauge iron-constantan thermocouple wire which was enclosed in woven glass insulation.

PLATE I
INSTRUMENT PANEL

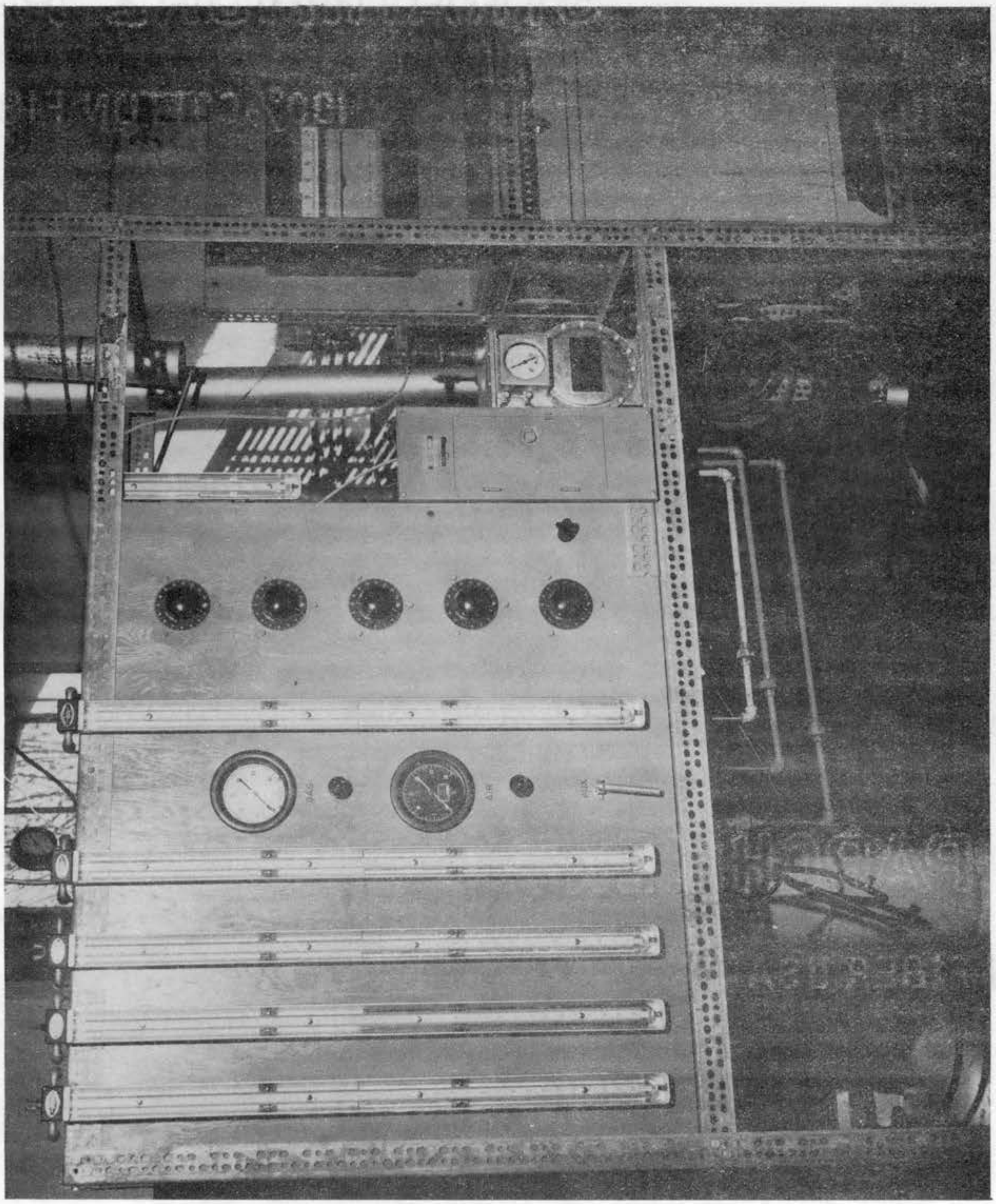


PLATE II
COMBUSTION EQUIPMENT

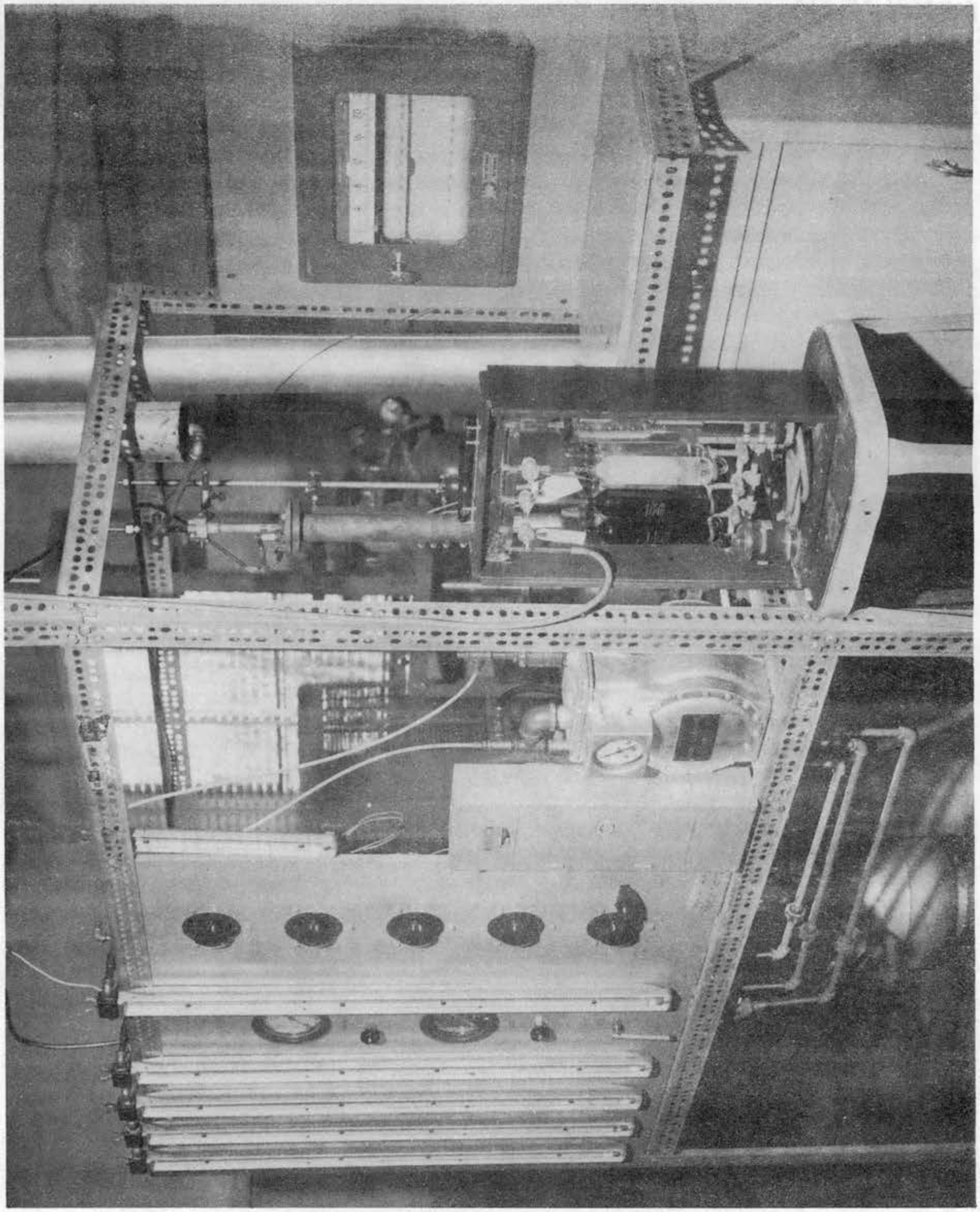
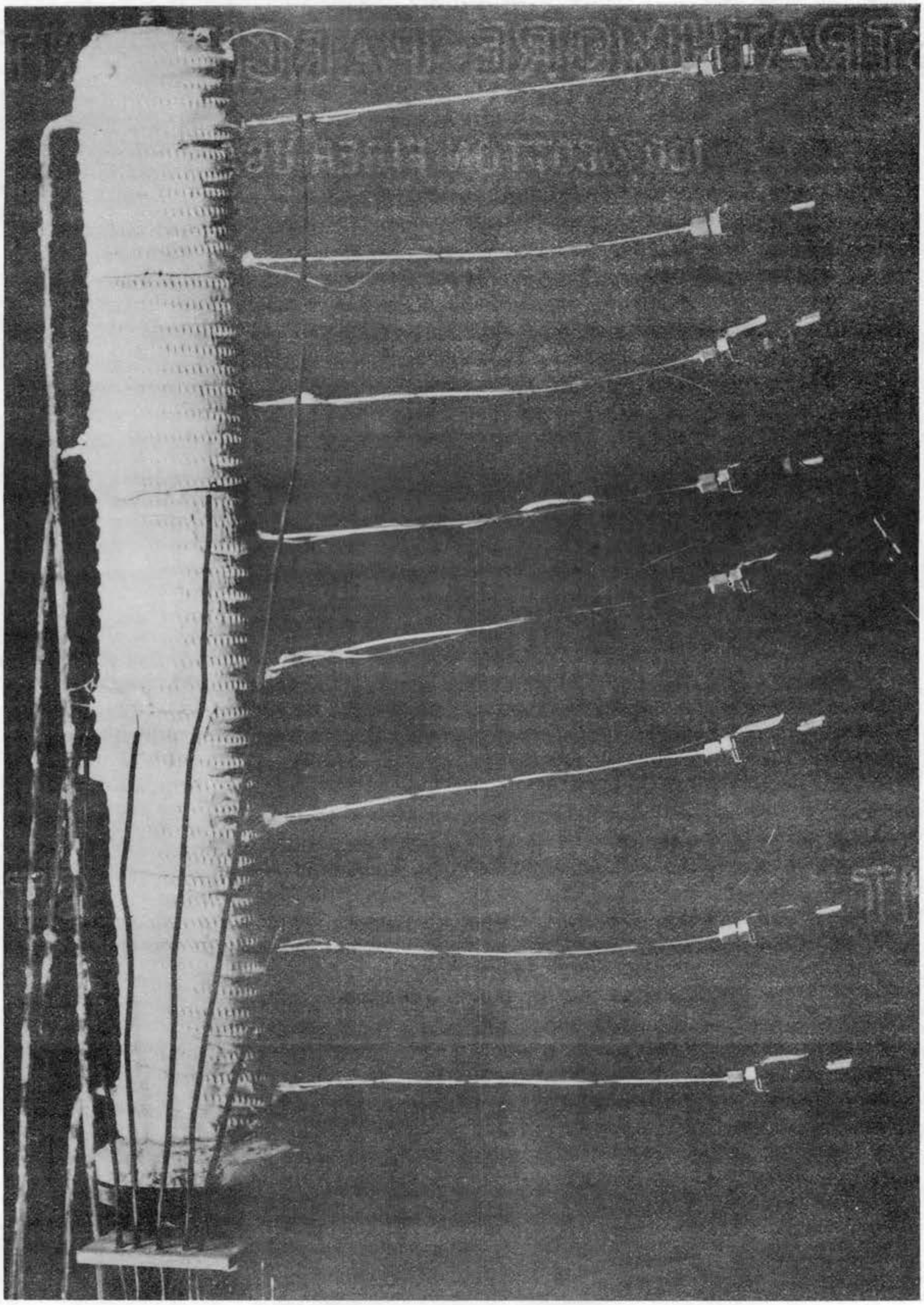


