CoA Memo. No. 169

November, 1968

THE COLLEGE OF AERONAUTICS

CRANFIELD

An investigation of combustion instability in aircraft-engine reheat systems

- by -

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SUMMARY

The principal objective of this study was to examine experimentally the effects of upstream temperature, velocity, gutter blockage, tailpipe length, and main and pilot fuel flows, on the form of combustion instability encountered in aircraft reheat systems which is sometimes referred to as 'buzz'. Tests were carried out at atmospheric pressure for upstream temperatures of between 200 and 500°C, and upstream velocities ranging from 140 to 200 ft/sec. Three values of stabilizer blockage were employed, namely 25, 30 and 35%. The tailpipe length was varied between 9 and 45 inches. Auto-correlation techniques were used in the frequency analysis of the buzz waveforms.

It was found that a certain minimum tailpipe length is necessary in order to produce buzz which is then strengthened as the tailpipe length is increased. Buzz also becomes more pronounced with an increase in gas velocity but stabilizer blockage appears to have no discernible effect.

The results of frequency measurements suggest that the mode of oscillation is primarily longitudinal. Buzz frequency is increased by an increase in upstream gas temperature and by a reduction in tailpipe length.

From analysis of the experimental data it is suggested that the phenomenon of buzz may be attributed directly to the locally injected pilot fuel flow. Buzz may be eliminated either by terminating the pilot fuel flow or by increasing its flow rate to a fairly high value.

Finally a buzz mechanism is proposed that is consistent with all the experimental observations.

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INTRODUCTION

In the design and development of reheat combustion systems a main objective is to achieve high values of propulsive and combustion efficiencies over a wide range of thrust boosts. Now a high propulsive efficiency entails uniformity of temperature and velocity at the nozzle exit, a condition that can only be attained by distributing the fuel and combustion process evenly across the jet pipe. This is simple to arrange when the thrust boost is high and mixture strengths are close to stoichiometric, but low thrust boosts cannot then be obtained because, with reduction in fuel flow, a point is soon reached when the overall mixture strength is too weak to sustain combustion.

As a means of overcoming this problem Rolls Royce have developed a novel form of reheat system in which fuel is supplied locally to the recirculation zones downstream of the gutters. By suitable gutter design it is possible to achieve a high combustion efficiency and, at the same time, obtain fairly uniform conditions of temperature and velocity at the nozzle and hence a high propulsive efficiency. At light-up, combustion is initiated in the recirculation zones of all gutters and is maintained by the locally-injected 'pilot' fuel whenever reheat is in operation. Higher thrust boosts are obtained by introducing 'filler' or 'main' fuel into the air flowing in between the gutters.

This 'distributed burning' type of reheat system, featuring piloted flame stabilizers, has been used for many years with considerable success. However, when operating at high thrust boosts it is characterized by the occurrence of a phenomenon known as 'buzz'. Buzz appears to be an oscillating pressure wave of low frequency that is manifested audibly as a harsh sound, much louder and quite distinct from the combustion noise normally present in an afterburner. Under some conditions the pressure waves associated with strong buzz can be so severe as to blow the flame off the gutter and extinguish the afterburner. The effect of buzz in a by-pass engine is most devastating when the pressure waves travel upstream through the by-pass duct and stall the L.P. compressor. The reduced air supply through the H.P. compressor starves the combustion chamber of air, causing the engine to flame-out.

Buzz is a relatively new hazard about which little is known. It was decided therefore to examine experimentally the effect on buzz of as many design and operating variables as the available rig facilities would allow.

The parameters studied were:

(a) Pilot fuel flow
(b) Main fuel flow
(c) Upstream gas temperature
(d) Upstream gas velocity
(e) Gutter blockage
(f) Tailpipe (burning) length

The purpose of the investigation was twofold:

(a) To discover those parameters which have most effect on buzz, with a view to providing a short-term remedy for the buzz problems encountered in present-day engines.

(b) To suggest a mechanism for buzz that is consistent with all the experimental observations, for consideration in the design of any future afterburner system employing piloted gutters.

GENERAL DESCRIPTION OF TEST RIG

The experimental rig employed is shown diagrammatically in figure 1. The flameholder, in the form of a circular Vee-gutter with its apex pointing upstream, was mounted in a steel duct of circular cross-section. Air was supplied from a three-stage centrifugal fan. In order to provide a variable air temperature at the gutter, a preheat combustion chamber was coupled to the fan exit. The preheater fuel was kerosine, although a gaseous propane torch-igniter was used to effect light-up. The fuel to the main-stream injectors and to the gutter pilot was propane.

Two temperature probes were located in the duct, one immediately downstream of the preheater, and the other just upstream of the flameholder. The duct was well lagged with asbestos tape between the preheater and the flameholder, so these two temperatures were effectively the same except for a slight temperature drop due to propane addition at the mainstream injector. Air metering was provided by a Venturi intake to the fan, the static depression at the throat being measured by means of a water manometer. Uniform conditions of velocity and fuel distribution were obtained by the use of a specially designed fuel injector supplemented by a mixing device located about 3 feet upstream of the stabilizer. Ignition of the flame was accomplished by means of a spark igniter mounted inside the lip of the gutter. A window of heat resistant glass was fitted in the final section of the duct to permit observations of flame initiation and blow off.

Three different stabilizers were used. They were all goemetrically similar Vee-gutters of 25, 30 and 35% blockage. Inside each gutter was a sintered metal plate through which propane fuel could be supplied to the recirculation zone from three symmetrically arranged stainless steel pipes welded to each gutter. These three pipes also supported the gutter in a circular flange of the same diameter as the pipe.

The tailpipe consisted of a number of flanged sections which could be combined to give burning lengths of 9.2, 21.3, 33.25, and 45 inches. The first section always contained the heat resistant window and igniter assembly.

PRELIMINARY RIG TESTS

In a preliminary series of tests, carried out mainly in order to check the instrumentation and develop suitable rig test procedures, the effect of varying tailpipe length on stability limits was investigated. All the runs to establish the weak and rich stability limits were carried out using main fuel only, the pilot being used solely for lighting up a flame on the gutter. The pilot fuel was turned off as soon as the main flow was sufficient to maintain stable combustion.

