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SUBJECT Feasibility of Combustion Processes in Supersonic Streams

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Summary

An attempt is made to show that flames and detonation waves stabilized at supersonic velocities may have practical applications. It is concluded that experimental work in this field would be advisable.

1. Introduction

Recent work on combustion has dealt with two broad fields: fundamental research, which comprises the work on chemical kinetics, the study of laminar flames, the various theories of turbulent combustion, etc. and, on the other hand, development work on combustion systems for practical applications: turbojets, ramjets, reheat systems and the like. All this work, with the exception of some observations on detonation waves (e.g. ref.7), deals with combustion in streams of very small dynamic pressure.

In this paper it is proposed to do some work on the feasibility of practical applications of high velocity flame fronts and of stabilized detonation waves. In a flame front the normal component of velocity is the burning velocity of the mixture; however, there seems to be no physical restriction on the velocity component parallel to the flame front.

2. Suppose we have a combustible mixture in laminar flow at a velocity V. If at some point a continuous source of ignition is inserted, a sheet of flame will propagate into the mixture at the laminar burning velocity. This flame front has many properties analogous to those of an oblique shock: the equations of state, of conservation of momentum and of continuity are satisfied in both cases. But while conservation of energy for the shock, which is adiabatic, leads to a shock angle solely dependent upon the deviation of the flow, in the case of a flame front the deviation of the flow is dependent on the quantity of heat added and on the burning velocity. It can be easily shown that the deviation angle is always positive through shocks, and negative through flame fronts (Ref.2, p.781).

From the viewpoint of efficiency, a considerable loss in total head occurs for large heat releases, being given approximately by $\Delta p_0 = -q \left(\frac{\Delta T}{T_1}\right)$. Under certain circumstances though, it is submitted that this may be tolerated, as illustrated in the examples of figs. 1, 3, 4, 5, discussed below. There is also a redeeming consideration: compact supersonic diffusers incur considerable losses in the constrained part of the diffusion process, so what is lost by burning at a high dynamic head may be partially recovered in not having to diffuse down to a low velocity.

3. As an example (chosen mainly for its ease of computation) let us consider a possible method of thrust boost at supersonic velocity.

Fig.1 represents an aerofoil in two dimensional flow with flameholders origniters at "I". Fuel is injected in such a manner that it mixes into the air passing between "I" and the foil, and is assumed fully dispersed before it reaches the flame front (dashed). Without fuel injection (top half of fig.1) the flameholder may be retracted into the wing, and the incremental drag is nil. When thrust boost is required, the flameholder is extended, and fuel is injected and ignited (lower half of fig.1). The increase in volume of the burnt gases acts as an aerodynamic wedge, keeping the pressure on the rear of the foil at a higher level than on the front by means of the shock generated at "I". The result, of course, is thrust; and Table I gives the specific impulse and other quantities in terms of "p " the free stream pressure and "C" the chord.

Table I

Mach number $M_\infty = 3.0$	Free stream temp. $T_\infty = 492^oF$	
Burning velocity V_2' ft/sec.	100	200
Heat addition, Δh_o, Btu/lb.air	1495	675
Depth of stream tube taking part in combustion, δ, ft.	.057C	.114C
Thrust F, lbs.	.069Cp	.069Cp
Thrust coefficient based on frontal area $(C_F - C_D)$	.155	.155
Fuel specific impulse, S.I., sec	193	214

The burning velocities quoted are far above the laminar flame speed of hydrocarbon-air mixtures. However, the configuration considered requires these burning velocities, and in fact it is found that some of the boron hydrides have heat release and burning rates in the range considered.

For a particular fuel and flight condition there will be one mixture strength of heat release Δh_0 and burning velocity V'_2 satisfying the geometry presented. This is not to say that a higher heat release is ruled out: it only intensifies the shock wave at "I", thus increasing the thrust, and possibly the specific impulse as well. This was not determined owing to the complicated interaction of the reflected shock with the flame front. In computing Table I, the drag due to fuel injection and to flameholding has been neglected. The latter in particular is really the crux of the matter, and might be very large. On the other hand, with the special fuel considered, it may be reduced to a negligible value by means of continuous chemical ignition. It should be emphasized that the above mentioned example was chosen for its ease of calculation, and not for any particular excellence of the scheme.