PLATE III
ORIGINAL COMBUSTION TUBE



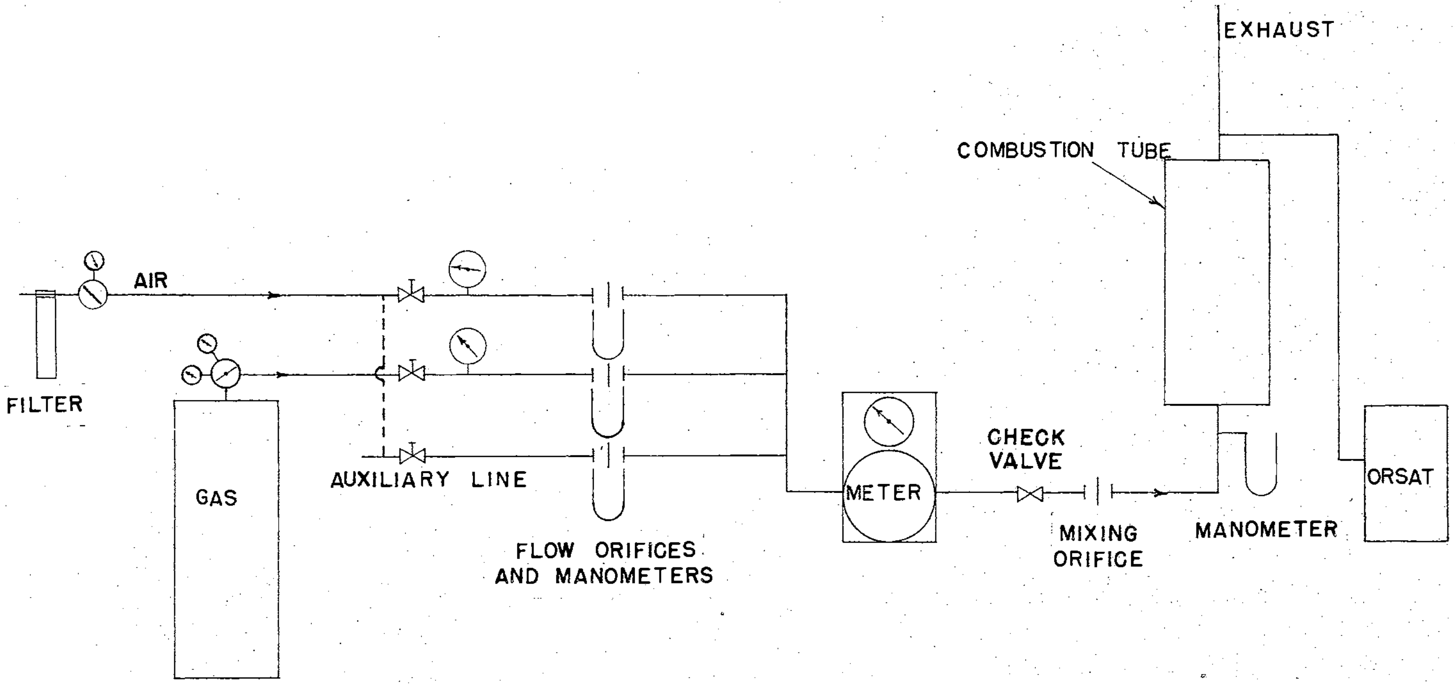


Figure 1. Flow Diagram

Four pressure taps of 3/16-inch steel tubing were also provided in order that the pressure drop could be measured across different sections of the tube and also to provide a means of extracting gas samples from different points along the tube during the combustion process.

The thermocouples and pressure taps were attached to the tube with silver solder to avoid possible difficulties involved in welding to the thin wall stainless tubing. The silver solder that was available had a melting temperature of 1200°F which was considered adequate in anticipation of temperatures near 1000°F. This later proved to be a mistake as temperatures above 1800°F were encountered.

The flow connections were attached to the bottom end of the tube by brazing, and were attached to the top end by a bolted flange in order that the sand pack might be easily replaced. In order to obtain a semi-adiabatic wall, the tube was coated with Saureisen No. 7 insulating cement and wound with five 18 gauge Nichrome V electrical resistance heaters with a power output of 1000 watts each. The coils were covered with a thin coat of Saureisen No. 6 cement to prevent sagging of the coils. Each heater covered an axial length of 4.5 inches and each was controlled through a separate 0-140 volt variable transformer.

