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THE COLLEGE OF AERONAUTICS

CRANFIELD

THE EFFECT OF COMBUSTOR OUTLET TEMPERATURE PROFILES ON RAMJET THRUST

by

M. R. WILLIAMS and S. W. GREENWOOD

M.O.S. Research Contract 7/Exptl./720.

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The Effect of Combustor Outlet Temperature Profiles on Ramjet Thrust

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SUMMARY

The desirability of obtaining an even distribution of temperature at the outlet of a ramjet combustor is indicated theoretically. Results of experiments on a particular combustion system over a limited range of conditions using a series of mixers are presented. The results suggest that mixers are desirable for high Mach Number ramjets operating at low overall fuel-air ratios.

The material presented in this report is based on the work carried out by M. R. Williams in partial fulfilment of the requirements for the Diploma of the College of Aeronautics, and is essentially a summary of his thesis.(1) The work was part of M.O.S. Research Contract 7/Exptl./720.

INTRODUCTION

The influence of combustor outlet temperature profiles on exhaust thrust has received brief mention in unclassified literature.[(2), (3)]. As far as the authors are aware, no detailed analysis of the problem has yet appeared, nor has any experimental data hitherto been made available.

A ramjet intended for operation over a long range under conditions where economical fuel consumption is important will operate at relatively weak overall fuel-air ratios, possibly in the range .01 to .03. For high stability and combustion efficiency it will be desirable to burn the fuel under richer conditions. This involves a large part of the air by-passing the combustion zone.

The question arises whether to expand the streams of combustion gas and by-pass air through the exhaust nozzle without mixing, or whether to mix them prior to expansion (Fig.1). A mixing system will inevitably produce a loss in total pressure, and hence on this count a reduction in outlet thrust. It is therefore necessary to investigate whether mixing of the two streams, referred to from here on as hot and cold streams respectively for convenience, will produce on other counts an increase in thrust on the unmixed case.

THEORETICAL ANALYSIS

Using the reference stations shown in Fig.2, it is shown in Appendix I that the outlet momentum thrust of each element of the exhaust nozzle flow can be written as a function of γ_7, ΔP_5 and P_5 for expansion over a given pressure ratio P_{t7}/P_7.

An assessment of the influence of an alteration in temperature profile on performance requires that a typical engine configuration be chosen, and the effects compared with those of an alteration in total pressure loss associated with mixing. For flight at a given altitude and Mach number a 'typical' intake pressure recovery may be assumed, so that P_{T3} may be taken as fixed. Expansion in the outlet nozzle to atmospheric pressure may be assumed, so that P_7 is fixed. P_{T5} will then be determined by the combustor pressure losses, including those caused by mixing. Expansion over a constant pressure ratio P_{T7}/P_7 may be assumed in seeking an indication of the effect of temperature profile. This is then compared with the effect of a variation in P_{T7}/P_7 caused by different mixing pressure losses.

Rather arbitrarily, the basis of the analysis was chosen as an engine operating at $M_1 = 3$ at an altitude of 60,000 ft. with the exhaust nozzle expanding the flow isentropically to the ambient pressure. The assumptions made in connection with this engine are given in Appendix 2. An important factor in the calculations is the determination of a value of γ for the expansion process, as this may be shown to have a significant effect on the results obtained. The value of γ during expansion was taken to be that at the exhaust nozzle throat. It was believed that this was an acceptable assumption for the purposes of this investigation, but in future studies this is a matter deserving closer attention. The design point performance of engines of this type operating at different fuel-air ratios is shown in Fig. 3, assuming a flat temperature profile at station 5. This curve demonstrates the need for low fuel-air ratios for low specific fuel consumptions, although the air specific thrust is also low under these conditions. The tendency therefore is to select a fuel-air ratio on the high side of that giving minimum fuel consumption.

The effect of uneven outlet temperature profile is shown in Fig. 4 where complete absence of mixing between the hot and cold streams is assumed, the overall effective fuel-air ratio being taken as .02 and for various values of the hot zone effective fuel-air ratio. The effect on outlet stream thrust is pronounced at high values of the effective fuel-air ratio in the hot zone. The effect on the engine nett thrust is considerable. At α_E = .04 in the hot zone, the loss of nett thrust is about 18%.

The penalty that may have to be paid for mixing the two streams is indicated in Fig. 5. The baffle loss coefficient is the aerodynamic loss in total pressure across the flame stabiliser divided by the approach dynamic pressure. A further drop in total pressure arises from heat addition in the combustion zone. From the aspect of the effect on nett thrust it appears that quite high values of baffle loss coefficient may be of less importance than uneven outlet temperature profiles at the Mach 3 condition. This conclusion should also hold for higher Mach numbers, but would be less valid at lower Mach numbers where pressure losses have a more marked effect on performance.

There is clearly a need for experimental investigation of this problem. In the following section some preliminary practical studies on a particular unit are described.

EXPERIMENTAL WORK

Some work was carried out at the College using a ramjet combustion system supplied by the National Gas Turbine Establishment (Fig. 6). It is not permitted to publish complete details of this system. However, the features of importance to this particular study are given. It will be seen that all combustion takes place in a central combustion zone, the by-pass air zone forming a cylindrical sleeve around it. The combustion system was followed by a mixer in some of the tests, and by one of a series of tailpipes of different length/diameter ratios. The system exhausted directly to atmosphere as shown in Fig. 7.

The air supply to the rig arrived via two paths, one of which contained a kerosene preheater permitting temperature control. This produced slight contamination of the supply air with exhaust products, but the quantities were small and were not thought to be significant in this particular programme of work. A mixer was positioned downstream of the junction of the air supply paths and upstream of the ramjet combustion system, and this produced even distributions of velocity and temperature at entry. Air flow to the rig was measured by means of a calibrated plain orifice and fuel flow using a rotameter. Air flow in the by-pass zone was determined by means of traversing total pressure tubes and outer wall static pressure tappings, in conjunction with entry total temperature measurements by means of a thermocouple.

The problem of outlet temperature profile determination was a major one. It was decided to use an uncooled traversing platinum platinum-rhodium thermocouple. This necessitated testing under conditions simulating the rather modest Mach number of 2, as testing at higher Mach numbers would have resulted in too high an outlet temperature for the instrumentation, the National Gas Turbine Establishment having stipulated operation at an overall effective fuel-air ratio of .02, and the air flow being divided roughly equally between the hot and cold zones. Even so, some of the thermocouple readings are higher than those for which the instrument is normally considered suitable and the results should be treated with reserve. It is necessary also to sound a note of caution about applying the results of these tests to applications where conditions differ widely from the tests.