Other configurations of either radial or 2 dimensional symmetry are shown in figs. 3 to 5. Assuming fig. 3 represents a body of revolution, the flamefront is stabilized on a gutter-like flameholder, and gradually propagates into the mixture, petering out as the mixture becomes too lean. Figs. 4 and 5 involve detonation waves stabilized in regions of decreasing cold flow velocity. A rough idea of the particle history in these cases may be gained from the T-V diagrams of each figure (see section 5).

4. In order to establish the feasibility of flameholding and ignition in a supersonic stream, it is proposed to do some experimental work. In this connection, the High Speed Aerodynamics section has some 5" x 5" test section nozzles, which the Gas Dynamics' Compressor could blow up to M = 2. Should these become available for the work proposed, they would greatly reduce the expense. A preliminary proposal for the experimental set-up is shown in fig. 6.

5. Calculations

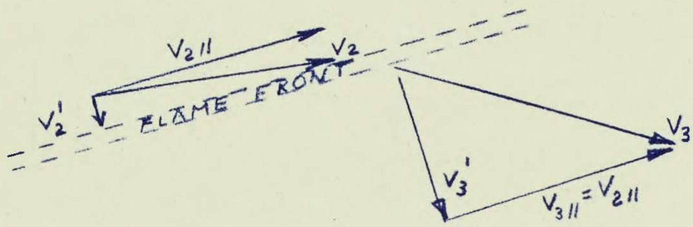
Symbols:

p	pressure	lbs/in^2
ρ	density	lbs/in^3
T	temperature	^oR
V	velocity	ft/sec.
M	Mach number	
q	Dynamic head	lbs/in^2
h	Enthalpy	Btu/lb
Δ	Increment	

Subscripts:

∞	Free stream
0	Stagnation
1	Behind Leading Edge shock
2	Behind Flame shock
3	Behind Flame front

The calculations were greatly simplified by using Spalding's T vs V chart for variable specific heat ratio (Ref.2) as well as tables, graphs and formulae from Ref.3. Fig.2 shows the steps on the above mentioned chart; starting at A_∞, B_2 represents the state just ahead of the flame front. The velocity here is resolved into two components, the one normal to the flame front being the burning velocity and represented by B_2' and B_2'' according as 100 fps. or 200 fps. be taken for the burning velocity V_2'.



Note that $B_2 B_2'$ represents the sine of the angle between V_2 and the flame front. Likewise $C_3 C_3'$ will represent the sine of the angle between V_3 and the flame front. Also, the total enthalpies at B_2, B_2', C_3 and C_3' are related by $h_{o_3} - h_{o_2} = h_{o_3}' - h_{o_2}'$.

To find C_3 we go along the momentum curve of B_2' until V_3' is attained, and on the same temperature level find C_3 where $V = V_3$ (for additional information please consult Ref.2). Knowing, then, the pressure distribution from shock tables, and the heat release from Fig.2, it is a simple matter to compute the data of Table I.