The complete combustion tube was then placed in a section of 8-inch pipe, and the annulus was packed with diatomaceous earth insulation.

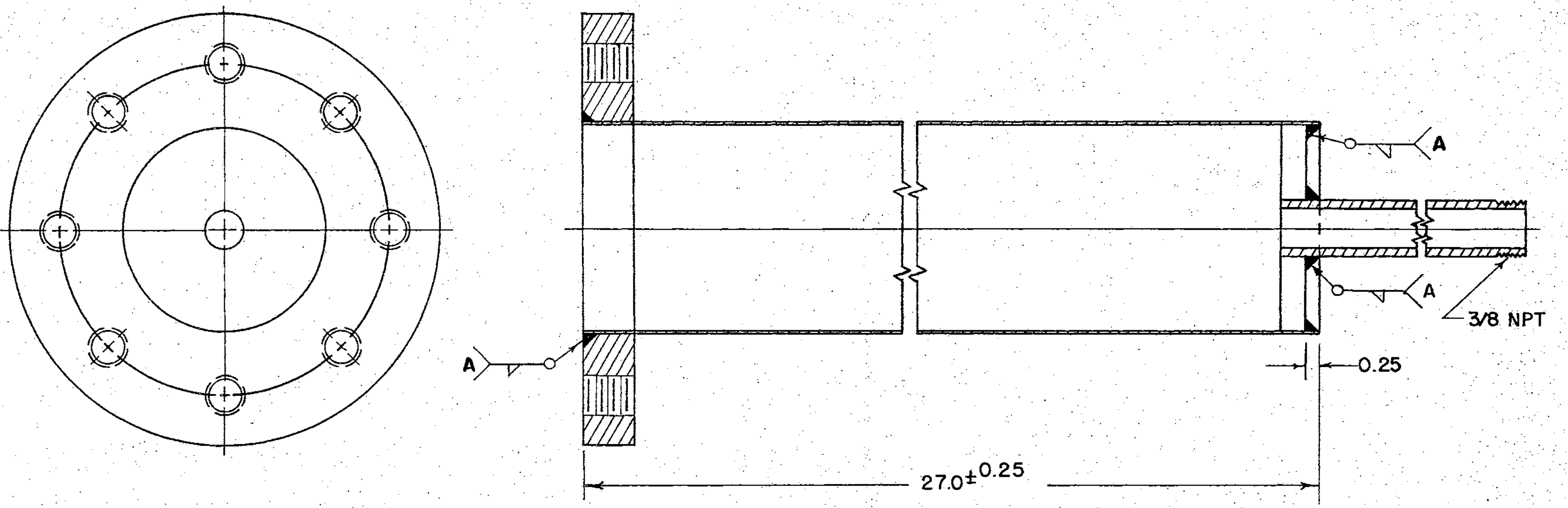
It was found that at temperatures above 900°F the dielectric strength of the insulating cement between the tube and the resistance coils had decreased enough that an electrical short-circuit was created which caused the heaters to burn out. This situation was corrected by coating the tube with 1/4 inch of Saureisen No. 6 cement, wrapping with asbestos paper, and covering this with 1/4 inch of cement before the resistance coils were wound upon the tube.

Some preliminary experimental work was done with a Vycor tube for reasons to be explained later. It was found that after two or three runs, in which the combustion zone was stopped at nearly the same point in the tube, that breakage of the tube occurred as the zone approached this point. This breakage is believed to be caused by a concentration of thermal stress in this section of the tube as a result of the high temperature gradient in the wall of the tube. This type of breakage occurred on two occasions, both near the point in the tube where previous runs had ended.

Because of the high temperatures (2000°F) observed with an optical pyrometer while experimenting in the Vycor tube, it was seen that it would be impractical to try to use the original tube with its silver-soldered connections and 1200°F iron-constantan thermocouples.

The final combustion tube design was of the same basic design as the first tube, being constructed of thin wall stainless steel tubing. Drawings for this tube are shown in Figures 2 and 3 and the assembly is shown in Plate IV. The radially mounted thermocouples and pressure taps were eliminated as were the Nichrome V resistance heaters which had a safe working temperature of 2200°F.

This tube was fitted with axially mounted, immersion type, Megopak Type K chromel-alumel thermocouples, and with contact mounted chromel-alumel thermocouples which were held in place by adjustable steel bands.



NOTES:

A. ARC WELD
B. SCALE: FULL

MATERIAL LIST:

1- FLANGE PLATE NO. 01
1- 27"- 2.0 o.d. x 0.032, TYPE 321 STAINLESS STEEL TUBING
1- 1/4" x 2.0" o.d. STAINLESS STEEL PLATE
1- 7.5"- 3/8" NOM. STEEL TUBING

OKLAHOMA STATE U.
PROJECT NO. 3242
MECHANICAL ENGINEERING
COMBUSTION TUBE
ENGR: E. WOODS DATE: 2-20-59
DRAWN BY: DUKE PLATE NO: 02