The outlet total pressure distribution was determined by means of a water cooled total pressure rake.

The combustion zone was first developed until it was found to produce smooth burning and an even outlet temperature distribution.

In establishing a procedure for testing, it was realised that some rather arbitrary decisions would have to be made about what to control and what to leave, as the number of variables involved is large. The procedure adopted in all tests was as follows: The total pressure just upstream of the combustion system was set to 1.16 x atmospheric pressure, and the total temperature was set to 127°C. to represent Mach 2 conditions in the stratosphere. The system is effectively operating in the lower stratosphere with combustor outlet pressures set at sea-level atmospheric. A stricter operating procedure would have been to throttle the exhaust flow in order to control to a given total pressure at entry to the combustor in order to simulate a fixed altitude, but this would have entailed increased complication. Each mixer and tailpipe combination was tested at four overall applied fuel-air ratios in the region .021 ± .003, in order to permit interpolation of the results to obtain data at an overall effective fuel-air ratio of .02, the combustion efficiency being unknown prior to the test.

It will be evident that the mixers giving higher pressure loss coefficients were therefore tested at lower inlet Mach numbers. The pressure loss coefficient is defined as the overall total pressure loss of the flame stabilisation, combustion and mixing system divided by the approach dynamic pressure. Moreover, the mixers affected the ratio of the air flows in the hot and cold zones as there was no separate control on this. Three of the mixers, numbers 5, 6 and 7 below, were designed with an eye to producing the same ratio and rather surprisingly did so. Nevertheless, care should be taken to view the quoted results in the light of the limitations of the experimental technique.

The following mixing systems were tested with tailpipes of chosen length/diameter ratio :-

(1) NO MIXER : The only mixing that occurs is that due to the interaction of the two parallel gas streams entering the tailpipe.

(2) 15° VORTEX GENERATOR : This mixer consists of a series of plates inclined at 15° to the by-pass flow extending part way across the by-pass annulus (Fig.8).

(3) 45° VORTEX GENERATOR : This mixer has a series of plates inclined at 45° to the by-pass flow and extending across most of the by-pass annulus (Fig. 9).

(4) N.G.T.E. RADIAL TUBE MIXER : A mixer designed and manufactured by the N.G.T.E. A series of tubes direct some of the by-pass air into the combustion gases (Fig.10).

(5) SLOTTED COLANDER : This is a colander extending across the by-pass flow and having a series of rectangular slots (Fig. 11).

(6) PLUNGED SLOT COLANDER : This is similar to the slotted colander, with two sides of each slot plunged (Fig. 12).

(7) RADIAL SCOOP : This mixer contains a series of channels or scoops open at the upstream end to direct all the by-pass air into the combustion zone (Fig. 13).

EXPERIMENTAL RESULTS

Fig. 14 shows outlet temperature and dynamic pressure profiles for the no-mixer case with two different tailpipes, together with data relating to the test conditions. In interpreting these and subsequent diagrams it should be remembered that the by-pass annulus is only ½" in width, so that lifting of the temperature curves in the outer ½" of the radius is the significant thing to look for. The velocity and temperature profiles are flatter with the longer tailpipe, but clearly the ordinary mixing process is not very effective. The temperature distribution factor F listed below the curves is defined in Appendix 3 and is a simple way of putting a figure to the degree of departure from the desired flat profile. It will be appreciated that the use of the factor F is a fairly severe simplification, though a convenient one. It takes no account, in particular, of the distribution of velocity at outlet. For complete mixing F = 0. In the worst case with no mixing F = 1. Even with the tailpipe with a length/diameter ratio of 6, F is only down to 0.29.

F is plotted against tailpipe length/diameter ratio in Fig. 15. Repeat tests indicate the degree of scatter.

The variation of the system's pressure loss coefficient with tailpipe length/diameter ratio is shown in Fig.16. It increases only slightly with increase in tailpipe length/diameter ratio. However, the overall conclusion to be drawn is that the no-mixer case is not promising.

Some test results using the N.G.T.E. radial tube mixer are presented in Fig.17. In this case, appreciable improvements in flattening the temperature profile are evident for quite modest pressure loss coefficients. The trends with this mixer are shown in Figs. 18 and 19. With a tailpipe length/diameter ratio of 2, an F of 0.155 is obtained for a pressure loss coefficient of 7.25.

It was found that plots of log F against log tailpipe length/diameter ratio could be represented by straight lines over the range of the tests. Such plots are shown in Fig.20 and may be useful for purposes of extrapolation.

All of the mixers took up a portion of the engine length less than a length/diameter ratio of 1. However, it was felt desirable to assess their comparative performance with relatively short tailpipes and this was done with a common tailpipe length/diameter ratio of 2. The complete results are given in Fig.21, and F is plotted against pressure loss coefficient in Fig.22.

The indications of these tests are that F values approaching zero, corresponding to substantially flat temperature profiles, may be obtained with pressure loss coefficients of about 15. In that the pressure loss coefficient of a system is higher than its baffle loss coefficient, reference to Fig.5 shows that the associated thrust loss due to the use of a mixer is likely to be relatively small.

CONCLUSIONS

1. Theoretical analysis indicates the desirability of obtaining flat outlet temperature profiles, for high Mach number ramjets for operation at weak overall fuel/air ratios.
2. Experiments over a limited range of conditions on a combustion system, in which part of the air is burned at a richer mixture ratio than the overall mixture ratio, indicate that substantially flat temperature profiles may be obtained for pressure loss coefficients of about 15.
3. If the experimental data leading to conclusion (2) above is accepted as a general indication of mixer performance, then mixers appear to be a practical proposition for ramjets designed to operate at Mach 3 and over at low overall fuel-air ratios.

REFERENCES

No.	Author	Title, etc.
1.	M.R. Williams	The effect of efflux temperature profiles on ramjet performance. College of Aeronautics Thesis, 1956.
2.	J. Friedman, W.J. Bennet & E.B. Zwick	Engineering application of combustion research to ramjet engines. Fourth Symposium (International) on Combustion (1952), The Williams and Wilkins Co.
3.	W.T.Olson	Combustion for aircraft engines. Proceedings of the Fifth International Aeronautical Conference, (1955).