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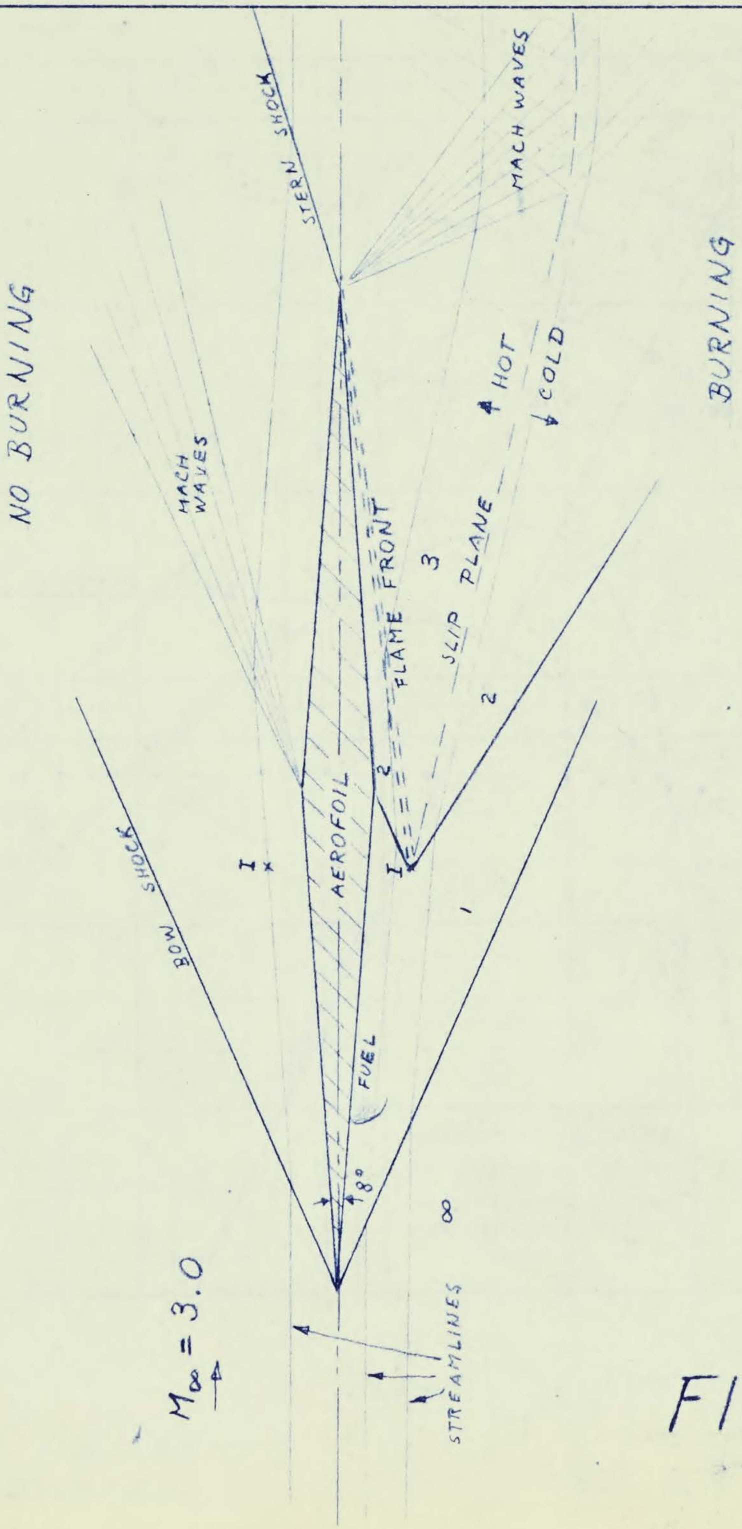
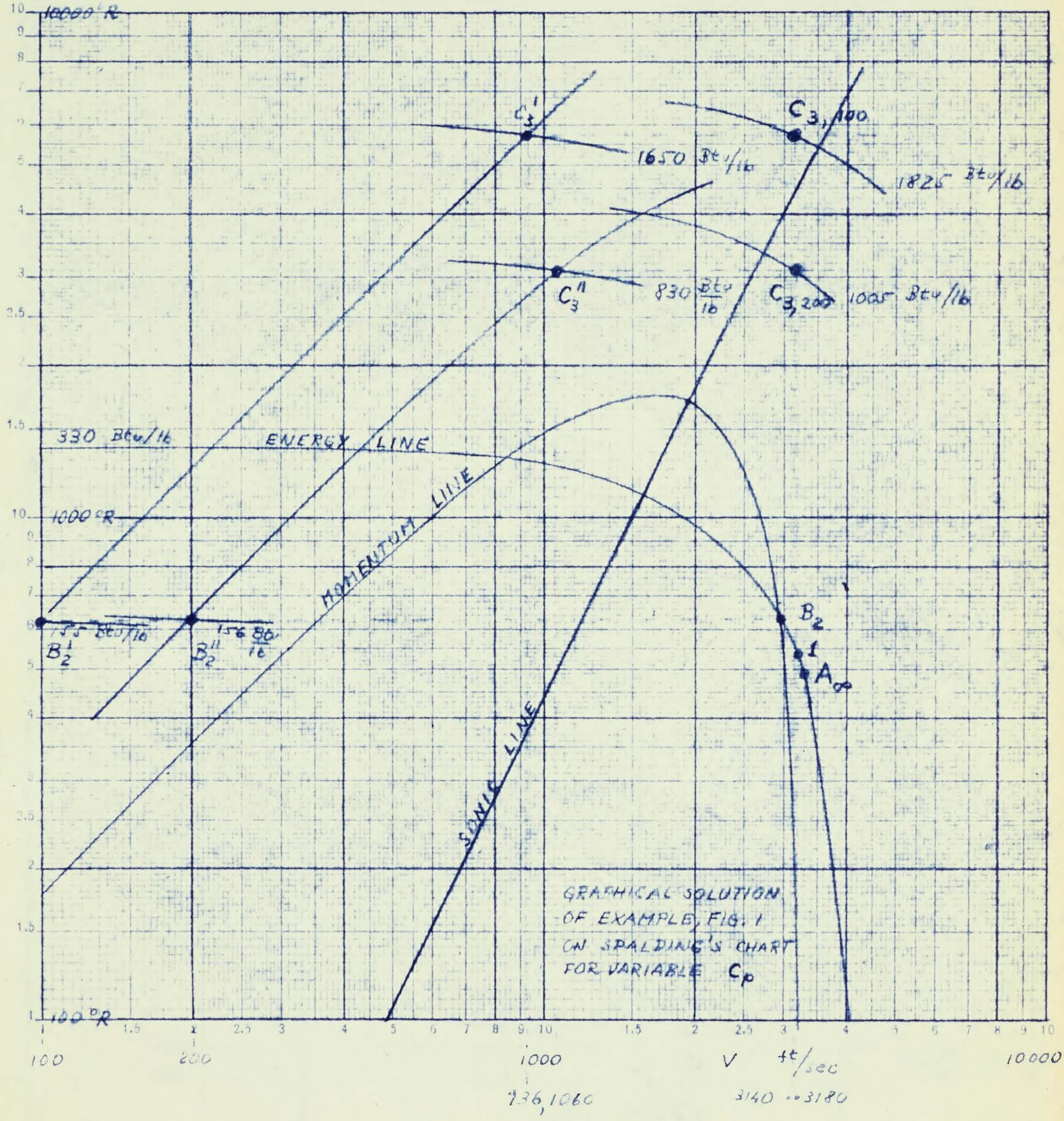


