March 1958 73/INT.AERO/10

MARK III INTAKE DESIGN
PART II

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MARK III INTAKE DESIGN

PART II

EFFECT OF INTAKE AND EJECTOR GEOMETRY

ON THRUST AND FUEL CONSUMPTION

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INTRODUCTION

An investigation has been made of the effect of capture area and ejector geometry on thrust and fuel consumption for the Mark III aircraft. This report is a continuation of the preliminary intake design presented in 73/Int.Aero/5. Various ejector configurations have been considered and comparison with a convergent - divergent nozzle plus door arrangement is included. An indication is also given of the effect of replacing the air driven fuel pumps of the Series II engine with mechanical pumps.

The calculations have been made for maximum R.P.M. A/B ON conditions and Mach. 92 cruise. Under these conditions sufficient bypass area should be available at all times to pass the required mass flow.

The values of thrust and fuel flow given are intended for comparative purposes only. When the intake and ejector systems are finalized a more accurate determination of performance will be feasible.

A summary of the configurations considered is given below:-

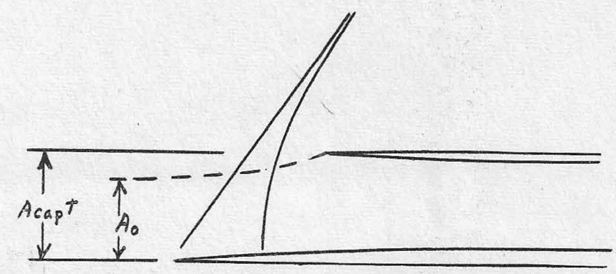
FIGS	DOOR	BYPASS	EJECTOR THROAT	EXIT	SHOWING
1 - 6	none	fixed	variable	variable	Effect of Exit Diameter
7 - 8	"	variable	"	"	Effect of variable vs fixed D_S & D_e
9 - 10	"	fixed	"	fixed	Effect of pressure recovery & capture area
11-12 Nozzle- Ejector-	variable none	none fixed	none variable	variable variable	Comparison of nozzle plus door with
13-14 Nozzle Ejector-	variable none	none variable	none variable	fixed fixed	ejector plus bypass " " "

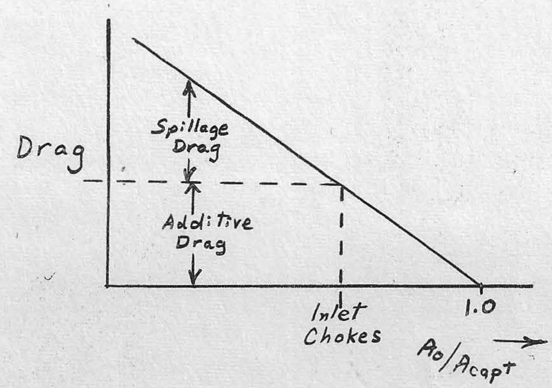
The curves show the jumps from subcritical to super critical inlet operation occuring at Mach 2.5. This is for convenience of calculation. The actual jump with probably be at Mach 2.4.

TERMINOLOGY

Spillage and Additive Drag:

When the inlet is running in the choked condition the drag associated with spillage will be called "additive drag". When the mass flow is reduced below choking the increase in drag will be called "spillage drag."





F_N = Net Thrust. Gross thrust minus momentum and spillage drag.

F_N' = Net Thrust minus additive drag.

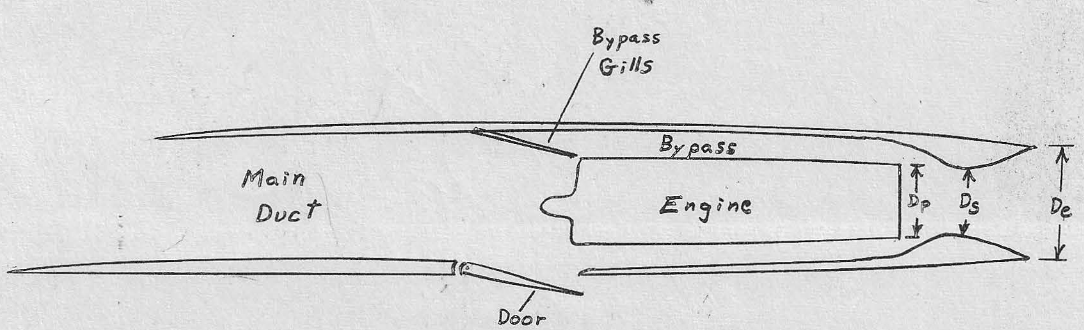
Variable Bypass - a bypass with varaible gills perferably at the bypass entrance, to control the amount of air going down the bypass.