APPENDIX I.

THEORETICAL ANALYSIS OF OUTLET MOMENTUM THRUST

It is necessary to make a number of assumptions:-

1) The static pressure is uniform across a station.
2) The flow is everywhere substantially axial in direction.
3) $P_{T5} = P_{T7}$, $T_{T5} = T_{T7}$, and $R_5 = R_7$.
4) An average value of specific heat ratio γ_7 may be assigned to each element of gas flowing in the outlet nozzle.

The outlet thrust due to the product of mass flow rate and velocity (here termed the "momentum thrust")

$$= \Sigma \; W_7 V_7 \text{ (taken over the whole outlet area)}$$

$$\Sigma \; W_7 V_7 = \Sigma \; W_5 V_7$$

At low values of M_5, $\frac{W_5}{A_5} = \sqrt{\frac{2 P_5 . \Delta P_5}{R_5 T_5}}$

Also $V_7 = \sqrt{2 C_{p7} . \Delta T_7}$

$$= \sqrt{2 R_7 . \frac{\gamma_7}{\gamma 7 - 1} . \Delta T_7}$$

$$= \sqrt{2 R_7 . \frac{\gamma_7}{\gamma_7 - 1} . T_{T7} \left[1 - \left(\frac{P_7}{P_{T7}} \right)^{\frac{\gamma_7 - 1}{\gamma_7}} \right]}$$

Thus : $\dfrac{\text{Element of Outlet Momentum Thrust}}{\text{Corresponding Element of Area at Station 5.}}$

$$= z = \left\{ \left[1 - \left(\frac{P_7}{P_{T7}} \right)^{\frac{\gamma_7 - 1}{\gamma_7}} \right] T_{T7} \, . \, 2 R_7 \, . \, \frac{\gamma_7}{\gamma_7 - 1} \, \frac{2 \, \Delta P_5}{R_5 \, T_5} \, . \, P_5 \right\}^{\frac{1}{2}}$$

Making the approximation $T_{T5} = T_5$ at low M_5.

$$z = \left\{ 4 \left[1 - \left(\frac{P_7}{P_{T7}} \right)^{\frac{\gamma_7 - 1}{7}} \right] \frac{\gamma_7}{\gamma_7 - 1} \, . \, \Delta P_5 \, . \, P_5 \right\}^{\frac{1}{2}}$$

Let the mean value of z over the station be $\bar{z}$. This may be compared with a value of z for the same total heat flow rate and total mass flow rate with a flat temperature profile, which we will term z'.

A factor of merit $Z = \dfrac{\bar{z}}{z'}$ may be determined.

A disadvantage of this method is that values must be assigned to γ_7. The values selected will have a marked effect on the results obtained.

For the purposes of this report, the factor of merit Z is not employed. A simpler criterion presented in Appendix 3 is used.

APPENDIX 2.

ASSUMPTIONS FOR THEORETICAL ANALYSIS OF PERFORMANCE OF TYPICAL ENGINE AT $M_1 = 3$, 60,000 FT.

Intake pressure recovery	P_{t3}/P_{t1}	=	0.7
Intake area ratio	A_1/A_3	=	0.6
Combustor baffle loss coefficient		=	6
Combustion efficiency		=	0.9

Exhaust nozzle
(a) $P_{t7} = P_{t5}$
(b) Expansion to $P_7 = P_1$
(c) γ_7 during expansion taken as value at throat.

Fuel — Kerosene.

APPENDIX 3.

In view of the need for obtaining a substantially flat temperature profile it was felt that the degree of departure from the flat profile could conveniently be expressed by the following simple relation:-

$$F = \frac{T_A - T_B}{T_C - T_D}$$

where T_A is the weighted mean temperature in a cross sectional area at outlet equal to the cross sectional area of the combustion zone.

T_B is the weighted mean temperature in a cross sectional area at outlet equal to the cross sectional area of the by-pass zone.

T_C is the weighted mean temperature of the combustion zone outlet, estimated from a heat balance assuming no combustion occurs in the tailpipe.

T_D is the weighted mean temperature of the by-pass air.

For a flat temperature profile $F = 0$. For the worst case of no mixing, $F = 1$.

SYMBOLS

A	element of area normal to flow
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
F	temperature distribution factor (defined in Appendix 3)
M	Mach Number
P	static pressure
P_T	total pressure
R	gas constant
T	static temperature
T_T	total temperature
V	speed
W	mass flow rate
α_A	applied fuel-air ratio
α_E	effective fuel-air ratio
γ	C_p/C_v
ΔP	$P_T - P$
ΔT	$T_T - T$