Buzz was not detected audibly at any stage in this initial phase of the test programme, i.e. with blockages from 25 to 42%, tailpipe lengths from 9.2 to 45 inches and upstream velocities from 100 to 300 ft/sec. The results obtained with 25% blockage are shown in figure 2, and illustrate that the main effect of an increase in pipe length is to contract the rich extinction limit. This is an important practical conclusion because it means that when a reheat jet pipe is made longer in order to improve combustion efficiency, the maximum thrust augmentation may actually be reduced due to the rich extinction occurring at a lower fuel/air ratio.

Of equal importance, however, is the fact that buzz was not detected during this initial phase of the test programme. All subsequent tests confirmed the tentative conclusion reached at this time, namely, that buzz does not occur in the absence of a local supply of pilot fuel to the stabilizer.

TEST PROCEDURE FOR INVESTIGATION OF BUZZ

In the first series of experiments the rig test procedure was as follows. After starting the fan and lighting up the preheat chamber, a value of air mass flow was selected and the temperature established at the desired level. Then, by opening the pilot propane injection valve and igniting, a flame was held on the gutter. The pilot flow was adjusted to the desired setting and the main fuel flow gradually increased. If buzz occurred the main fuel flow was increased further until either buzz ceased, or the flame blew off the gutter. If this point denoted 'end-of-buzz' the main fuel flow was increased still further until a rich extinction occurred. Main and pilot fuel flow readings were taken at 'start of buzz', 'end of buzz' and/or the rich extinction point. This procedure was repeated for a rnage of pilot flows from zero to a flow at which a rich extinction occurred with pilot fuel alone. The general pattern of the results obtained is shown in Figure 3.

Sometimes it was difficult to detect the onset of buzz above the generally high noise of the rig, especially when buzz was very weak.

However it was observed that as buzz started the level of the water manometer fell immediately to the rich extinction value; this occurrence was sometimes used to indicate the 'start-of-buzz'.

Similarly it was not always possible to detect an 'end-of-buzz' point audibly because sometimes it was masked by the rough combustion noise normally encountered near rich extinction.

When very low pilot flows were used the flame could not be established by pilot flow alone. It was then necessary to light up normally, open the main flow valve and progressively reduce the pilot flow to its desired setting as the main flow was increased.

RESULTS

Figure 3 shows a typical stability loop drawn as a graph of pilot fuel flow versus main fuel flow, and illustrates the various combustion regions encountered during the operation of the rig. The experimental procedure employed to construct this figure is demonstrated in figure 4. When the pilot flow was set to A and the main flow increased steadily to A1, no buzz was detected and stable combustion was observed right up to the rough running associated with rich extinction. Setting the pilot flow to B and then increasing the main flow produced a weak buzz between B1 and B2. Beyond B2 there was no audible buzz and combustion was stable up to the point of rich extinction, B3.

As the pilot fuel flow was reduced from B to C the strength of buzz gradually increased, with the 'start-of-buzz' and 'end-of-buzz' points occurring at progressively higher main flows. Over this range the pilot fuel flow had very little effect on the rich extinction point.

As the pilot flow was further reduced below C buzz gradually decreased in strength. With zero pilot flow there was stable combustion without buzz right up to the point of rich extinction.

Under more arduous combustion conditions, e.g. at lower temperatures or high velocities, the curves of pilot/main fuel flow all had the same general characteristics of the graph shown in figure 5. This figure is basically the same as figure 4 except that there is no longer a region of stable combustion beyond the 'end of buzz' line, i.e. the lines denoting 'end of buzz' and 'blow off' now coincide.

From figures 3, 4 and 5 it is clear that the effect of pilot fuel on flame stability is twofold.

(1) Except at high pilot fuel flows the rich extinction limit is seriously curtailed and the attainable thrust boost thereby markedly reduced.

(2) Inside the rich extinction limit lies a region of strong buzz. For all practical purposes the line representing 'start of buzz' marks the limit of useful operation of the system.

Only at zero or high pilot fuel flows does the system exhibit the wide stability limits normally associated with simple Vee gutter stabilizers.

From these figures and many others described in reference 1 the following conclusions may be drawn

(a) The phenomenon of 'buzz' may be attributed directly to the locally injected pilot fuel. In the absence of pilot fuel it is impossible to obtain buzz, although combustion can be rough and noisy near the rich extinction limit.

(b) It is impossible to initiate buzz when the pilot fuel flow is high.

(This seems to be the most practical method of avoiding buzz with present-day reheat systems employing piloted gutters).

(c) The closer together are the lines representing 'start of buzz' and 'end of buzz' the greater is the strength of buzz.

(d) Strong buzz causes the flame to blow off the gutter well inside the normal rich extinction limit.

(e) Under conditions of weak buzz, when a blow-off does not occur, it is possible to obtain stable combustion between the 'end-of-buzz' and the rich extinction point.

(f) Buzz does not occur if the tailpipe length is short. Buzz may be generated by an increase in tailpipe length and becomes progressively stronger with further increase in tailpipe length.

(g) Buzz becomes stronger with increase in gas velocity.

(h) A change in gutter width has no discernible effect on buzz.

MEASUREMENTS OF FREQUENCY AND NOISE LEVEL

Both audio and visual recordings of buzz were made from which the effects of tailpipe length and upstream gas temperature on buzz frequency were found. Also measured on a number of afterburner configurations was the increase in decibels in moving from a non-buzzing to a buzzing condition.

The recording and subsequent analysis were made in three separate phases

Phase I - Sound recording
Phase II - Photographic analysis
Phase III - Frequency analysis

Phase I - Sound recording

The layout of the sound recording equipment in relation to the rig is shown in figure 6. A two-track tape-recorder was employed, the lower track being used for a running commentary on fuel flows, temperatures and other relevant data, together with the point denoting the onset of buzz. The upper track was used to record the combustion noise for a given pilot flow setting as the main flow was steadily increased.

Tape recordings were made for the conditions listed below:

	Run 1	Run 2	Run 3
Upstream Temperature (°C)	440	440	300
Upstream Velocity (ft/sec)	140	140	140
Blockage (%)	25	25	25
Tailpipe length (inches)	45	33.25	45

The only difference between runs 1 and 2 was that of tailpipe length, so that any changes of frequency and/or amplitude could be related to tailpipe length alone; similarly any changes of frequency and/or amplitude with gas temperature could be found by comparing runs 1 and 3.

Phase II - Photographic analysis

During Phase II the upper track tape recordings obtained in Phase I were examined using a cathode ray oscilloscope and a polaroid camera, as illustrated schematically in figure 7. The basis of the method employed is described in detail in reference 1, the essential feature being that the gain in decibels between a buzzing and a non-buzzing condition could readily be obtained by direct measurement from the face of the C.R.O.