Variable Door - a door in the main duct (or in the forward section of the bypass) which can be opened to dump air outside the aircraft.

D_p = Engine nozzle diameter

D_s = Ejector throat diameter

D_e = Ejector exit diameter



DISCUSSION:

1. Variation of Exit Diameter:

To produce maximum thrust an ejector should expand the primary and secondary mass flows down to ambient pressure at the exit. As the exit diameter deviates from design there is a fall off in thrust. Optimum exit diameters are plotted against Mach number in figure 15.

The ejector throat diameter has a large effect on pumping but a fairly small effect on thrust. Indications are that for a given μ and P_p/P_a the maximum thrust occurs with the smallest D_S that will pass the required flow. In figure 1-6 the ejector throat has been varied to provide the correct pumping in all cases. In figure 7 and 8 a variable bypass is required to regulate the flow.

A fixed exit diameter of 53" is excellent for A/B ON operation between Mach 1.2 and 2.5 and reasonable up to Mach 3.0. However, if it is used for A/B OFF, Mach .92 cruise, there is a large loss in performance. If a fully variable ejector is not possible a good compromise would be a 2 position ejector regulated by A/B setting, so that:

A/B ON D_e = 53" and D_s about 39"

A/B OFF $D_e = D_s$ = 33"

This arrangement would still require some sort of variable "door" in the main duct to handle the reduced R.P.M. cases.

2. Pressure Recovery and Capture Areas:

Two pressure recovery curves are considered. These are given in figure 13 of 73/Int.Aero/5. The "High" pressure recovery curve is obtained from the calculated shock structure, and the "Low" curve assumes additional losses. The "Low" curve is shown dotted in figure 13. At Mach 3.0 the engine requires a capture area of 11.6 ft^2, using the high pressure recovery, or 10.6 ft.^{2} using the low pressure recovery. If the low capture area is combined with the high pressure recovery the inlet opearates satisfactorily up to about 2.7 Mach number. Above this the inlet starves the engine.

The results of figure 9-10 are summarised below:

		PERFORMANCE Below M=2.7	PERFORMANCE Above M=2.7
High capture area	- High pressure recovery	poor	best
" " "	- Low pressure recovery	poor	poor
Low capture area	- High pressure recovery	best	fair
" " "	- Low pressure recovery	good	poor

Since an accurate determination of pressure recovery will be possible only after wind tunnel tests are made, a safe approach is to choose a low capture area. A compromise would be to choose a capture area mid-way between the two limits, with the view that this corresponds to a probable pressure recovery value.

3. Nozzle vrs Ejectors

In figures 11-14 the thrust and fuel consumption of a covergent - divergent nozzle is compared with that of an ejector. In figures 11 and 12 the exit diameters of both are considered variable. The nozzle configuration controls the inlet flow by means of a variable door in the duct, and the ejector does so by varying D_S (and hence bypass flow.) In figures 13 and 14 the exit diameter of both are fixed at 53". The nozzle configuration again regulates the flow by means of a door, but the ejector has a fixed throat of 41" and must regulate bypass flow by means of a variable bypass entrance or restrictor area.

The ejector gives better performance in all cases. Furthermore a nozzle with door is apt to interfer with both the internal air flow in the duct and the external air flow around the aircraft.

The ejector and nozzle thrust curves do not coalesce at Mach 3.0 where the bypass flow is zero. This is because air is still required to drive the fuel pumps and has been disposed of: down the bypass in the case of the ejector, or through the side of the aircraft in the case of the nozzle. The mass of air required to drive the fuel pumps is small (3% W_E), but the corresponding momentum drag at Mach 3.0 is large. A considerable improvement in performance is achieved by going to mechanically driven fuel pumps at high Mach numbers, as is shown by the dotted lines in figures 11-14. An allowance of ½% gross thrust was made for driving the mechanical pumps.

Calculations using mechanical pumps were made only at Mach 2.5 and 3.0. All other calculations consider air driven fuel pumps.