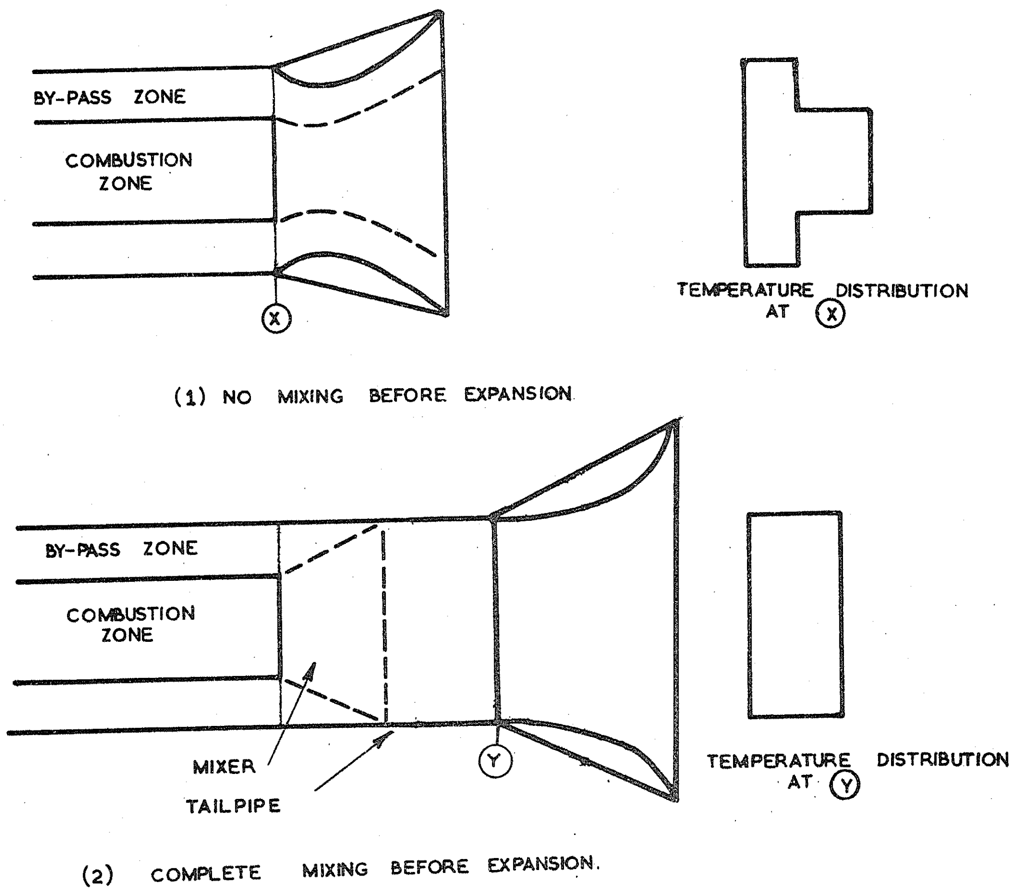


FIG. I IDEALIZED PICTURE OF ALTERNATE SYSTEMS FOR EXHAUSTING AT LOW OVERALL FUEL-AIR RATIOS.

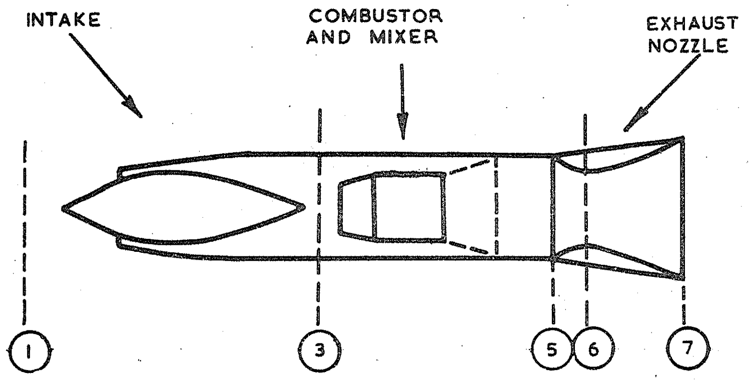


FIG 2 RAMJET REFERENCE STATIONS.

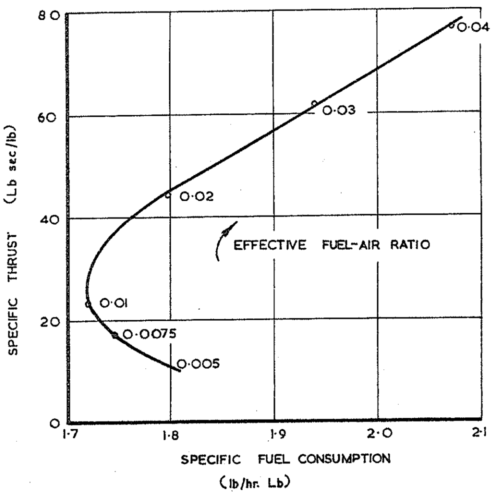


FIG. 3 TYPICAL THEORETICAL DESIGN POINT PERFORMANCE OF A SERIES OF SUPERSONIC ENGINES-OUTLET GASES COMPLETELY MIXED.

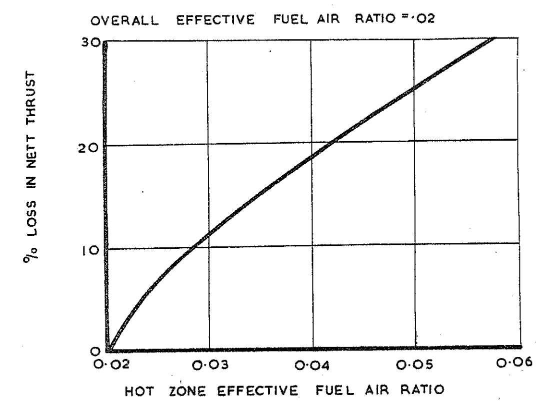


FIG. 4 THEORETICAL EFFECT OF COMBUSTION ZONE FUEL AIR RATIO ON NETT THRUST OF TYPICAL SUPERSONIC ENGINE — OUTLET GASES UNMIXED.

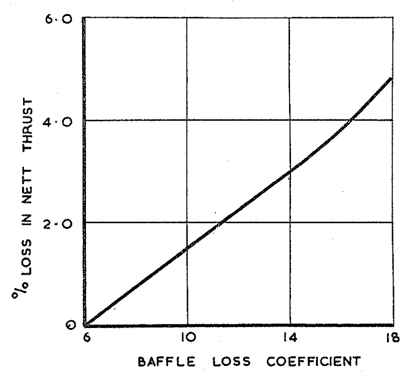


FIG. 5 THEORETICAL EFFECT OF COMBUSTOR BAFFLE LOSS COEFFICIENT ON NETT THRUST OF TYPICAL SUPERSONIC ENGINE.

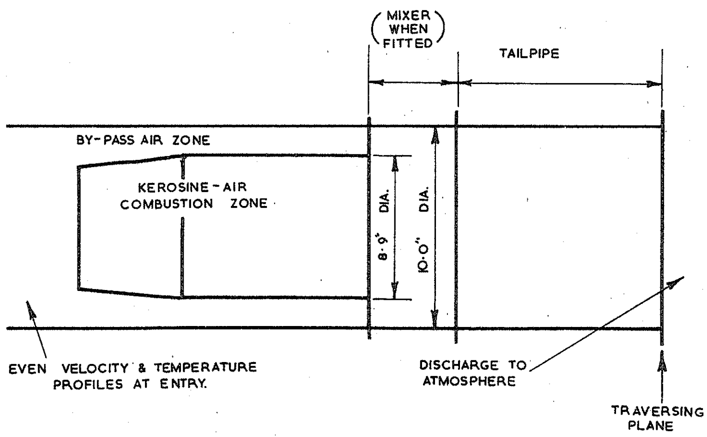


FIG. 6 RAMJET COMBUSTION SYSTEM USED IN EXPERIMENTAL WORK - DIAGRAMMATIC.