Examples of such traces are shown in figure 8. Plate A shows stable combustion before the start of buzz. Plate B illustrates a strong, well developed buzz with an amplitude increase of 15.72 decibels compared with Plate A. Plate C demonstrates stable combustion between 'end of buzz' and rich extinction, the sound level being 14.55 decibels down compared with B.

In all some 36 photographs were produced and these reinforced the previous conclusions in that

(a) A reduction of tailpipe length from 45 to 33.25 inches resulted in a weakening of buzz.

(b) A reduction in upstream temperature from 440 to 300°C produced a strengthening of buzz.

(c) The closer were the 'start-of-buzz' and 'blow-off' lines on the pilot/main flow graphs, the stronger was the buzz.

Phase III - Frequency analysis

The purpose of this phase was to investigate the fundamental frequencies present during buzz. Due to the random nature of the combustion waveforms auto-correlation techniques were used to determine the relevant frequencies.[2] The results of this phase are summarized in Table 1 and show that:

(a) Buzz frequency is increased by an increase in gas temperature or a reduction in tailpipe length.

(b) The mode of oscillation present during buzz contains a large longitudinal component.

(c) Shortening the tailpipe length, or decreasing the gas velocity, weakens buzz.

PROPOSED MECHANISM FOR BUZZ

Introduction

In reheat systems featuring conventional plain baffle flameholders and upstream fuel distribution, the fuel-air ratio is sensibly the same in both the stabilizer recirculation zone and the main propagation zone. This means that as the reheat fuel flow is raised the mixture strength in all combustion regions increases uniformly until eventually the rich extinction point is reached and the flame blows off the gutter.

In the present experiments, however, using stabilizers which embody the basic design principles of the Rolls Royce piloted gutter, a vital deviation from conventional practice as outlined above is that appreciable variations in mixture strength are always present, particularly in the stabilizer recirculation zone. These variations are of no special significance provided the mixture strength always lies within the normal stability limits of the system. If, however, due to a change in operating conditions a situation is created whereby in some regions of the flame the fuel-air ratio is within the limits of inflammability, while in other regions it lies outside these limits, conditions then become conducive for the onset of combustion instability.

Piloted gutters, in common with all other forms of bluff-body flameholder, create in their wake a low-velocity recirculation zone in which combustion may be initiated and maintained, and from which flame can spread into the high-velocity stream. However, a unique feature of the piloted gutter is that, instead of receiving its fuel from a single upstream injector, the recirculation zone is supplied with fuel from two separate sources,

(a) the main injection manifolds and (b) a pilot injector located inside the gutter itself. Thus the mixture strength in the recirculation zone is affected by the amounts of fuel supplied to both 'pilot' and 'main'. Under these conditions, and especially when the fuel-air ratio associated with either source is approaching the rich extinction value, an increase in fuel flow from either source can lead to the onset of buzz.

Mechanism of buzz

For any given value of pilot fuel flow, as the main fuel flow is increased the fuel-air ratio in the recirculation zone rises until eventually a rich extinction occurs. When this happens the pilot fuel, instead of being consumed in the recirculation zone, is released down the jet pipe. After a certain time interval, depending upon the reaction rate of the mixture, this pocket of unburned mixture, being surrounded by high-temperature combustion products, 'explodes' causing a pressure wave to travel upstream. When this pressure wave reaches the gutter it momentarily halts the pilot fuel flow, thereby reducing the fuel-air ratio in the recirculation zone to a value within the stability limits. The gutter flame is then immediately re-ignited by the hot combustion products that are induced upstream by the pressure wave, assisted by the hot gases still present in the recirculation zone from the previous flame. However, once the pressure wave has passed by, the pilot fuel flow is restored, the recirculation zone again becomes over-rich, flame extinction occurs, and the cycle is repeated.

Thus the mechanism starts with a local rich extinction behind the stabilizer caused primarily by the pilot fuel. This momentary rich extinction produces a pocket of unburnt mixture which moves downstream. From then onwards the sequence of events is as follows:

1) The pocket ignites explosively downstream of the gutter.
2) A combined pressure wave and flame front moves upstream.
3) The flow of pilot fuel into the recirculation zone is halted.
4) The gutter flame relights since the local fuel-air ratio has fallen to within the stability limits.
5) Flame spreads rapidly from the re-established gutter flame and engulfs the next pocket of gas which was produced while (2) was occurring.
6) The cycle is repeated starting at 1).

Note on step (3). The pressure wave travelling upstream affects the pilot fuel flow more than the main flow because its pressure energy is far less than the momentum energy of the high velocity main flow but is comparable to the momentum energy of the pilot flow.

It is of interest at this stage to examine the extent to which this proposed mechanism for buzz is consistent with experimental observations.

COMPARISON WITH EXPERIMENT

Influence of pilot fuel

Observation:- Buzz does not occur when the pilot fuel flow is zero or has a high value.

Explanation:- In the absence of pilot fuel the system behaves in the conventional manner and buzz is not produced. As the pilot fuel flow is increased a point is eventually reached where the pockets of unburnt fuel-air mixture are too rich to burn and an upstream pressure wave is no longer generated. Under these conditions it is believed that a continuous recirculation zone is established at a short distance downstream of the gutter, allowing the pilot fuel to escape downstream where it burns in a steady manner.

Influence of tailpipe length

Observation:- With increase in tailpipe length buzz becomes stronger and its frequency is reduced. At very short tailpipe lengths buzz cannot be produced.

Explanation:- With long pipe lengths, when buzz is present, the initial increase in gas pressure, caused by re-ignition of the gutter flame, is continually and progressively strengthened as it travels along the jet pipe by the energy released in combustion. Moreover, since stability limits are narrowed by an increase in tailpipe length, as shown in figure 2, buzz, being associated with the rich extinction limit, now occurs at a mixture strength that is nearer to the stoichiometric value and hence the rate of heat release is higher. The rate of pressure rise is also enhanced in long pipes by the increased volume of mixture involved in combustion and by the high level of combustion efficiency associated with long jet pipes. Hence at long tailpipe lengths buzz will be strong, and conversely at short tailpipe lengths buzz will be weak or even non-existent.

The observed reduction in buzz frequency with increase in pipe length is consistent with a longitudinal mode of oscillation. The frequency of the synchronising pressure variations varies with tailpipe length, i.e. buzz frequency changes with the resonant frequency of the tailpipe.