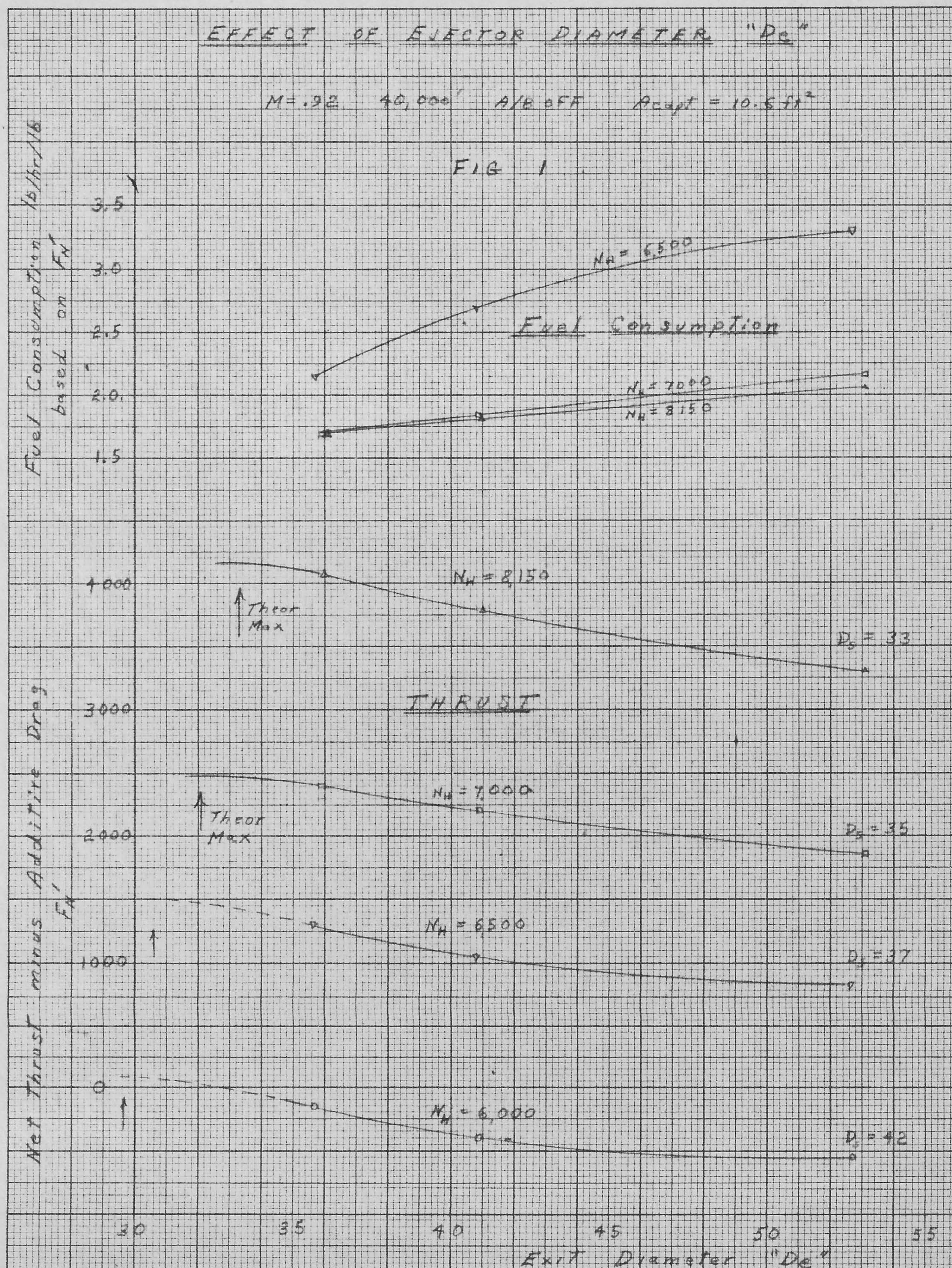
CONCLUSIONS:-

1. A variable exit area is required to avoid serious losses in thrust at either .92 cruise or Mach 3.0

2. The capture area should be as small as possible consistent with thrust requirements at Mach 3.0. In view of the range of possible pressure recovery values a mean capture area of about 11.0 ft^2 appears reasonable .