Figure 2. Combustion Tube

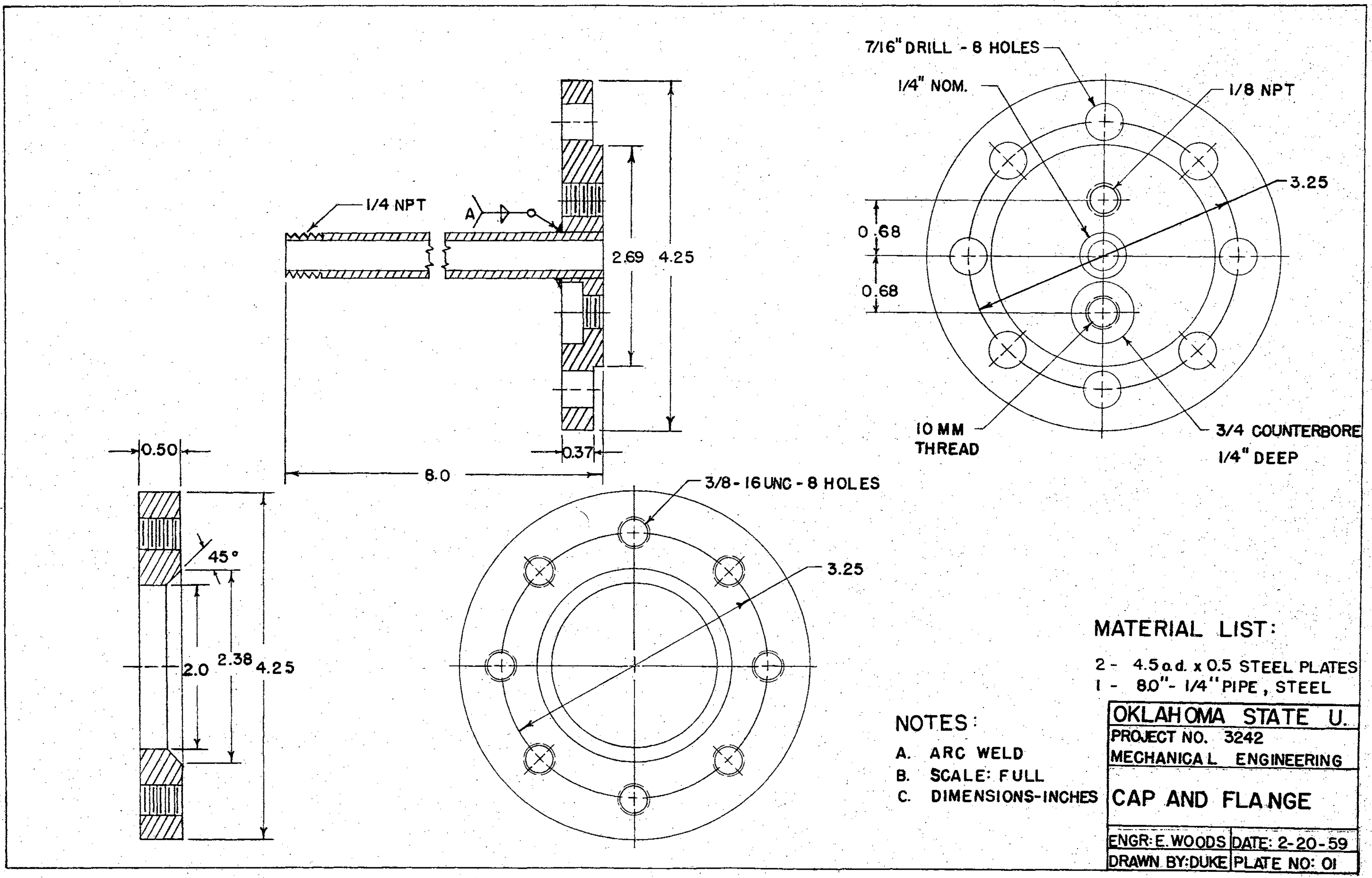
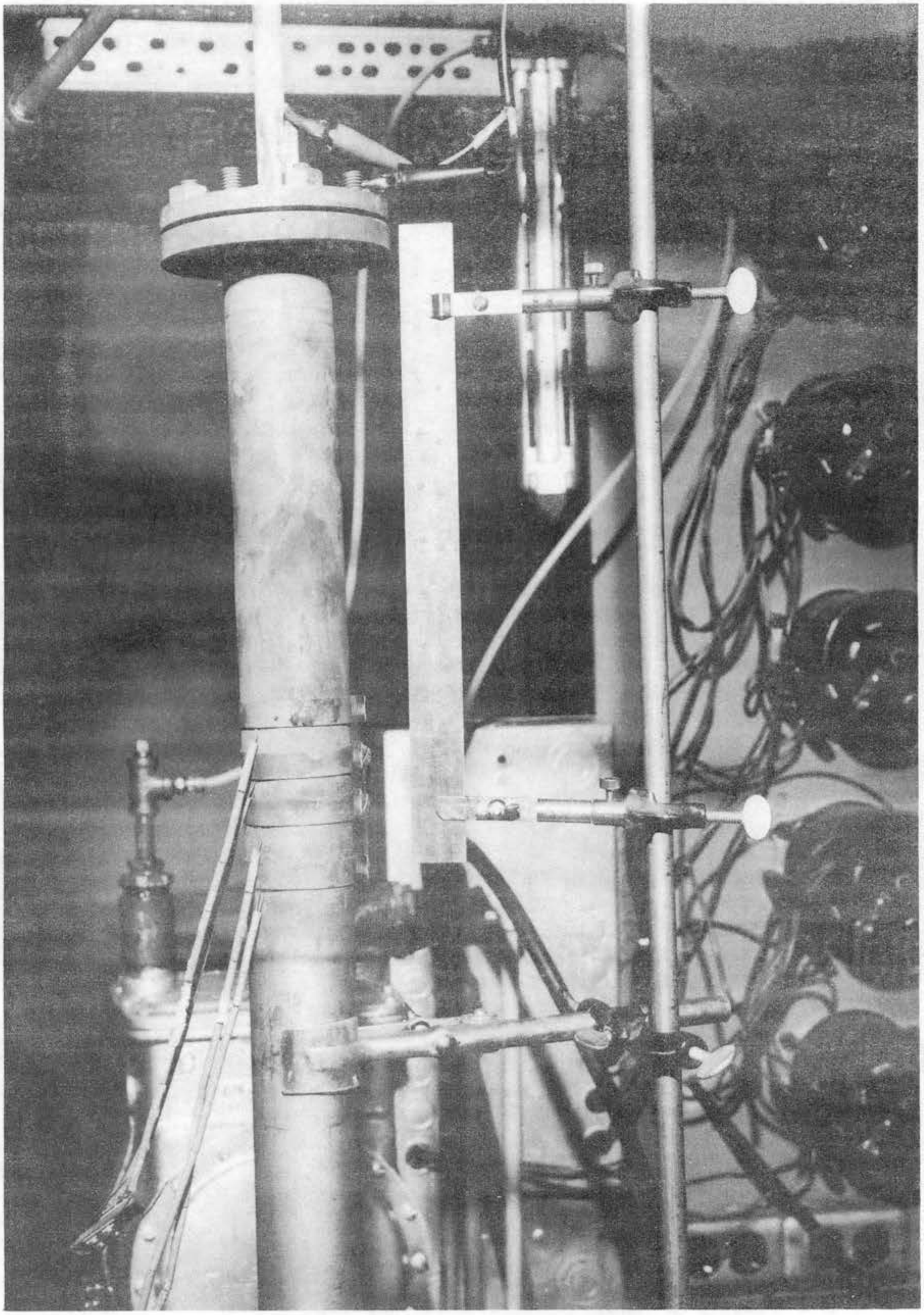


Figure 3. Combustion Tube Cap

PLATE IV
COMBUSTION TUBE ASSEMBLY



The bulk temperature of the combustion zone, in excess of 2400°F, exceeded the working temperature of the immersion type thermocouples and caused their failure. The attempt to measure the centerline temperatures was then abandoned.

Orifice Meters. The orifice meters for measuring the rate of flow of gas and air were constructed from Catawissa orifice unions for 1/4-inch pipe. The pipe leading to and away from the orifices was 0.374-inch i.d. stainless steel tubing.

The dry test meter used to calibrate the orifices was an American Model 5B Ironcase, serial no. 4984254, 25psi maximum working pressure meter of the bellows type. This meter was proved by the Tulsa Division of the American Meter Company and was also checked against an available wet test meter in the low flow ranges.

Ignitor. Attempts to ignite natural gas with a resistance coil were unsuccessful because of heat loss to the sand, and the space limitations made the use of a larger coil impractical.

A 10 mm. automotive spark plug mounted through the cap of the tube successfully served as an ignitor for the gas-air mixture. Electrical energy was supplied from a six-volt battery through an ignition coil.

Recorder. The temperature recorder was a Weston Model 6702, serial no. 200372, multipoint potentiometric type with a three second print cycle. It was originally equipped with a 0-1200°F range for Type J iron-constantan thermocouples. It was later converted to a temperature range of 0-2400°F using Type K chromel-alumel thermocouples.

Gas Analysis Apparatus. The exhaust gas was analyzed with the

Burrell Gas Analysis Apparatus no. 39-540 of the Orsat type which permitted the determination of the carbon dioxide, carbon monoxide, and oxygen content of the exhaust gas. The sample gas was cooled by passing it through a copper tube between the combustion tube and the Orsat apparatus.

CHAPTER IV

PROCEDURE

The procedure for making a test run was to pack the tube with 20-40 Ottawa sand up to six inches from the top of the tube. Then, approximately four inches of 3/16-inch o. d. alundum balls, along with a small amount of sand, was added. The remainder of the tube was filled to slightly above the top with 3/8-inch alundum balls. This was found to be sufficient to hold the sand pack in place. The cap was then bolted in place, and the contact type thermocouples were attached at a distance of 9, 10, 11, and 12 inches from the exhaust end of the combustion tube.

The inlet pressure for a predetermined flow rate of gas and air was estimated from data obtained from preliminary trial runs, and the desired differential pressure across the orifices was determined from the flow rate curves.

With the temperature recorder and ignitor on, a stoichiometric mixture of fuel and air was admitted to the combustion tube at a low flow rate. A sharp rise in exhaust gas temperature indicated ignition of the mixture and at this time the flow rate was increased to the desired rate.

Advance of the combustion zone was determined visually in the uninsulated tube by the use of a scale mounted parallel to the tube.