Influence of gutter blockage

Observation:- Variation in blockage from 25 to 35% has no appreciable effect on buzz.

Explanation:- An increase in gutter blockage affects buzz in two ways. Firstly, it increases the amount of mixture entrained in the recirculation zone, which in turn increases the volume of mixture in the unburned pockets, thereby tending to produce more powerful explosions and stronger pulsations.

Secondly, by widening the stability limits of the stabilizer flame (assuming, of course, that increase in blockage is accomplished by raising the gutter width) the onset of buzz is delayed to a higher fuel-air ratio. In consequence the burning rate of the pockets of unburnt mixture is reduced and their eventual explosion tends to occur with less violence. Thus a change in blockage has two opposing effects on the strength of buzz and the nett result appears to be quite small.

Influence of gas velocity

Observation:- Buzz is weakened by a reduction in gas velocity.

Explanation:- There are two main factors which together contribute to the observed weakening of buzz with reduction in gas velocity.

1) With reduction in velocity, stability limits are widened and buzz, being associated with rich extinction, occurs at richer mixture strengths where reaction rates, and hence also rates of pressure rise, are lower.
2) At lower velocity less mixture is entrained in the recirculation zone and thus the unburnt pockets generated downstream are smaller and explode with less violence.

Influence of gas temperature

Observation:- Buzz is non-existent below 280°C, emanates strongly at about 300°C, and then weakens off with further increase in gas temperature.

Explanation:- Although a flame may burn in a tube the enclosed column of gas will not vibrate unless it receives an initial shock. The 'shock' in the buzz mechanism is the sudden ignition of a pocket of unburnt mixture in the tailpipe. If the heat release rate of this mixture is low the resulting pressure wave will be too feeble to initiate buzz. Referring now to figure 9, if the energy level must exceed a certain value, say AA, before buzz can start, there must be some value of upstream gas temperature below which these is no buzz. In the Cranfield experiments this temperature corresponds to 280°C. Also from figure 9 it is clear that when buzz does start, at a gas temperature of 300°C, it exists only over a narrow range of fuel-air ratios, BB, close to stoichiometric, where burning rates are high and strong pressure pulsations are generated.

With further increase in gas temperature the mixture strength of the unburnt pockets moves further away from stoichiometric to, say, point C′, thereby producing a decline in the rate of combustion and in the strength of buzz.

CONCLUSIONS

1) The phenomenon of buzz may be attributed directly to the pilot fuel injected locally into the stabilizer recirculation zone. Buzz does not occur when the pilot fuel flow is high. Thus two practical solutions to the buzz problem in aircraft reheat systems are:-
   - (a) turn off the pilot fuel as the main fuel flow is increased, or
   - (b) set a high pilot fuel flow prior to increasing the main fuel flow.

2) Shortening the tailpipe length or decreasing the gas velocity weakens buzz.

3) Over the range of gutter blockage from 25 to 35% there is no discernible effect on buzz.

4) There is a minimum gas temperature below which it is impossible to initiate buzz. Above this temperature buzz emanates very strongly but declines in strength with further increase in temperature.

5) The mode of oscillation present during buzz is primarily longitudinal.

6) Buzz frequency increases with increase in gas temperature or reduction in tailpipe length.

7) 'Buzz' is believed to be the audible manifestation of a self-perpetuating cycle of events which starts with the extinction of the gutter-stabilized flame by the locally-injected pilot fuel and ends with its re-ignition by a wave front that is generated by spontaneous ignition in the tailpipe of the pocket of unburnt mixture produced by the previous extinction, and which momentarily halts the supply of pilot fuel to the gutter flame. This mechanism for buzz is consistent with and fully supports the experimental observations expressed in the above conclusions.