3. The ejector with bypass gives much better performance than the nozzle with door.

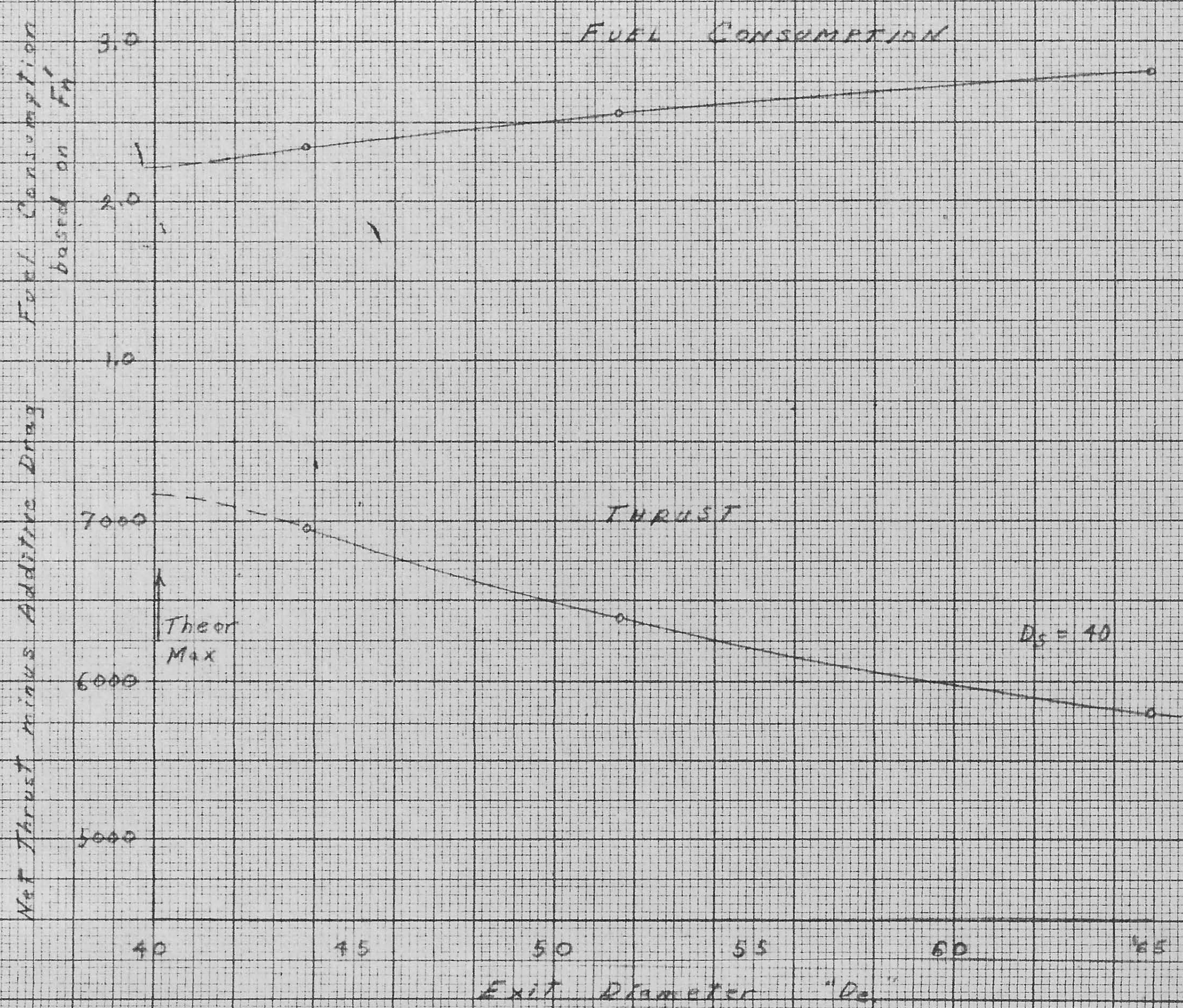
4. There is considerable gain in performance at high Mach numbers in using mechanical rather than air driven fuel pumps.


EFFECT OF EJECTOR DIAMETER "De"
M = .92 40,000' A/B OFF Acapt = 10.6 ft²
FIG 1
Fuel Consumption lb/hr/lb based on Fn'
3.5
3.0
2.5
2.0
1.5
NH = 6500
Fuel Consumption
NH = 7000
NH = 8150
Net Thrust minus Additive Drag Fn'
4000
3000
2000
1000
0
NH = 8,150
Theor Max
Ds = 33
THRUST
NH = 7,000
Theor Max
Ds = 35
NH = 6500
Ds = 37
NH = 6,000
Ds = 42
30
35
40
45
50
55
Exit Diameter "De"

EFFECT OF EJECTOR DIAMETER "D_e"

M = .92 40,000' A/B ON $A_{capt} = 10.6\ ft^2$

FIG 2.



EFFECT OF EJECTOR DIAMETER "D_e"