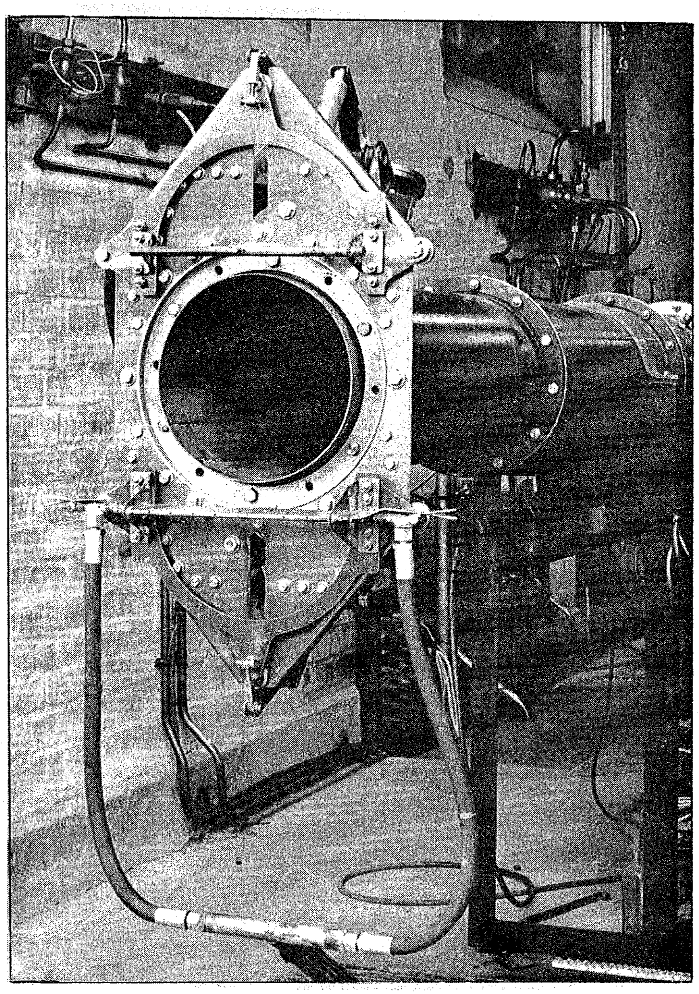


FIG. 7. TAILPIPE EXHAUST SHOWING TRAVERSING GEAR

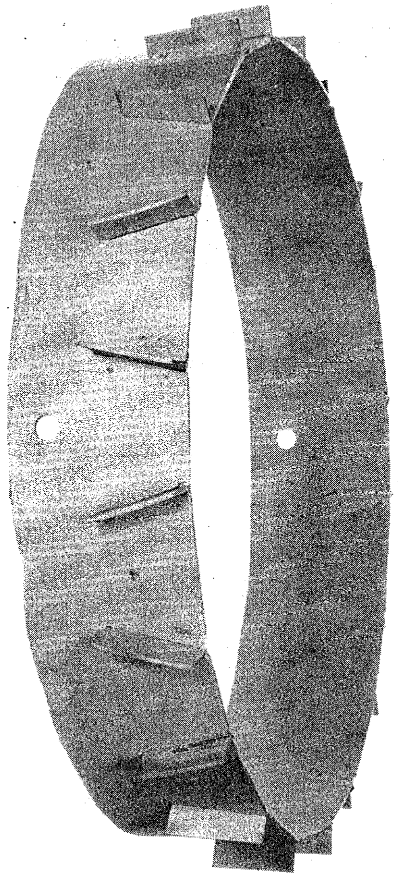


FIG. 8. 15° VORTEX GENERATOR MIXER

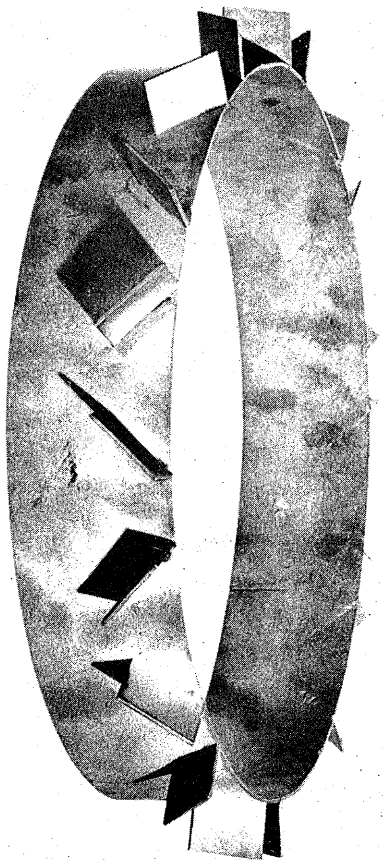


FIG. 9. 45° VORTEX GENERATOR MIXER

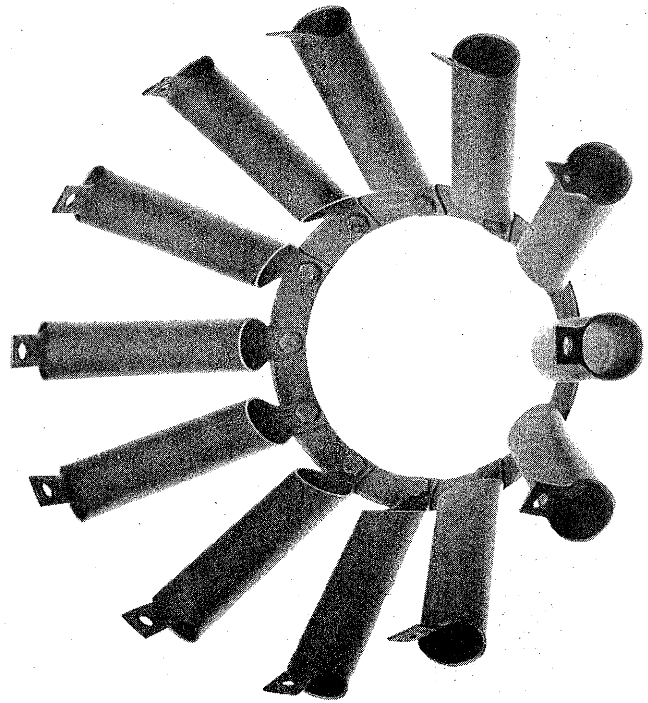