As the combustion zone approached the downstream thermocouple the gas rate was decreased for lean mixtures and increased for rich mixtures to attempt to stabilize the movement of the zone as indicated by the recording of a constant temperature at each of the points. If stabilization was not accomplished by the time that the zone reached the upstream thermocouple, the fuel-air ratio was reduced enough that the zone moved downstream to a point above the downstream thermocouple, and then a new trial gas rate was tried. For lean mixtures this procedure permitted the stabilization rate to be bracketed between mixtures that caused upward and downward movement. It is also possible to move the zone downstream with very rich mixtures and this permitted the rich stabilization rate to be bracketed, also, for flow rates in which the required mixture richness could be obtained without exceeding the maximum differential pressure for the gas orifice manometer.

CHAPTER V

RESULTS

The original intent of this study was to burn a methane-air mixture in a porous, unconsolidated sand pack under semi-adiabatic conditions.

After several unsuccessful attempts to propagate a methane-air combustion wave within the sand pack even at preheat temperatures of 1100°F, it was decided that commercial propane might be a more suitable fuel because of its lower ignition temperature of 920°F compared to 1200°F for methane.

This change of fuel, along with a change to an uninsulated Vycor tube, which permitted visual observation of the process, and the use of alundum balls to hold the sand surface in place, proved fruitful in that a combustion zone was successfully propagated within the sand pack.

At this time, observations of the combustion zone with an optical pyrometer indicated sand temperatures from 1880°F to 2250°F which was beyond the 1200°F range of the temperature recorder that was available and was also beyond the working limits of the original combustion tube because of the silver solder that had been used in its construction. The idea of maintaining the wall of the tube at a nearly adiabatic condition was also discarded since the maximum safe working temperature of the Nichrome V electrical resistance heaters was 2200°F.

The outside wall temperature of the Vycor tube was between 1000°F and 1500°F as indicated by temperature indicating pencils. Breakage of the tube occurred as has been described in the chapter on equipment.

Trial runs were made using an open-top stainless steel tube. These runs were successful so a tube with a bolted-flange cap with a 3/8-inch exhaust outlet was constructed, as has been previously described (Plate IV). This type of tube permitted the exhaust gas to be sampled and its temperature to be measured without contamination from outside air.

Rates of Advance. An insufficient quantity of data was obtained for stoichiometric mixtures to give quantitative results of the maximum rate of advance of the combustion zone as a function of fuel-air flux. However, it was observed that combustion zone velocity did increase as the flow rate was increased at constant fuel-air ratios and appeared to be the greatest near the stoichiometric mixture for a given flow rate.

Data obtained by direct observation of the advance of the zone during preliminary runs with commercial propane indicated combustion zone velocities of 21 to 24 ft/day for fuel-air fluxes of 4200 to 4600 scf/hr-ft^2 at nearly stoichiometric fuel-air ratios, and velocities of 14 to 16 ft/day at fluxes of 2560 scf/hr-ft^2. During one run in which the combustion zone was allowed to advance, then was deliberately extinguished by shutting off the gas flow, and then was relighted at the downstream end of the tube, a combustion zone velocity of 30 ft/day at a stoichiometric fuel-air flux of 2540 scf/hr-ft^2 was observed for a short period of time until the hot downstream section of the sand pack was cooled by convection. The minimum velocity of zero occurred at the stabilization limit.

In a forward combustion trial run it was not possible to advance the combustion zone within the sand pack as a result of stabilization of the upstream face of the zone at the sand face. The combustion zone became longer as the fuel-air rate was increased, but the above condition still persisted. Attempts to move the zone downstream by using very lean and very rich mixtures resulted in extinguishment of the zone.

Stabilization Limit. The term stabilization limit is used here to mean the fuel-air mixtures for which combustion is sustained, but for which the combustion zone neither advances nor recedes, relative to the combustion tube. It was found that definite limits exist for both rich and lean fuel-air mixtures as is shown in Figure 4, which is a plot of the data in Table I. These limits merge to a lower limit at an air flux of approximately 2080 scf/hr-ft^2 for the system under study. The fuel flux for the stabilization limit was found to increase from 70.2 to 110 scf/hr-ft^2 when the air flux was increased from 2362 to 6210 scf/hr-ft^2, although the percentage of gas decreased as the air rate was increased.

For fuel-air ratios that lie within the stabilization limits, the combustion zone moved upstream, and for mixtures in a region outside the stabilization limit the combustion zone moved downstream until an arbitrary limit was reached at which combustion ceased after twelve to fifteen minutes. This limit was determined only for lean mixtures, at a fuel rate which was equal to the stoichiometric fuel rate at the lower