$M = 1.50$ 50,000' A/B ON $A_{c \cdot opt} = 10.6$

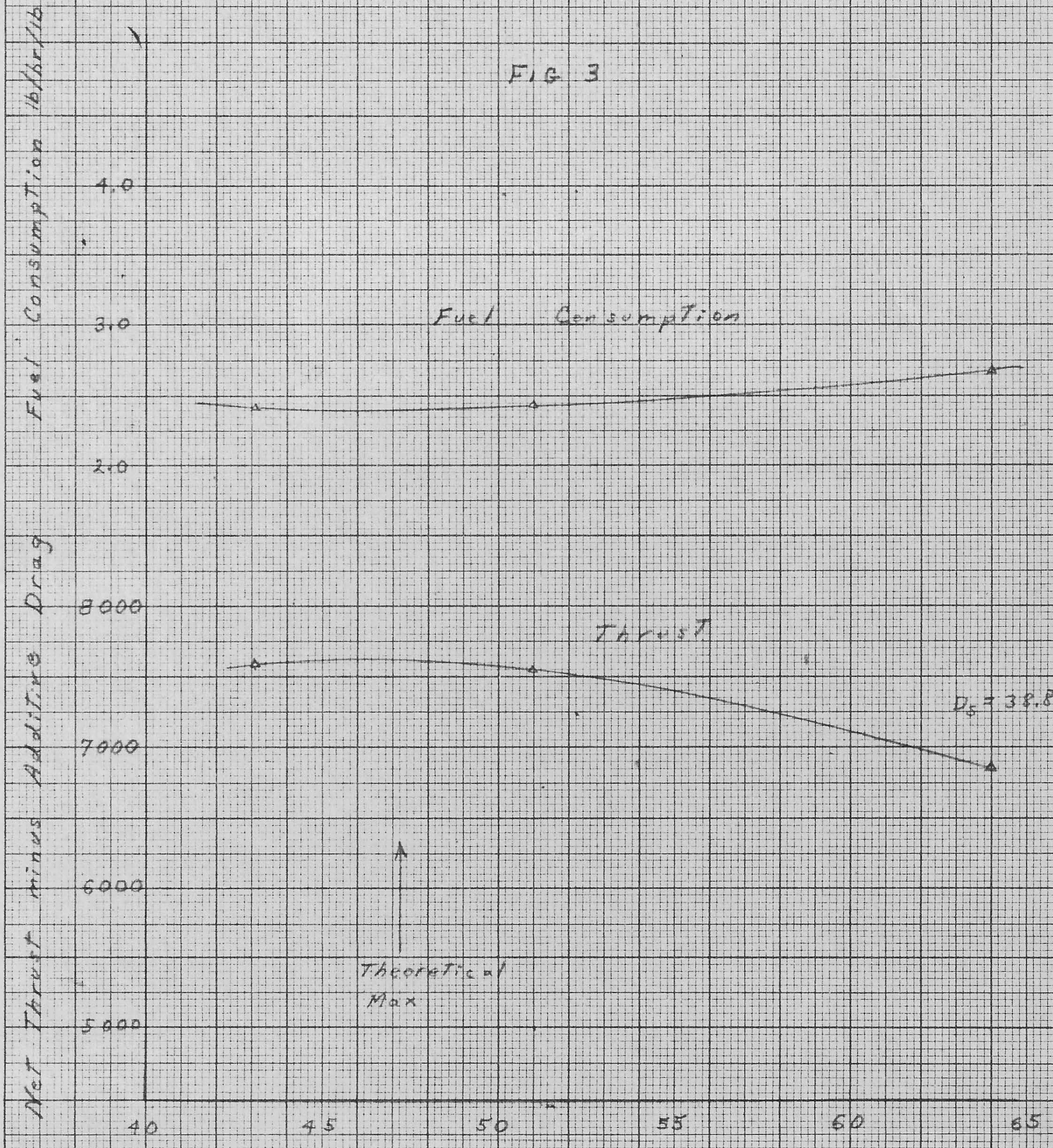
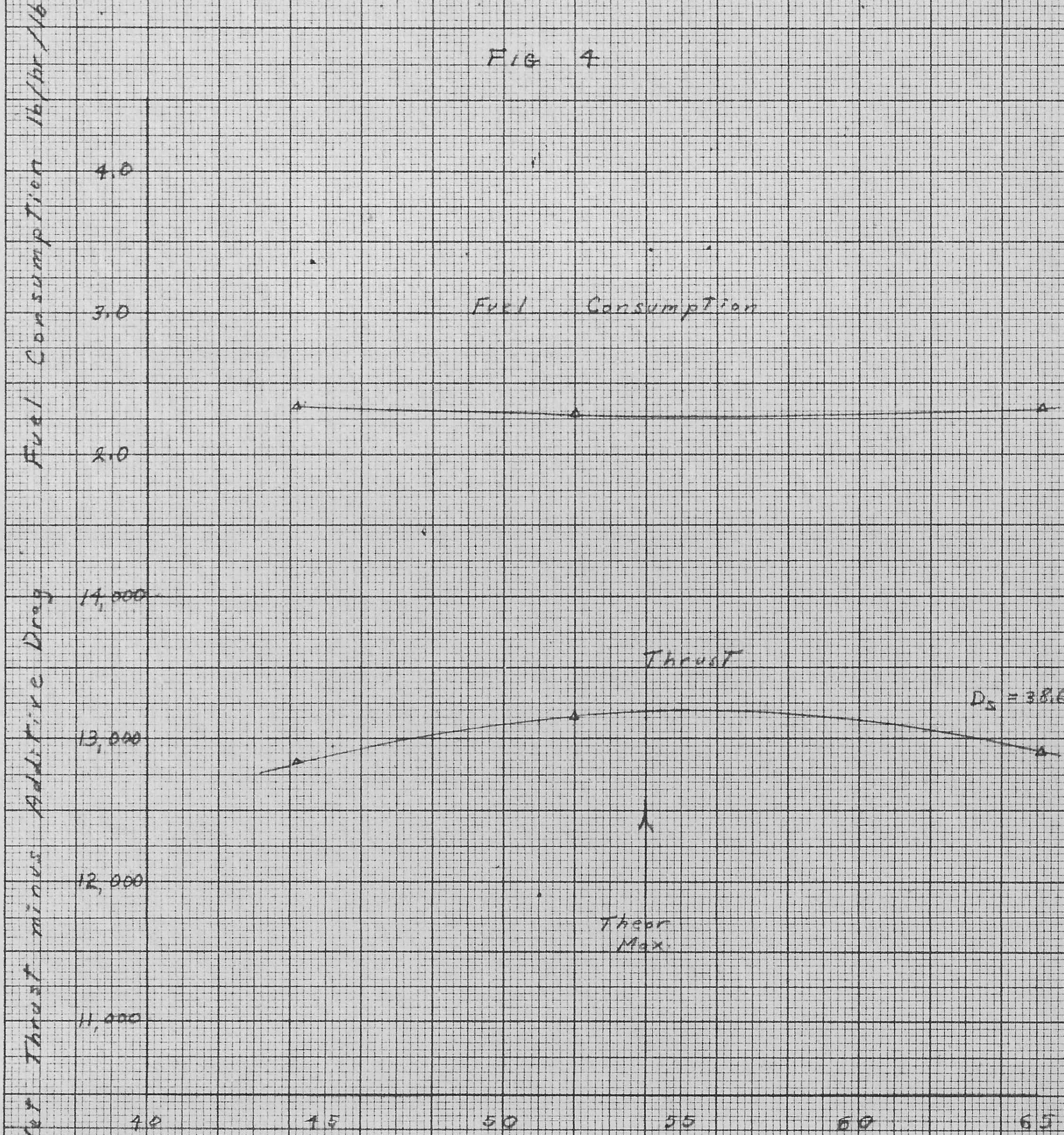