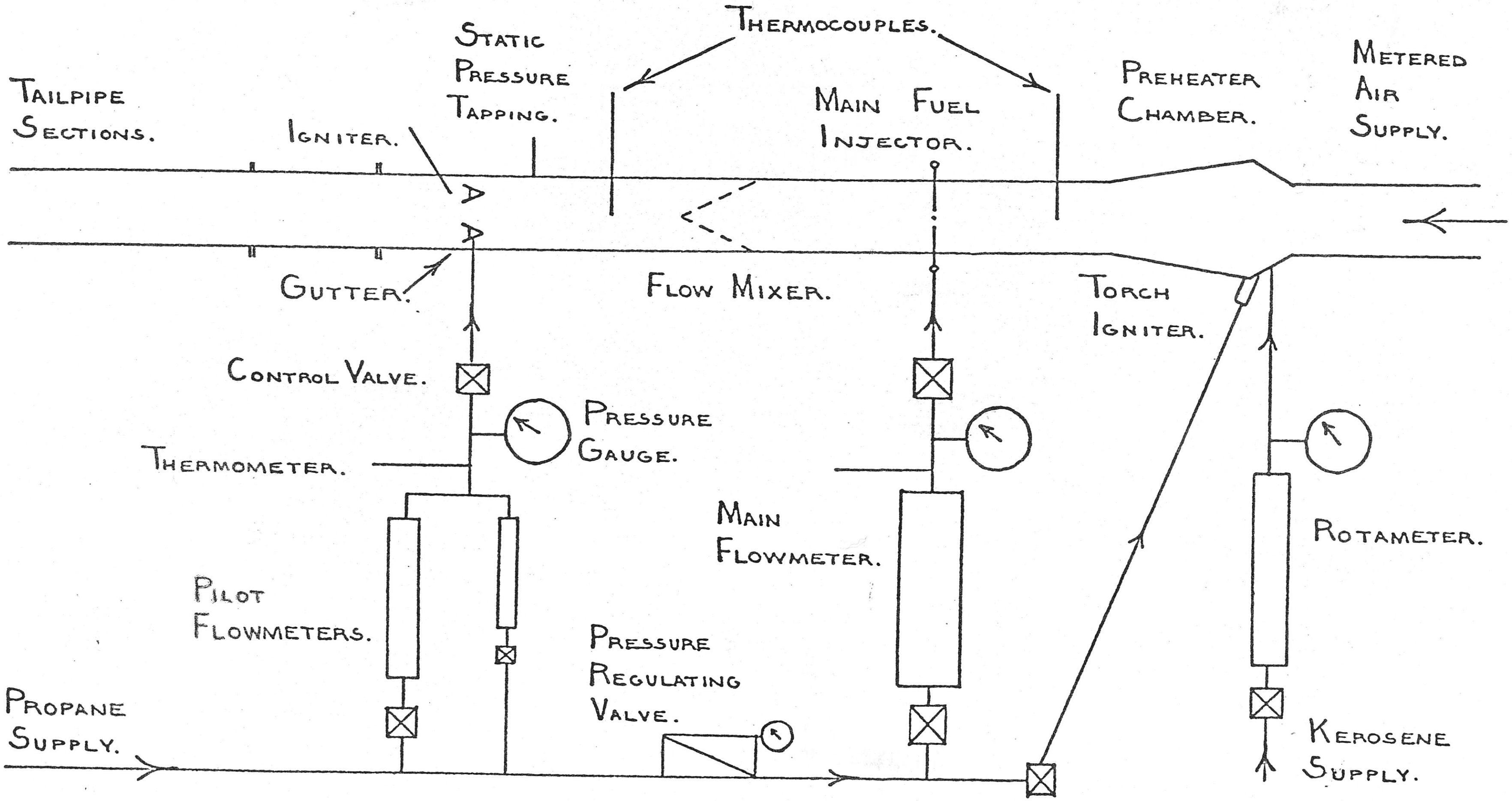
REFERENCES

1.	Squire, P.C. Verdin, H.W.P.	An Investigation of Combustion Instability in Aircraft Reheat Systems. College of Aeronautics Thesis, 1968.
2.	H.B. Gatland R.J.A. Paul	A Correlator based on Delta Modulation Techniques. College of Aeronautics Report E and C No. 3.

TABLE 1

Type of Combustion	Upstream temperature °C	Tailpipe length inches	Frequency cycles/sec.	Amplitude volts - RMS
Stable	440	45	515	2.25
Buzz present			164	5.0
Stable	300	45	450	3.5
Buzz present			154	5.5
Stable	440	33.25	267	3.0
Buzz present			250	4.2