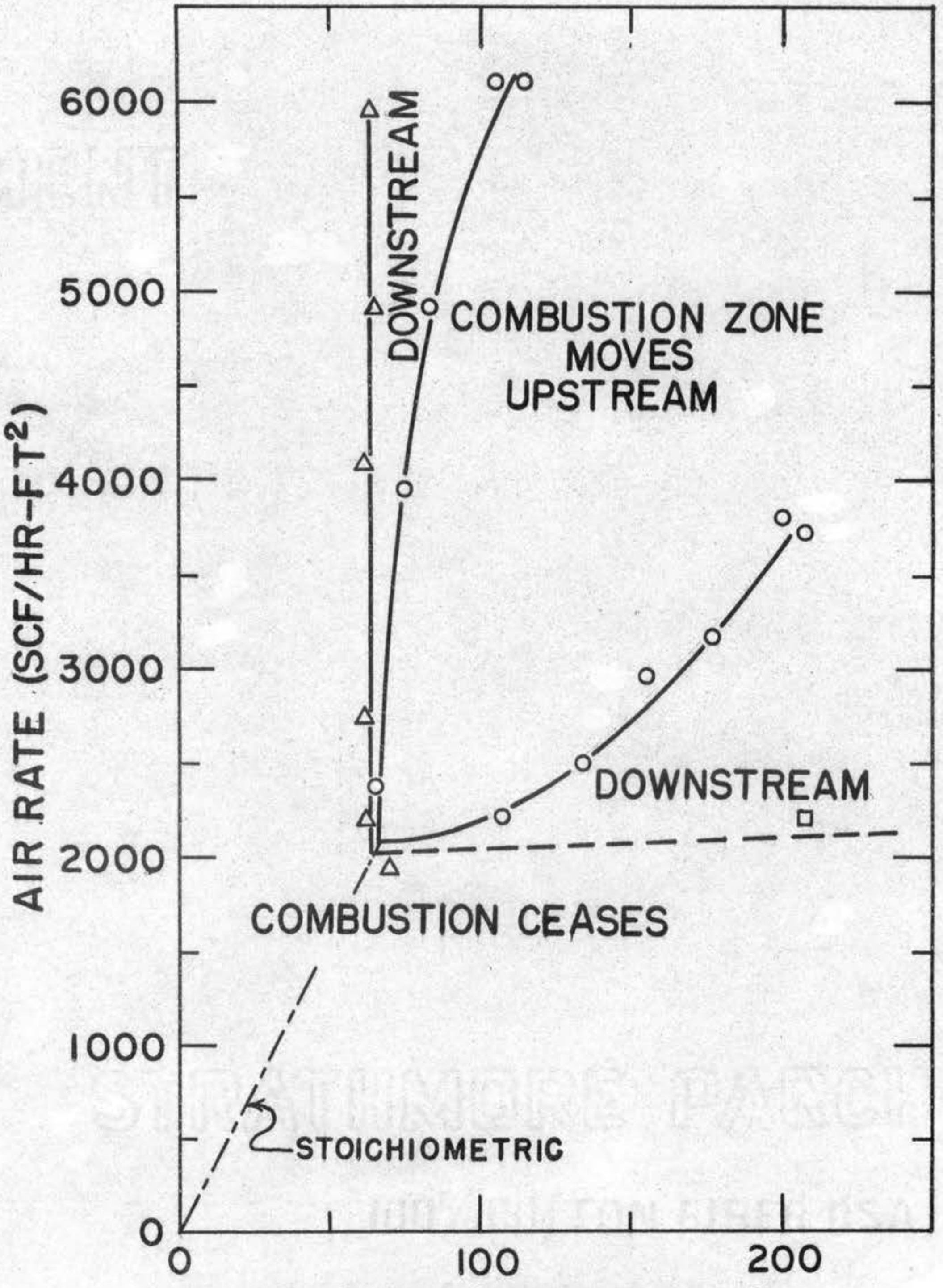


FIGURE 4 STABILIZATION LIMITS

○ STABILIZED

□ MOVES DOWNSTREAM

△ COMBUSTION CEASES

TABLE I

DATA

Run Number	u_A $\frac{scf}{hr-ft^2}$	u_g $\frac{scf}{hr-ft^2}$	$\frac{u_g \times 100}{u_A + u_g}$ %	Wall Temperature (Maximum) °F	Exhaust Temperature °F	Zone Movement*	H_C $\frac{Btu}{hr}$	$\frac{H_1 \times 100}{H_C}$ %
12-29-06	3967	75.7	1.87	1460	420	S	5310	89.0
12-30-02	6100	105.0	1.69	1600	700	DS	7720	77.6
12-30-04	6100	115.6	1.86	1600	750	US		
12-30-08	5963	67.9	1.13			O		
12-31-03	4082	66.5	1.61			O		
12-31-07	3807	199.5	4.97	1620	550	US		
12-31-08	3761	208.7	5.25	1700	530	DS		
12-31-14	2959	154.6	4.96	1600	435	S		
12-31-21	1950	71.2	3.52			O		
1-01-07	4931	83.0	1.66	1500	500	S	5830	84.5
1-01-10	4931	70.6	1.41			O		
1-02-02	2201	69.3	3.05			O		
1-02-06	2362	70.2	2.89	1340	320	S	4920	94.5
1-02-09	2959	68.3	2.26			O		

* DS -- Downstream, US -- Upstream, S -- Stabilized, O -- Out

TABLE I (Cont'd)

Run Number	u_A $\frac{\text{scf}}{\text{hr-ft}^2}$	u_g $\frac{\text{scf}}{\text{hr-ft}^2}$	$\frac{u_g \times 100}{u_A + u_g}$ %	Wall Temperature (Maximum) °F	Exhaust Temperature °F	Zone Movement*	H_C $\frac{\text{Btu}}{\text{hr}}$	$\frac{H_1 \times 100}{\bar{H}_C}$ %
1-05-04	2201	207.3	8.61	1000	460	DS		
1-05-06	2110	382.6	15.36			O		
1-06-03	2614	334.9	11.35			O		
1-11-03	3165	178.4	5.34	1550	620	S		
1-11-04	2477	135.3	5.18	1450	450	S		
1-11-05	2201	108.3	4.68	1370	360	S		

stabilization limit as may be seen from Figure 4. It was not possible to obtain this limit for rich mixtures because of the inability to obtain the necessary vapor rate at the required pressure from the normal butane container.

Temperatures. The exhaust gas temperatures were measured for the purpose of obtaining a heat balance on the combustion process and were found to increase with flow rate from 320°F at the minimum flux rate to 725°F at the 6000 scf/hr-ft^2 lean mixture stabilization limit. These temperatures were measured with a chromel-alumel thermocouple in the exhaust line and were recorded every 24 seconds by a multipoint recorder. The combustion tube wall temperatures given in Table I were measured to determine when stabilization was accomplished and to give an indication of how the temperature varied with flow rate. It should be emphasized that these are not bulk temperatures of the combustion zone which exceeded 2400°F as has been previously explained.

Figure 5 shows the surface temperature of the tube for fluxes at which stabilization occurred. These temperatures would be expected to increase with increasing flux as was observed since an increased rate of heat release was necessary to maintain stabilization. It should not be inferred from this that the maximum combustion zone temperature increased proportionally because it would be possible for the wall temperature to increase as a result of the increased volumetric rate of heat release with a subsequent change in the temperature profile.

The exhaust gas temperature profile for lean mixtures also shows a temperature increase with increasing flux. However, a smooth curve cannot

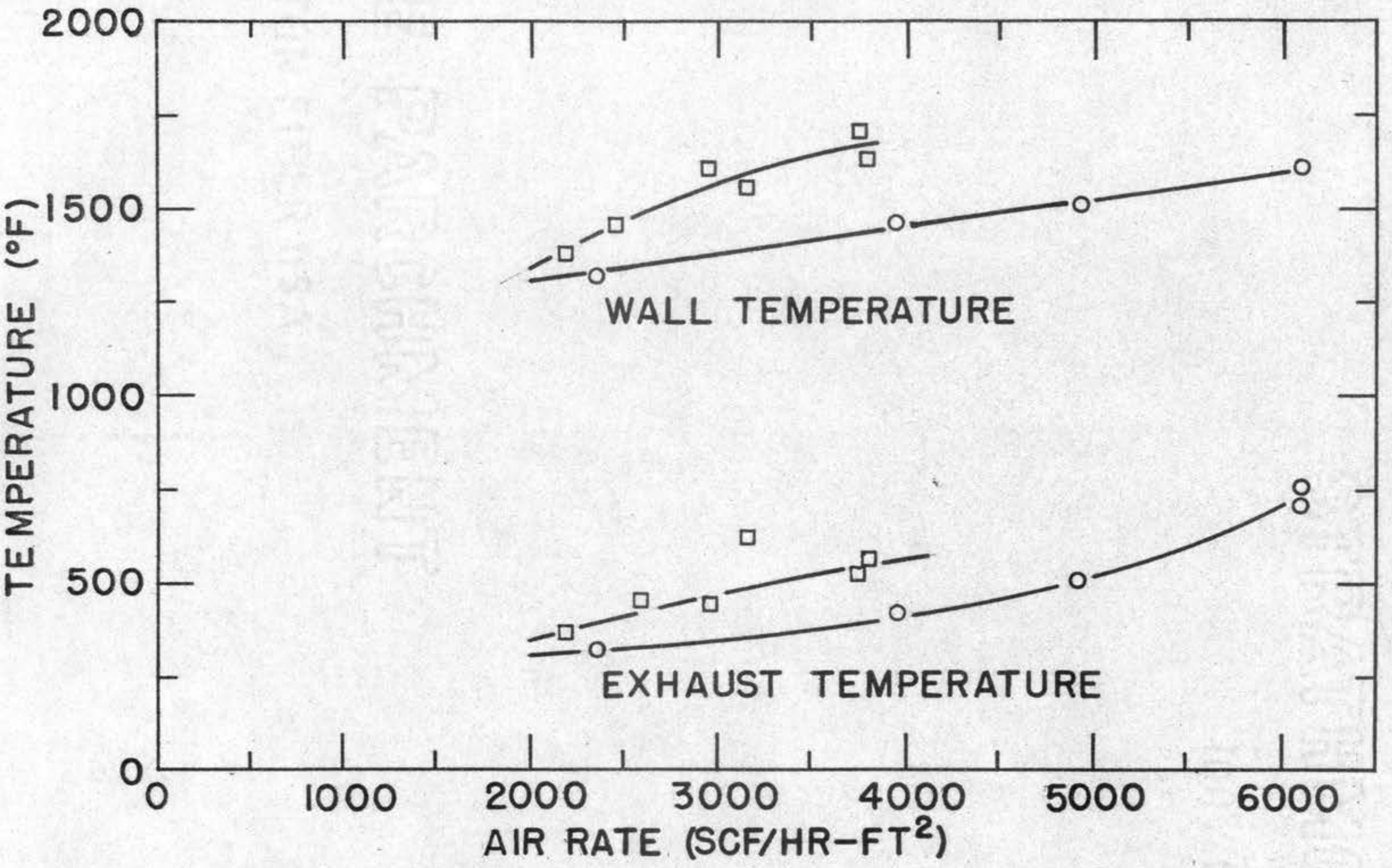


FIGURE 5 WALL AND EXHAUST TEMPERATURES AT STABILIZATION

○ LEAN MIXTURES
□ RICH MIXTURES

be drawn through the rich mixture exhaust gas temperatures because it was not possible to maintain high butane vapor rates for a sufficient period of time to permit exhaust gas temperature stabilization, although combustion zone stabilization did occur.