FIG. 10. N.G.T.E. RADIAL TUBE MIXER

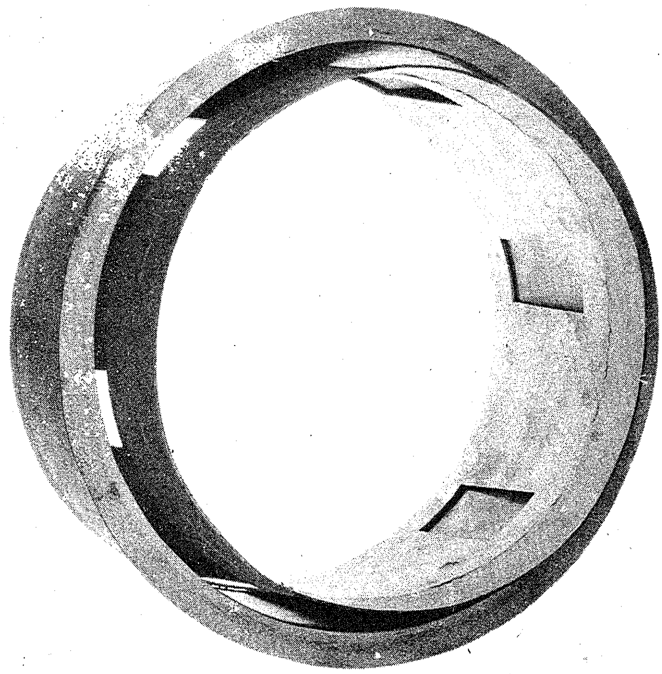


FIG. 11. SLOTTED COLANDER MIXER

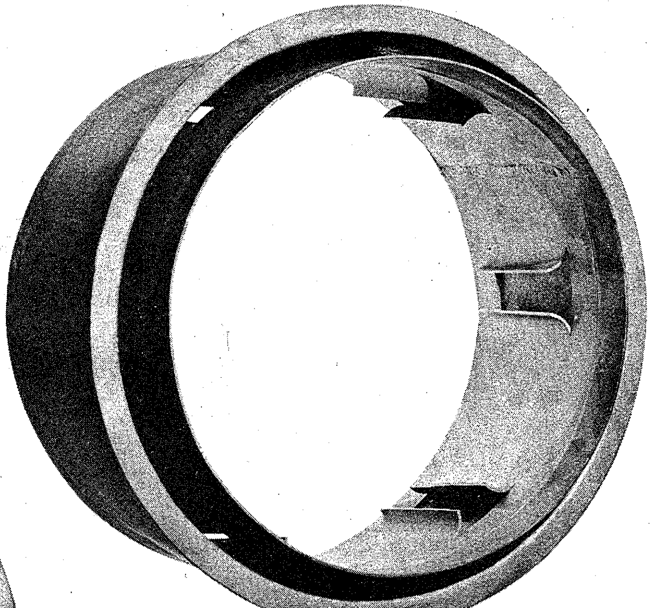


FIG. 12. PLUNGED SLOT COLANDER MIXER

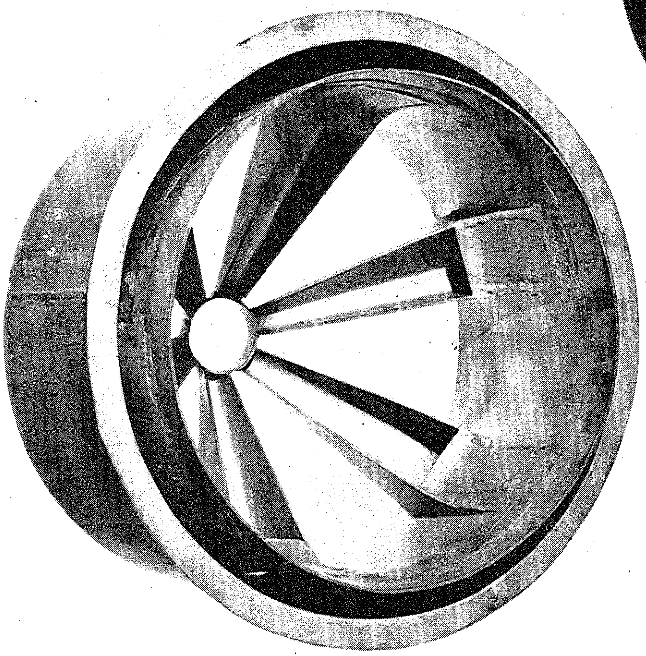
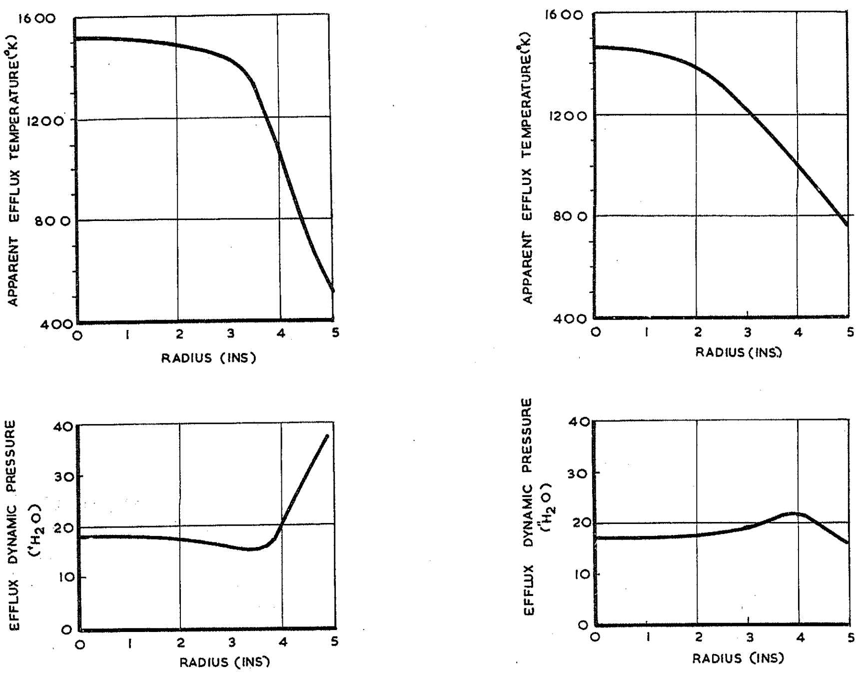