FIG. 1



Arrangement of Test Rig

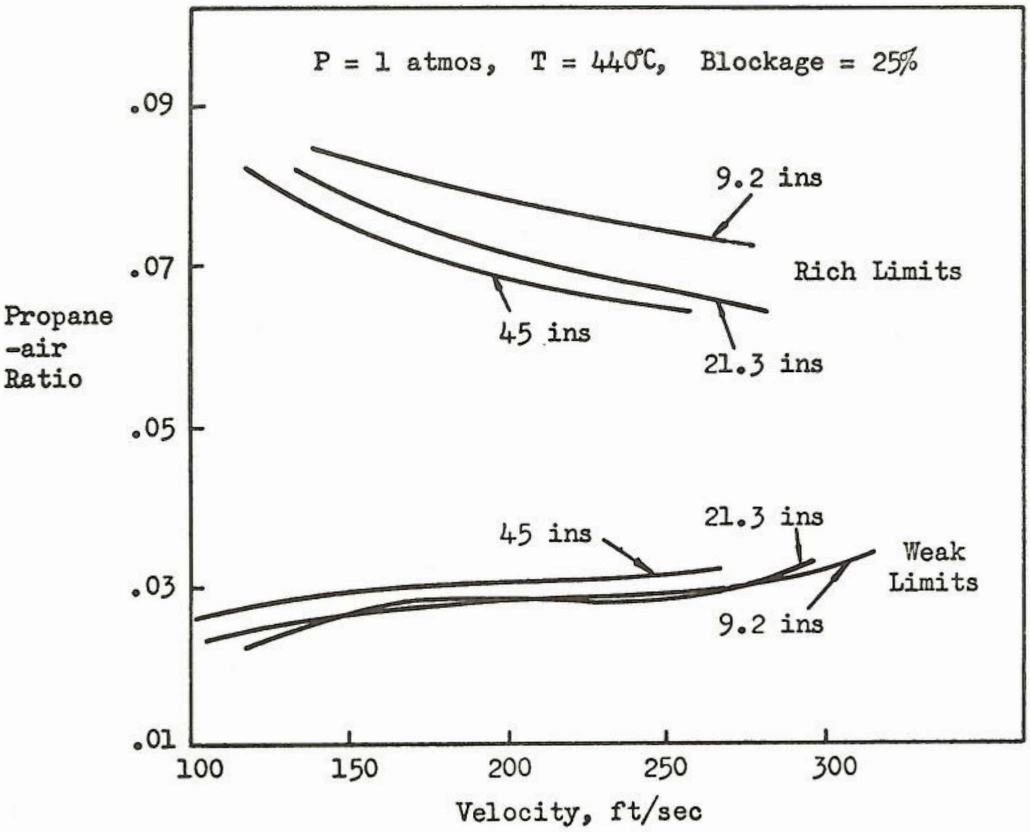


FIG. 2 VARIATION OF VEE-GUTTER STABILITY LIMITS WITH PIPE LENGTH

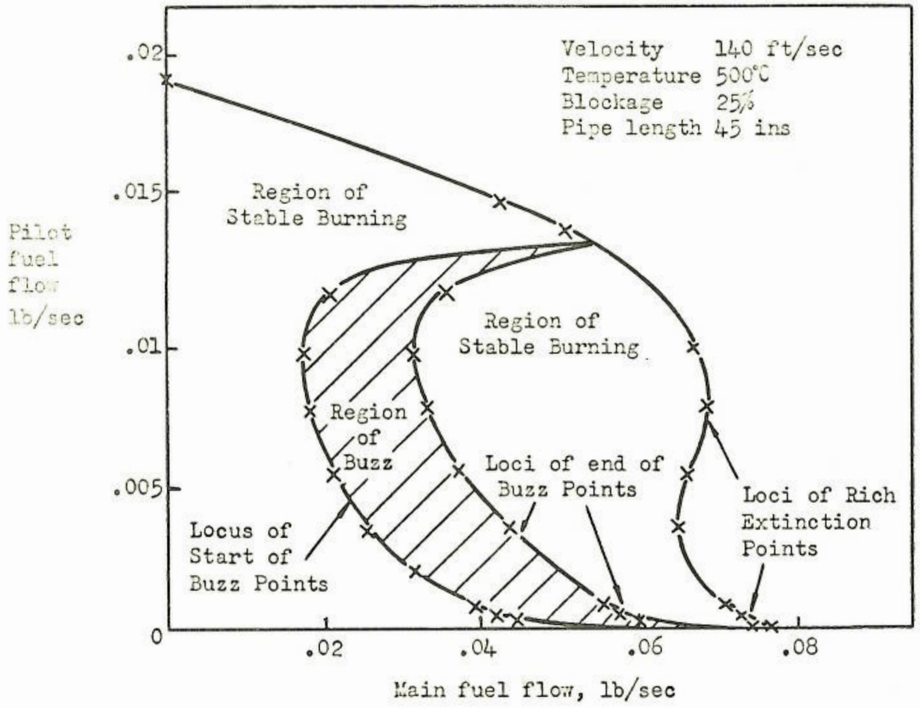


FIG. 3 STABILITY LOOP FOR PILOTED VEE-GUTTER

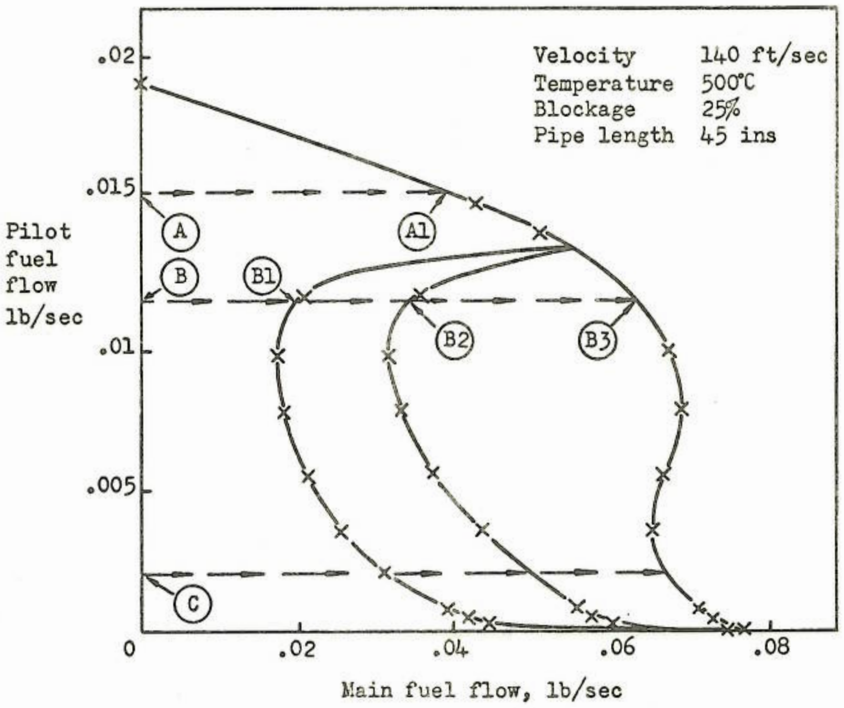