An interesting note in the temperature distribution was the high thermal gradient at the upstream face of the combustion zone. It was possible to touch the Vycor or the stainless steel tubes without discomfort as close as 1½ inches upstream from the red hot (1200°F) leading edge of the combustion zone. For this reason it is believed that any transient temperature effect would have very little effect upon the use of temperature profiles to measure advance rates in this type of system.

Porous Material. The 20-40 mesh Ottawa fracturing sand used for a porous matrix in this study appeared to be relatively inactive as far as catalytic action was concerned, although slight color changes from its original ivory color did occur at times; however, no chemical analysis was made. Passing fuel and air through a heated bed resulted in a change to a light reddish brown color, and after the combustion zone had passed through the sand, it had a bleached white appearance. Slight consolidation of this sand occurred at times. It readily disintegrated when handled.

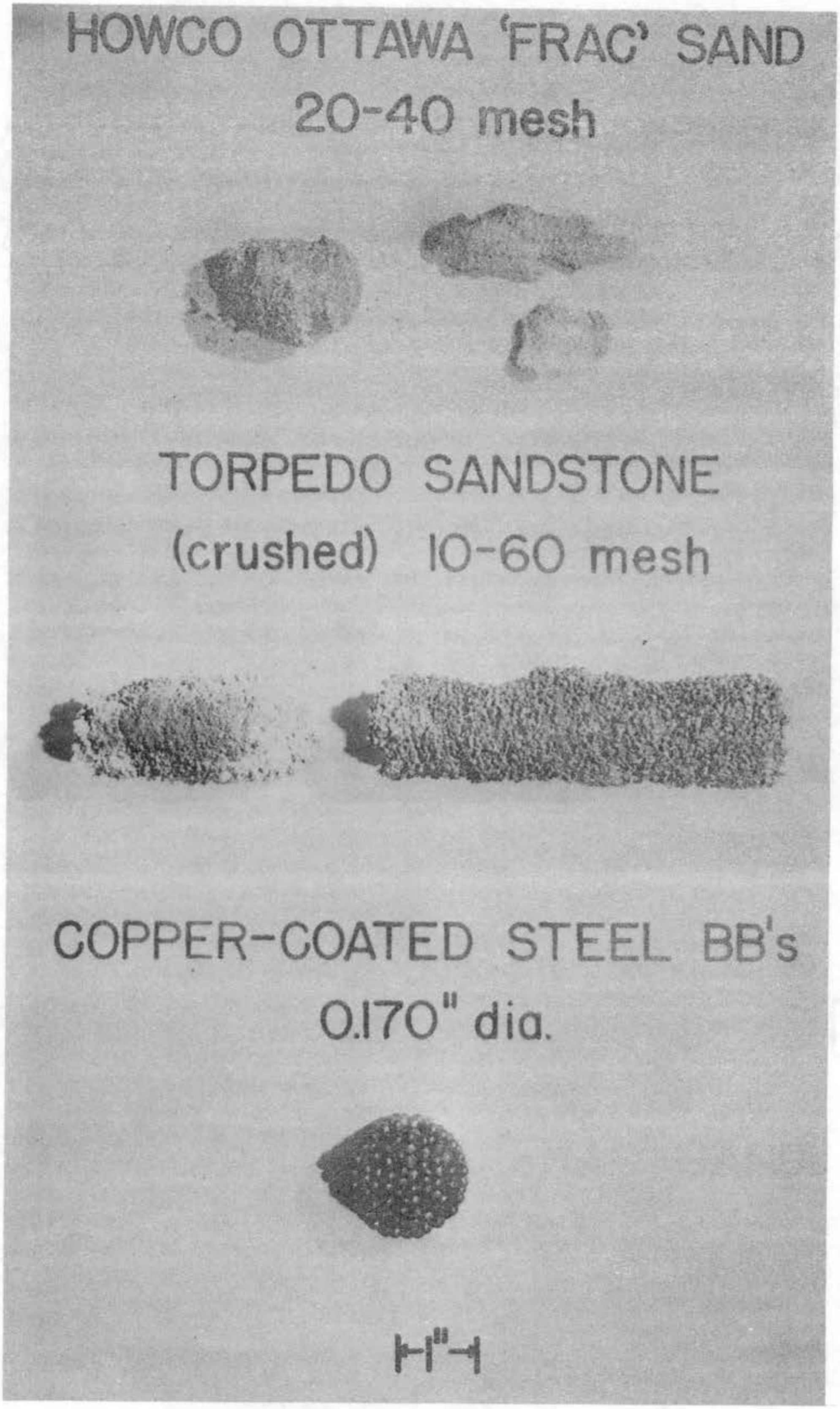
The porosity of the sand when packed was found to average 35.7 per cent and the air permeability of the porous material in the tube as packed was 126 darcys; however, it should be noted here that the pressure drop was measured across the tube length which included 5¼ inches of 1/16 to 3/16-inch alundum balls and 3/4 inch of 3/8-inch alundum balls on top of the pack of 22½ inches of Ottawa sand. Van Poolen (8) gives the porosity of this sand as 35 per cent and the permeability as 121 darcys.

During preliminary runs with commercial propane, some crushed Torpedo sand ranging in size from 10 to 60 mesh was used for a porous bed. It was found that this sand was firmly consolidated after the combustion zone had passed through it, as may be observed in Plate V.

Copper coated steel BB's were used in an early attempt to hold the sand face in place. It was found that these also became well consolidated when subjected to the combustion zone temperatures which exceeded the 1980°F melting point of copper. This mass of consolidated material is also shown in Plate V.

The high thermal gradients in the sand pack were indicative of low thermal conductivity as might be expected in an unconsolidated material.

PLATE V
CONSOLIDATED POROUS MATERIAL



CHAPTER VI

SUMMARY AND CONCLUSIONS

Combustion Zone Movement. The combustion zone may be stabilized or moved up or down stream by controlling the rate of heat generation within the system. When the rate at which heat is produced is equal to the rate of heat loss, the combustion zone becomes stabilized. If the heat generated is less than the heat loss then the heat transfer downstream by convection at the combustion front exceeds the heat transfer upstream by radiation and conduction, and the combustion zone is forced to move upstream into the zone that has been heated by the exhaust gases. If the reverse is true, that is, if the rate of heat generation exceeds the rate of heat loss, then the zone moves upstream at a rate which is dependent upon the quantity of excess heat that is supplied and upon the thermal diffusivity of the porous matrix.

It may be noted from Figure 4 that the fuel rate for stabilization increases with increasing air flux. This is thought to be the result of the higher temperature gradient which was necessary to maintain the heat transfer equilibrium at the combustion zone front which is necessary for stabilization. This higher temperature resulted in higher heat losses from the uninsulated tube, and also, more fuel was required to heat the increased quantity of excess air to the exhaust temperature.

A reduction in the rate of heat loss from the tube wall could be expected to reduce the required fuel rate at any given air flux.

The rich mixture stabilization limit may also be assumed to occur when heat transfer equilibrium is established at the combustion zone front and would, therefore, be a function of the completeness of the combustion reaction instead of being dependent upon the fuel rate as was the lean limit. This would suggest a correlation of the air flux at the stabilization limit as a function of $CO_2/CO_2 + CO$. However, insufficient exhaust gas analysis data was obtained during this study to permit a correlation of this type. In a system of reduced heat loss, the necessary rate of heat release could be obtained with a higher percentage of carbon monoxide in the exhaust gas which would tend to increase the allowable percentage of gas for a given air flux, or reduce the air flux for a given gas rate.

Air and Fuel Flux. It may be observed from Figure 4 that the minimum fuel flux as well as the minimum total flux occurs at a stoichiometric mixture as would be expected since the maximum rate of heat release per unit volume is obtained when the combustion reaction approaches completeness and the excess air is a minimum. It is a reasonable assumption that if external heat losses were reduced the minimum total flux would occur at a stoichiometric mixture at a lower fuel flux.