FIG. 1



NOTE: LOG-LOG COORDINATES.

FIG. 2

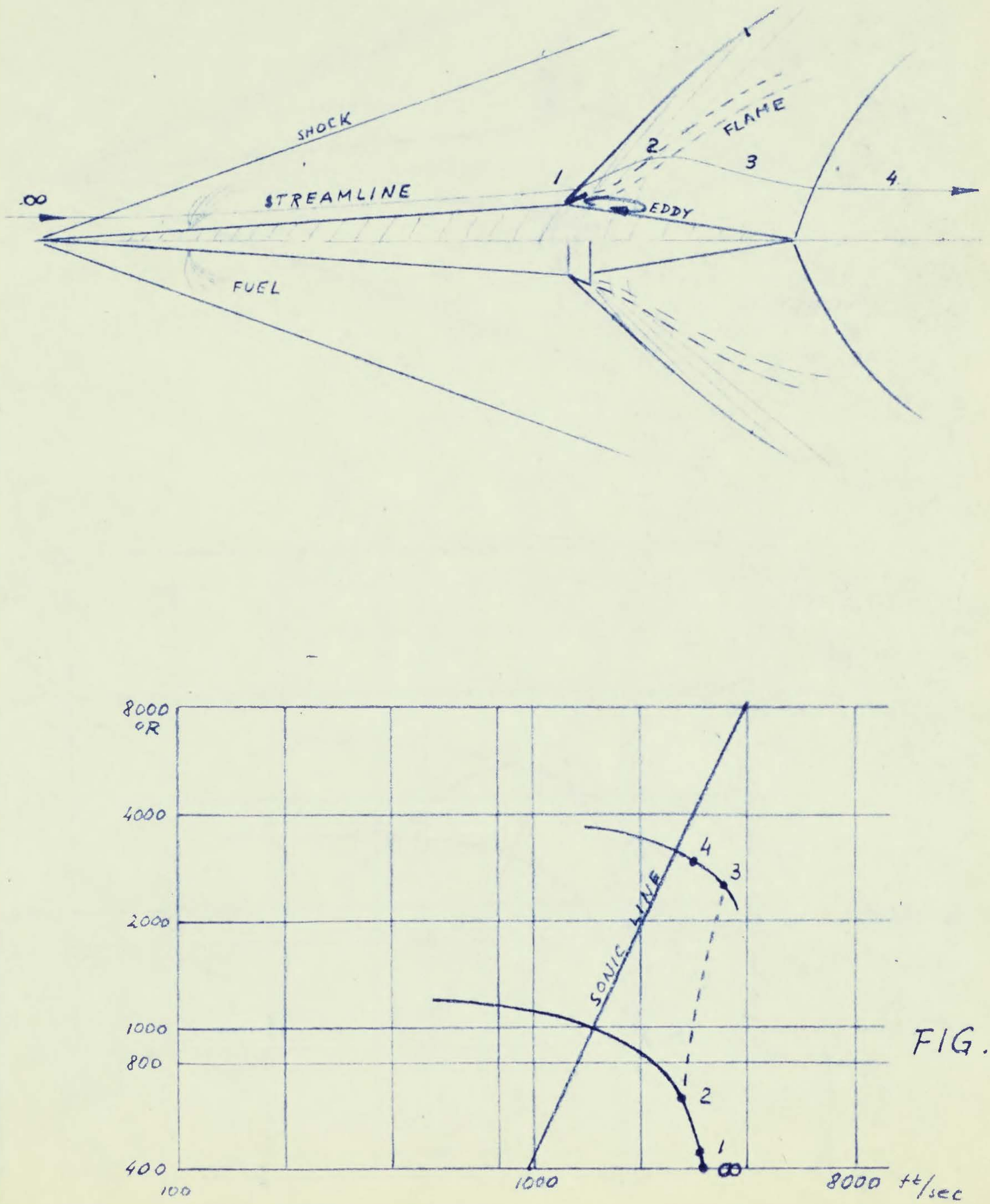
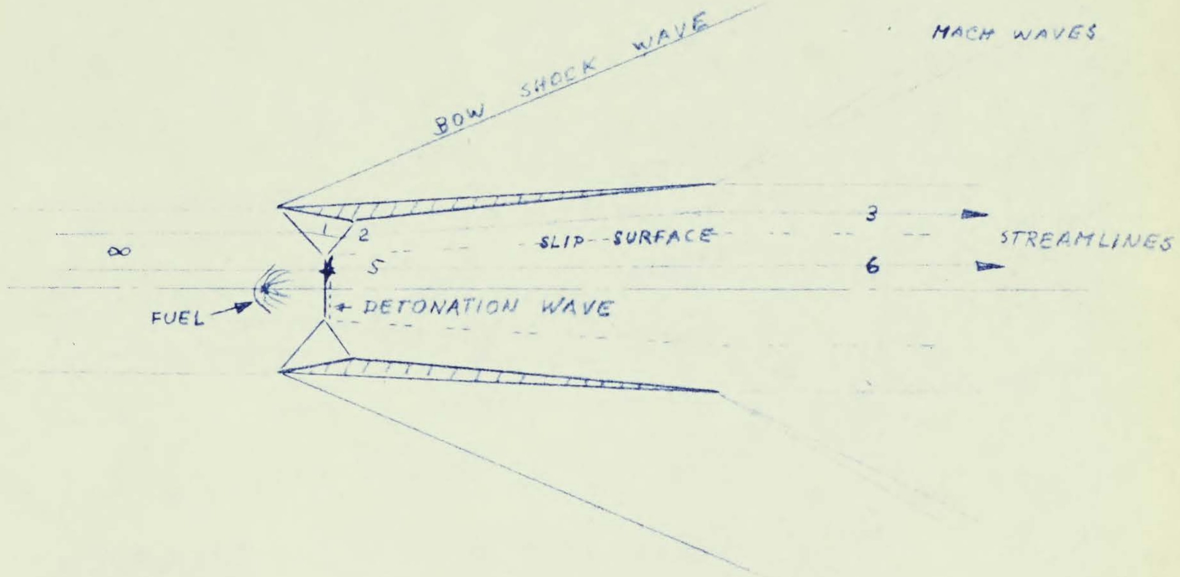