FIG. 4 STABILITY LOOP FOR PILOTED VEE-GUTTER

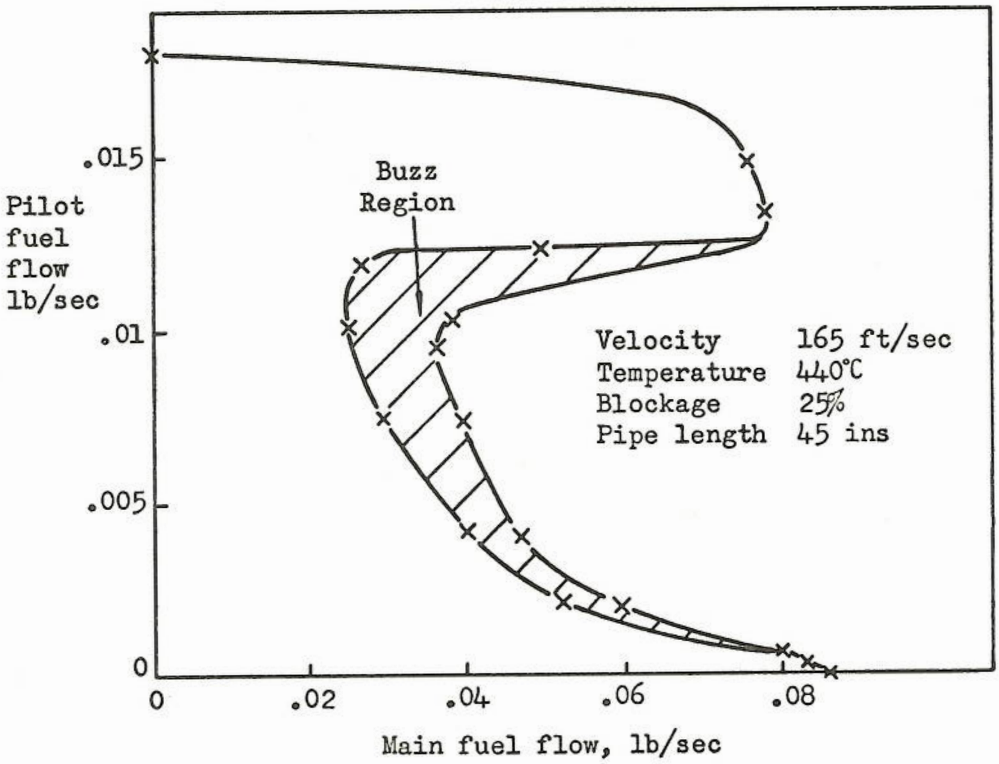
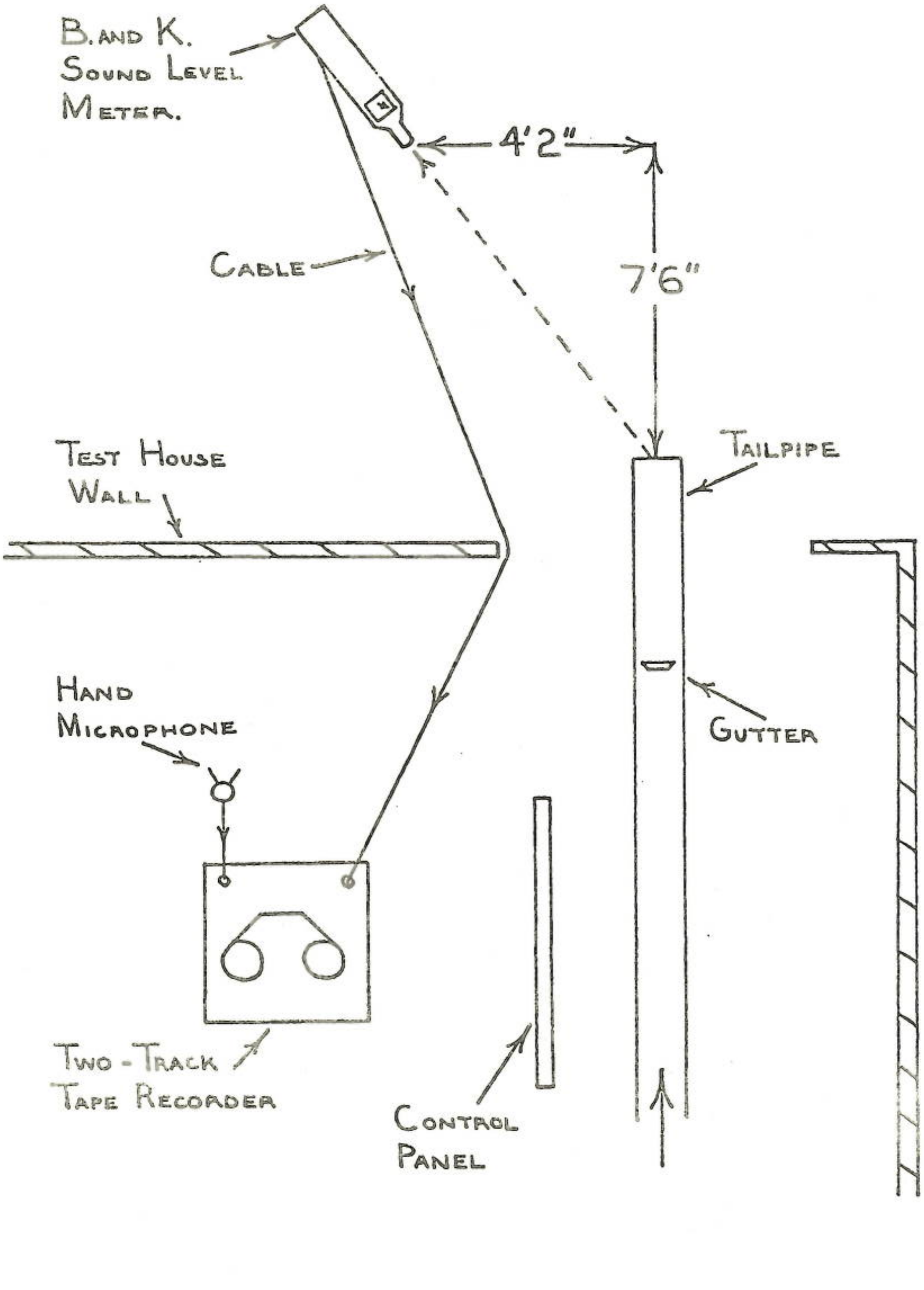
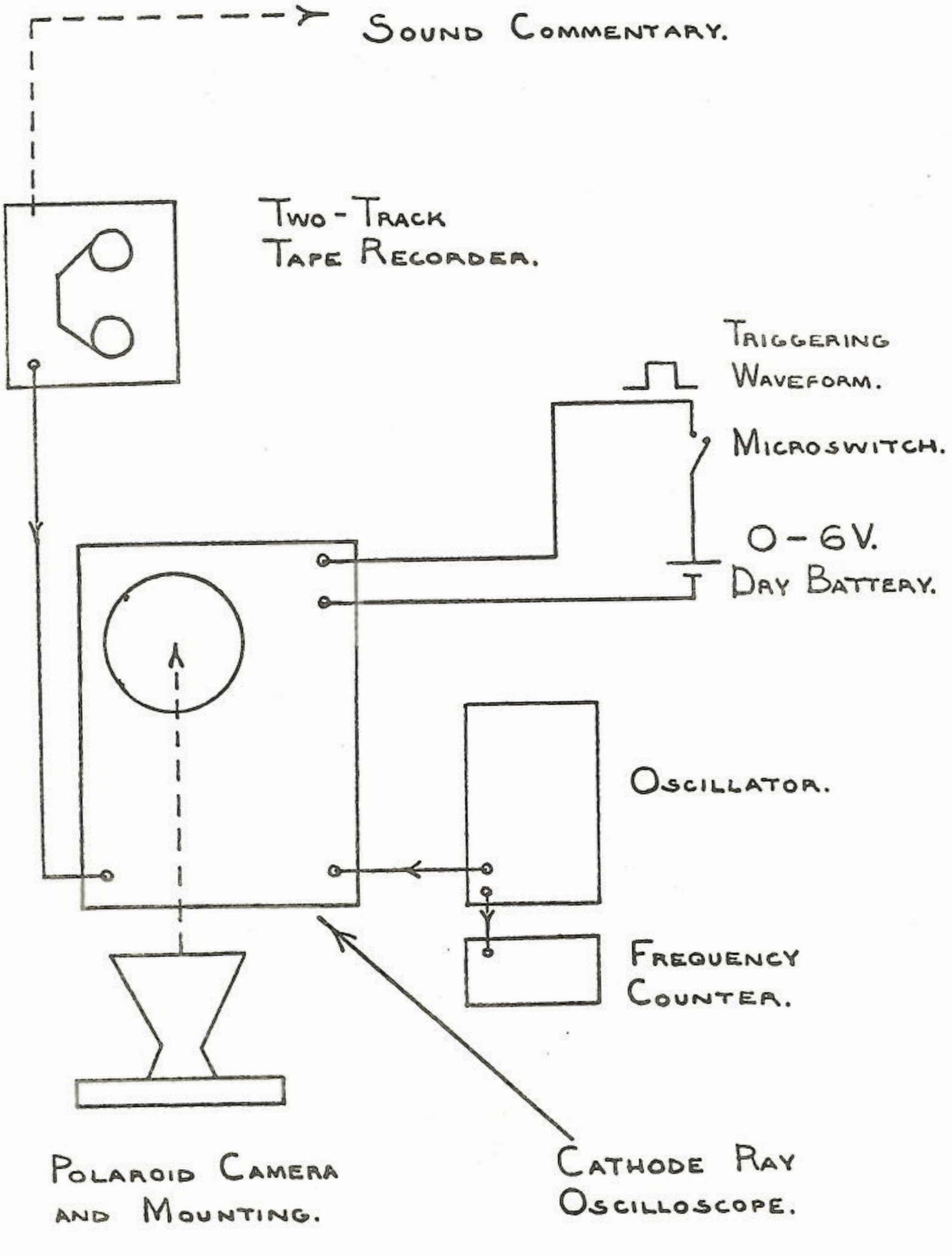


FIG. 5 STABILITY LOOP FOR PILOTED VEE-GUTTER



Location of Sound Recording Equipment.