FIG. 13. RADIAL SCOOP MIXER



TAILPIPE LENGTH / DIA. RATIO	2
PRESSURE LOSS COEFFICIENT	5·96
COMBUSTION EFF'Y %	92·3
INLET MACH. No.	0·146
BYPASS FLOW / TOTAL FLOW %	42·4
F	0·530

TAILPIPE LENGTH / DIA RATIO	6
PRESSURE LOSS COEFFICIENT	6·48
COMBUSTION EFF'Y %	101·8
INLET MACH No.	0·143
BYPASS FLOW / TOTAL FLOW	42·4
F	0·290

FIG. 14 EFFLUX TEMPERATURE & DYNAMIC PRESSURE PROFILES AT VARIOUS TAILPIPE LENGTH / DIA. RATIOS OVERALL EFFECTIVE FUEL AIR RATIO = ·02

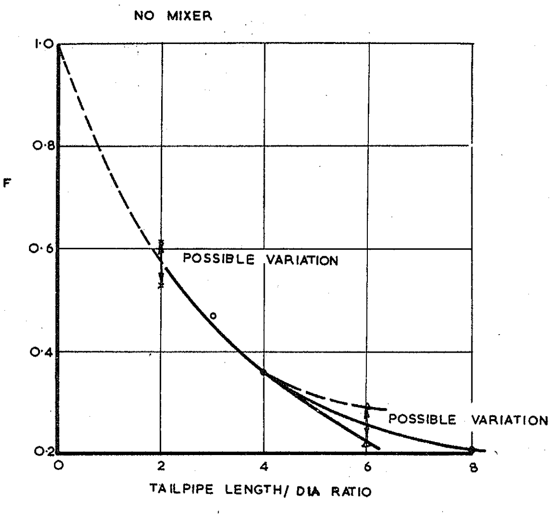


FIG. 15

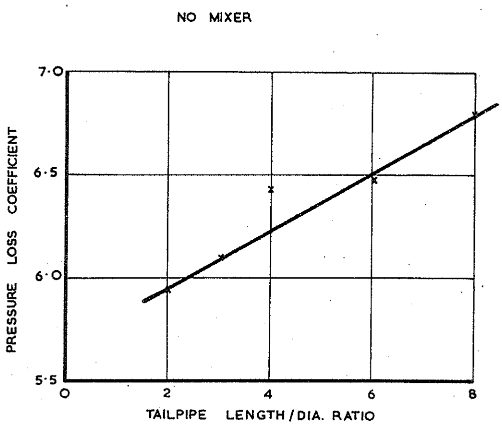
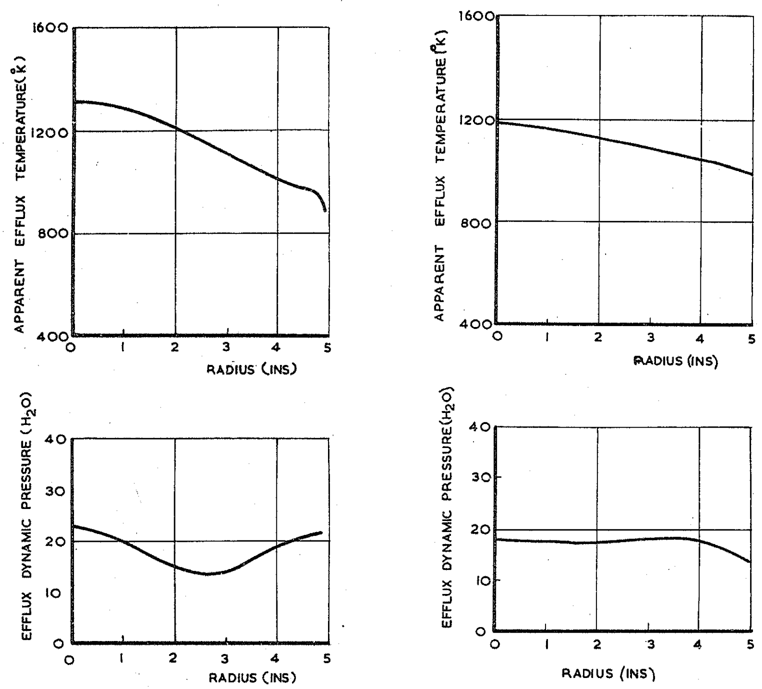


FIG. 16



TAILPIPE LENGTH / DIA. RATIO 2
PRESSURE LOSS COEFFICIENT 7·25
COMBUSTION EFFICIENCY % 92·7
INLET MACH No. 0·138
BYPASS FLOW / TOTAL FLOW % 42·8
F 0·155

TAILPIPE LENGTH/DIA. RATIO 6
PRESSURE LOSS COEFFICIENT 8·13
COMBUSTION EFFICIENCY % 90·8
INLET MACH No 0·135
BYPASS FLOW / TOTAL FLOW 43·4
F 0·069

FIG. 17. EFFLUX TEMPERATURE & DYNAMIC PRESSURE PROFILES AT VARIOUS TAILPIPE LENGTH / DIA. RATIOS.