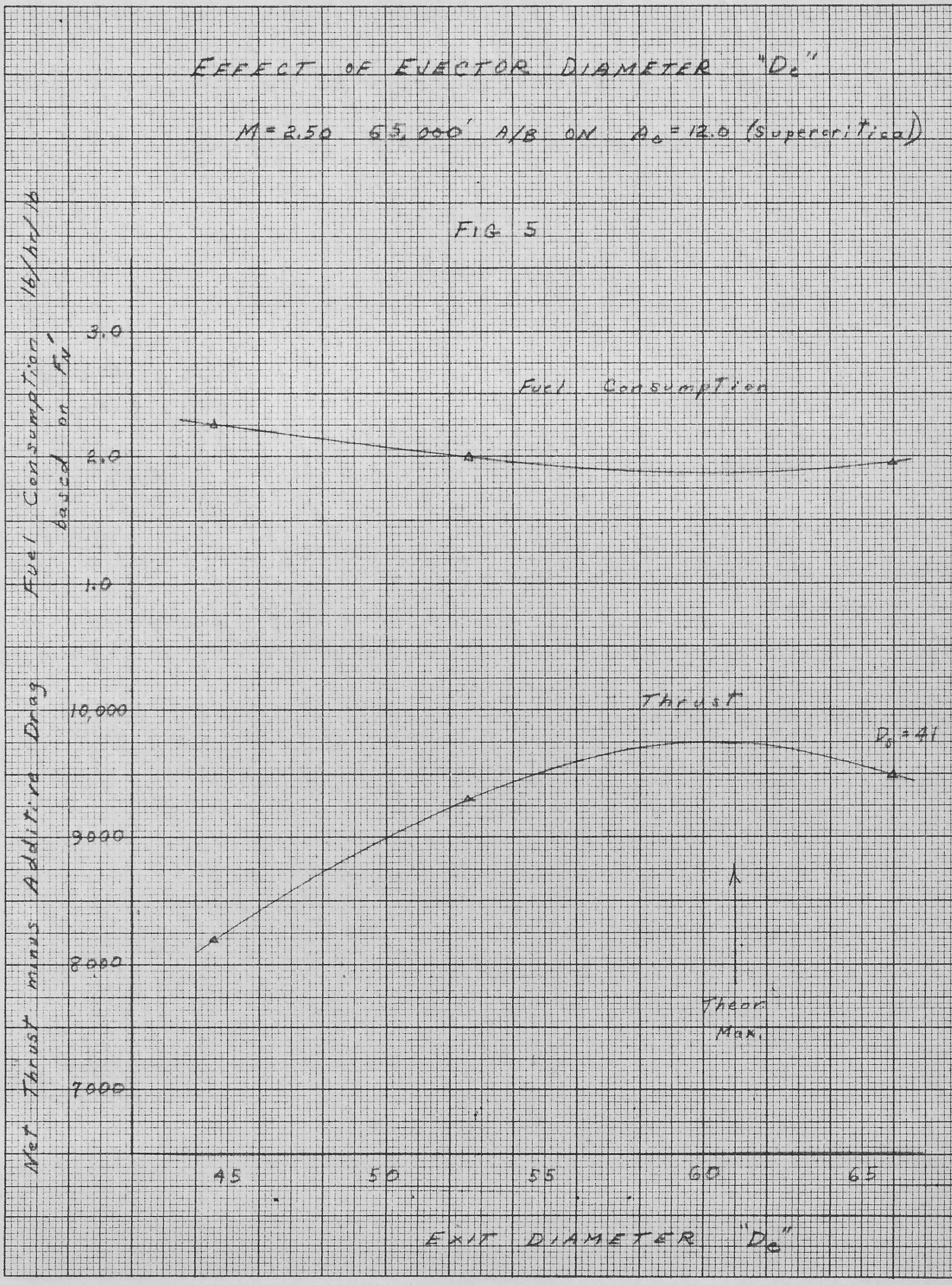
FIG 3

EFFECT OF EJECTOR DIAMETER "De"