FIG. 6



Block Schematic Diagram for Photographing Combustion Waveforms.

FIG. 7

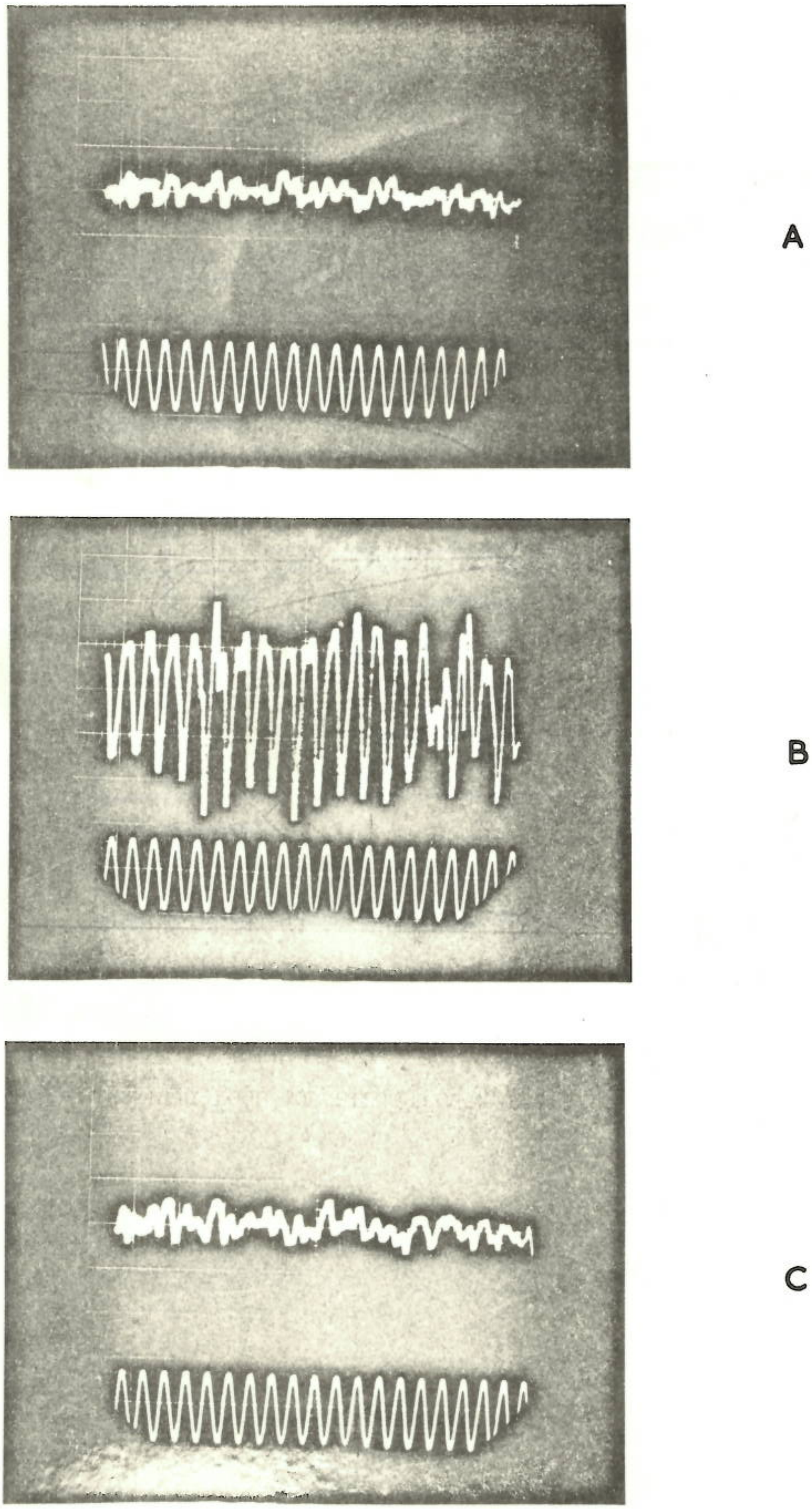


FIG. 8

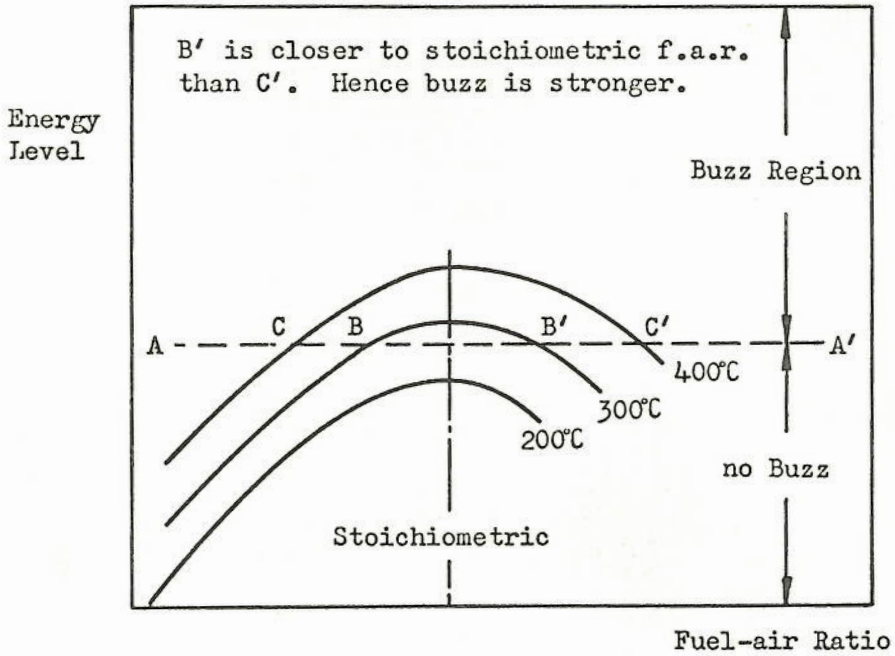


FIG. 9 DIAGRAM ILLUSTRATING EFFECT OF TEMPERATURE ON BUZZ