In view of the above discussion, a reduction in external heat loss would be expected to increase the range of fuel flux for which the combustion zone would advance as well as decrease the minimum total flux.

It may be noted that the minimum air flux of 2080 scf/hr-ft^2 is much higher than the 9.0 scf/hr-ft^2 reported by Martin, et al (3) in their experiments with a system containing heavy crudes; therefore, justification of this value is desirable.

Calculations of the heating value per pound of air supplied for stoichiometric mixtures of air and paraffin hydrocarbons ranging from methane to octadecane ($C_{18}H_{38}$, melting and boiling point 82°F and 586°F respectively) indicate a maximum deviation of 20 Btu/lb of air from an average of 1270 Btu/lb of air supplied. The heating value per pound of air supplied for stoichiometric mixtures with pentatriacontane ($C_{35}H_{72}$, melting point - 176°F, boiling point - 628°F) also agrees with this value. However, data were not available for hydrocarbons between octadecane and pentatricontane. (9). On the basis of this constant heating value for a stoichiometric mixture of fuel and air, it may be seen that if stabilization in gaseous fuel systems or minimum rate of advance in liquid and solid fuel systems is to be a function of the rate of heat release, then the minimum air flux must be independent of the heating value of the paraffin hydrocarbon fuel, at least for the range indicated above.

The results of a heat balance on the combustion tube for lean mixtures which were based upon the reaction $C_4H_{10} + (6.5+0.21X)O_2 + (24.5+0.79X)N_2 = 4CO_2 + 5H_2O + 0.21XO_2 + (24.5+0.79X)N_2$, where X is the volume of excess air, are given in Figure 5. It may be observed from this figure that the heat loss from the tube wall approaches a minimum value of 4650 Btu/hr at the minimum total flux, and it can be

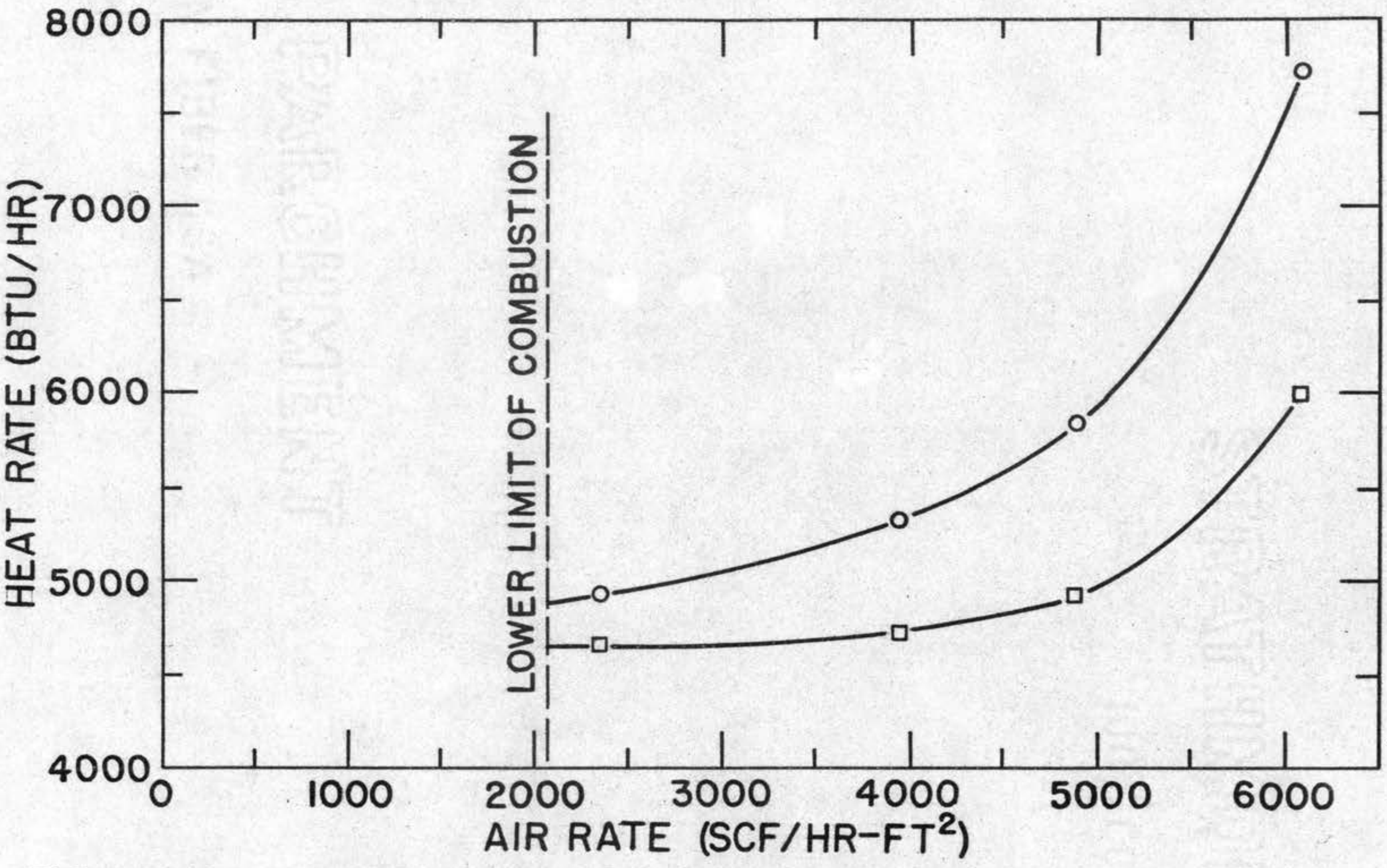


FIGURE 6 HEAT RATE AT STABILIZATION

○ HEAT GENERATED

□ HEAT LOSS

calculated that the exhaust heat loss for this flux was 400 Btu/hr. By assuming that the combustion tube had adiabatic walls, such as the systems used by Reed (1) and Martin (3), the rate of heat generation at the lower stabilization limit could be reduced by approximately 4650 Btu/hr. In this case, the fuel flux would be reduced from 70.2 to 5.45 scf/hr-ft^2 and the air flux would be reduced from 2170 to 168 scf/hr-ft^2 which is within the range investigated in the combustion of tar sands.

It should also be realized that even though the weight of air required for a given heat release is independent of the fuel, the rate of heat generation for sustained combustion may vary for different hydrocarbons which would in turn change the required fuel and air fluxes. For instance, Martin, et al (3) and Reed, et al (1) sustained the combustion of heavy crude oils and tar sands at temperatures as low as 500°F to 600°F whereas the self-ignition temperature of normal butane is approximately 960°F and of methane is 1346°F. (10). The necessity of maintaining a higher combustion zone temperature to permit ignition of the mixture would mean that higher exhaust gas temperatures would be encountered with a resulting larger exhaust gas heat loss, and also, the quantity of heat required to raise the temperature of the porous matrix to this temperature increases as a result of its heat capacity which also increases with increasing temperature. All of this results in a higher fuel and air flux for sustained combustion which in turn increases the volume of exhaust products to be heated to this higher exhaust temperature. Also worthy of note is the fact that as external heat loss is reduced, the necessity of having complete combustion becomes less important since the desired heating rate can be maintained with a higher percentage of carbon monoxide in the exhaust gas which further reduces the minimum air flux required for sustained combustion.

CHAPTER VII

RECOMMENDATIONS FOR FUTURE STUDY

An interesting avenue of future study in the field of in situ combustion would be to determine the effect of supplying gas along with the air to the combustion zone in a crude oil saturated sand pack.

It would also be interesting to determine the limits of combustion, as well as mixtures for constant combustion zone velocity, for the combustion of different hydrocarbons in a consolidated core. The effects of porosity, permeability, and increased pressure might also be studied.

It is suggested that the use of a combustion tube with controlled heat loss, and a complete analysis of the exhaust gas be seriously considered in future studies. The possibility of obtaining centerline temperatures by the use of platinum-platinum-rhodium thermocouples also exists. This would permit a better analysis of the system on the basis of heat transfer and temperature distribution.

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