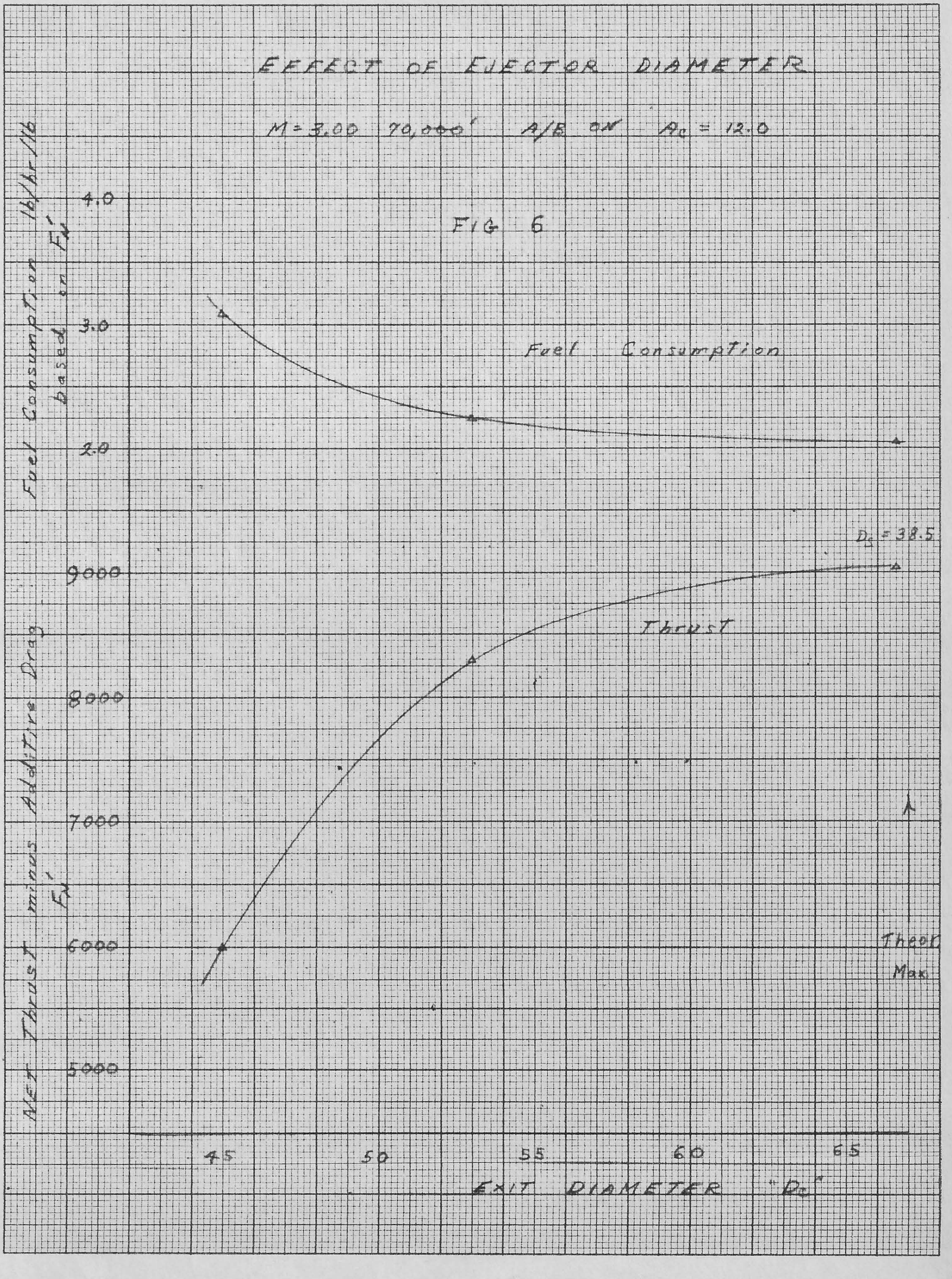
M = 2.00 50,000' A/B