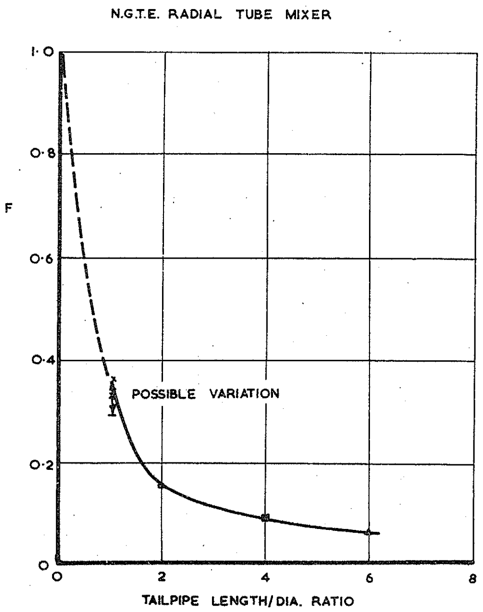


FIG. 18

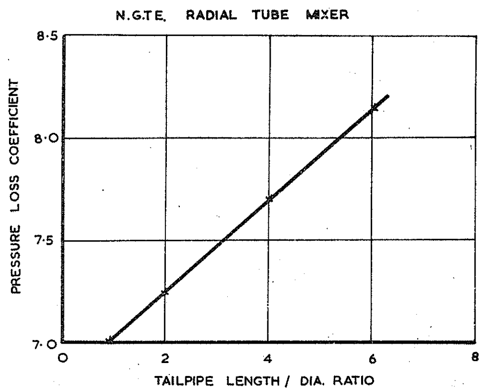


FIG. 19

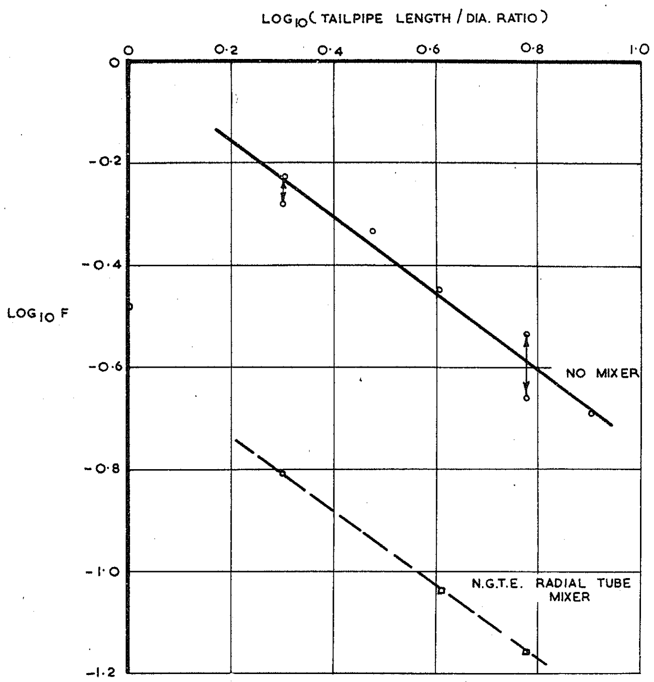


FIG. 20

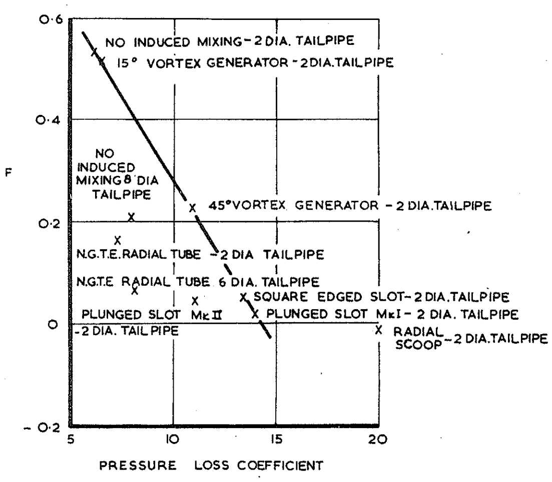
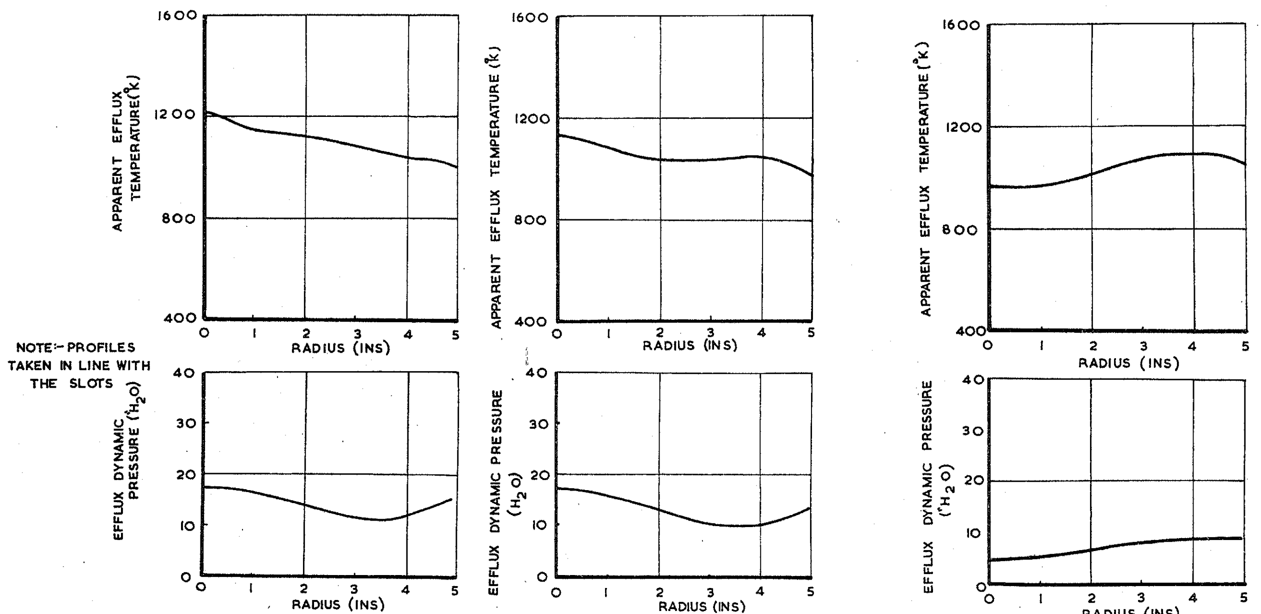


FIG. 22 MIXER PERFORMANCE COMPARISON



	Mixer type: Slotted colander, in line of slots	Slotted colander, between slots	Mixer type: Plunged slot colander, in line of slots	Plunged slot colander, between slots	Mixer type: Radial scoop, in line of scoops	Radial scoop, between scoops
TEMP. RATIO ACROSS COMBUSTOR	2·72	2·68	2·76	2·87	2·68	2·77
PRESSURE LOSS COEFFICIENT	13·46	13·34	14·10	13·9	21·0	18·8
COMBUSTION EFF'Y	83·4	82·2	86·7	93·6	83·3	88·9
INLET MACH No.	0·107		0·105		0·088	
BYPASS FLOW/TOTAL FLOW %	30·0		29·7		31·0	
F	0·0645	0·0419	0·0289	0·0091	−0·0335	0

FIG. 21 EFFLUX TEMPERATURE AND DYNAMIC PRESSURE PROFILES WITH TAILPIPE LENGTH/DIA. RATIO OF 2