SHOCK
STREAMLINE
FLAME
EDDY
FUEL
∞
1
2
3
4
8000 °R
4000
2000
1000
800
400
100
1000
8000 ft/sec
SONIC LINE

FIG. 3


BOW SHOCK WAVE
MACH WAVES
∞
2
1
SLIP SURFACE
3
STREAMLINES
5
6
FUEL
DETONATION WAVE

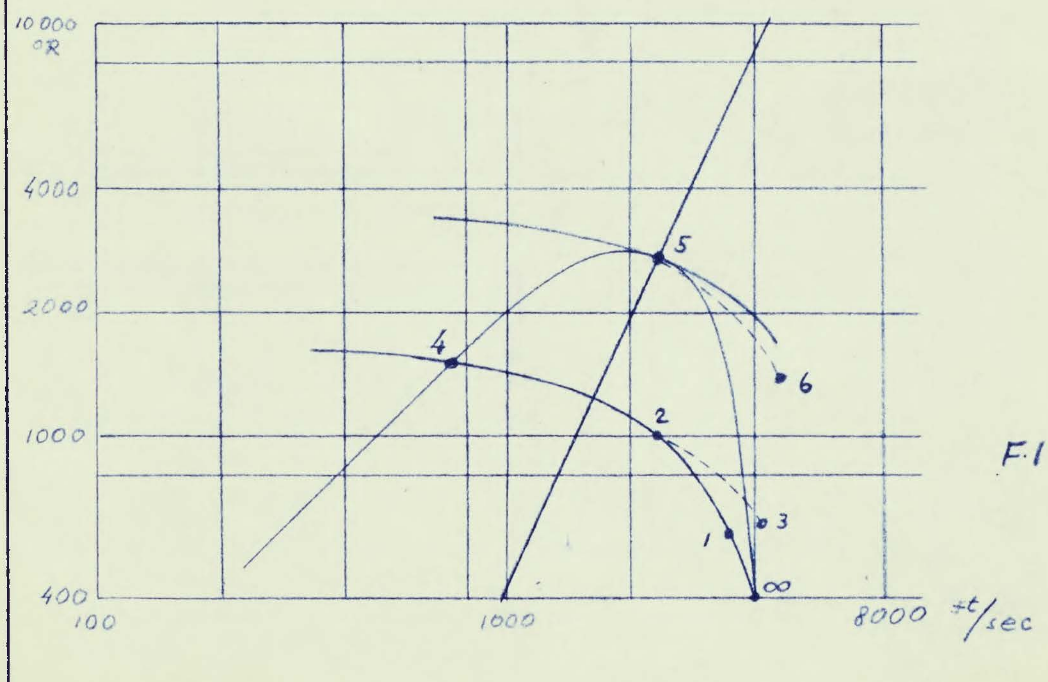

10 000 °R
4000
2000
1000
400
100
1000
8000
ft/sec
5
4
6
2
3
1
∞

FIG. 5