ON Ae = 10.5

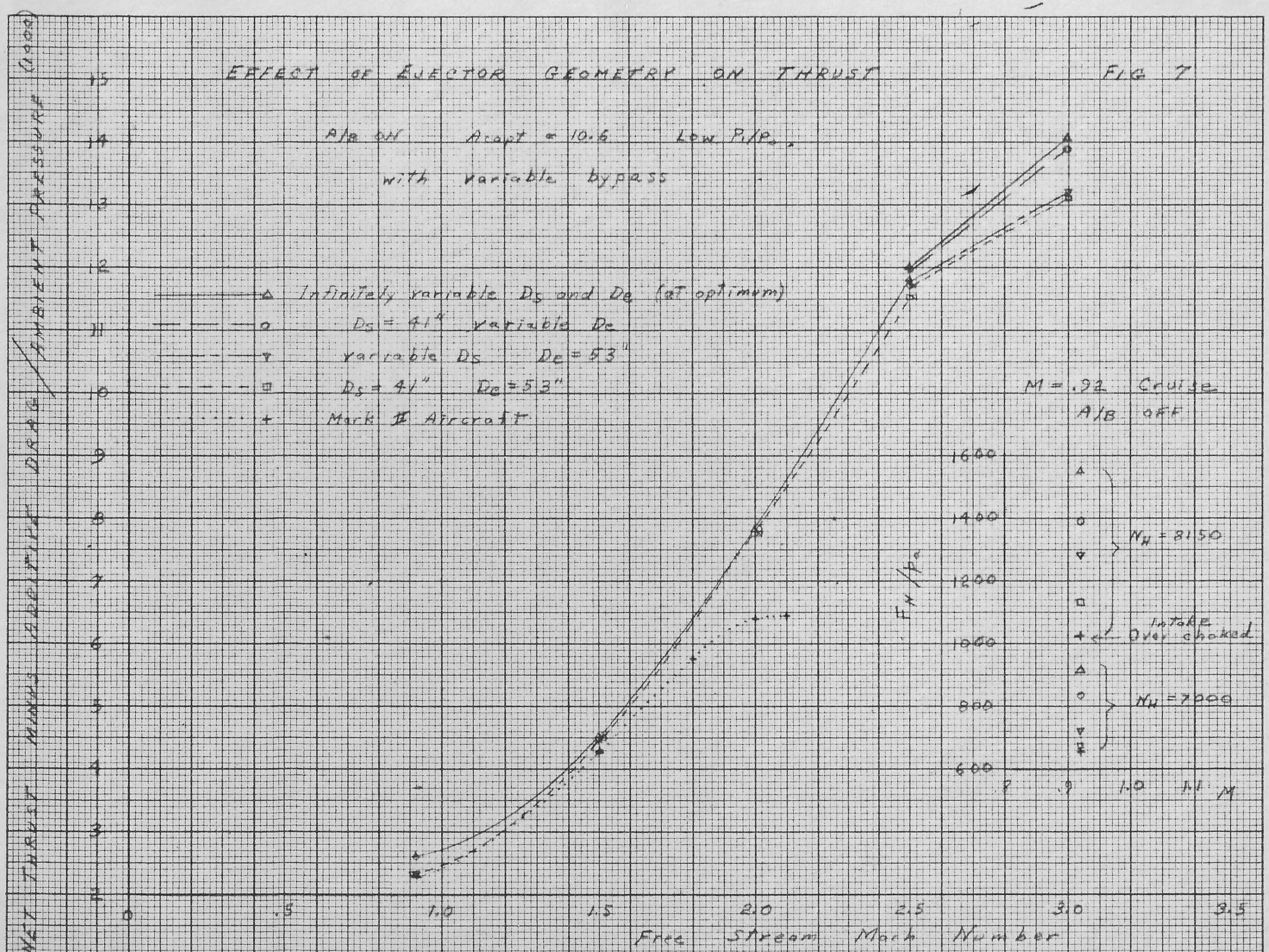
FIG 4



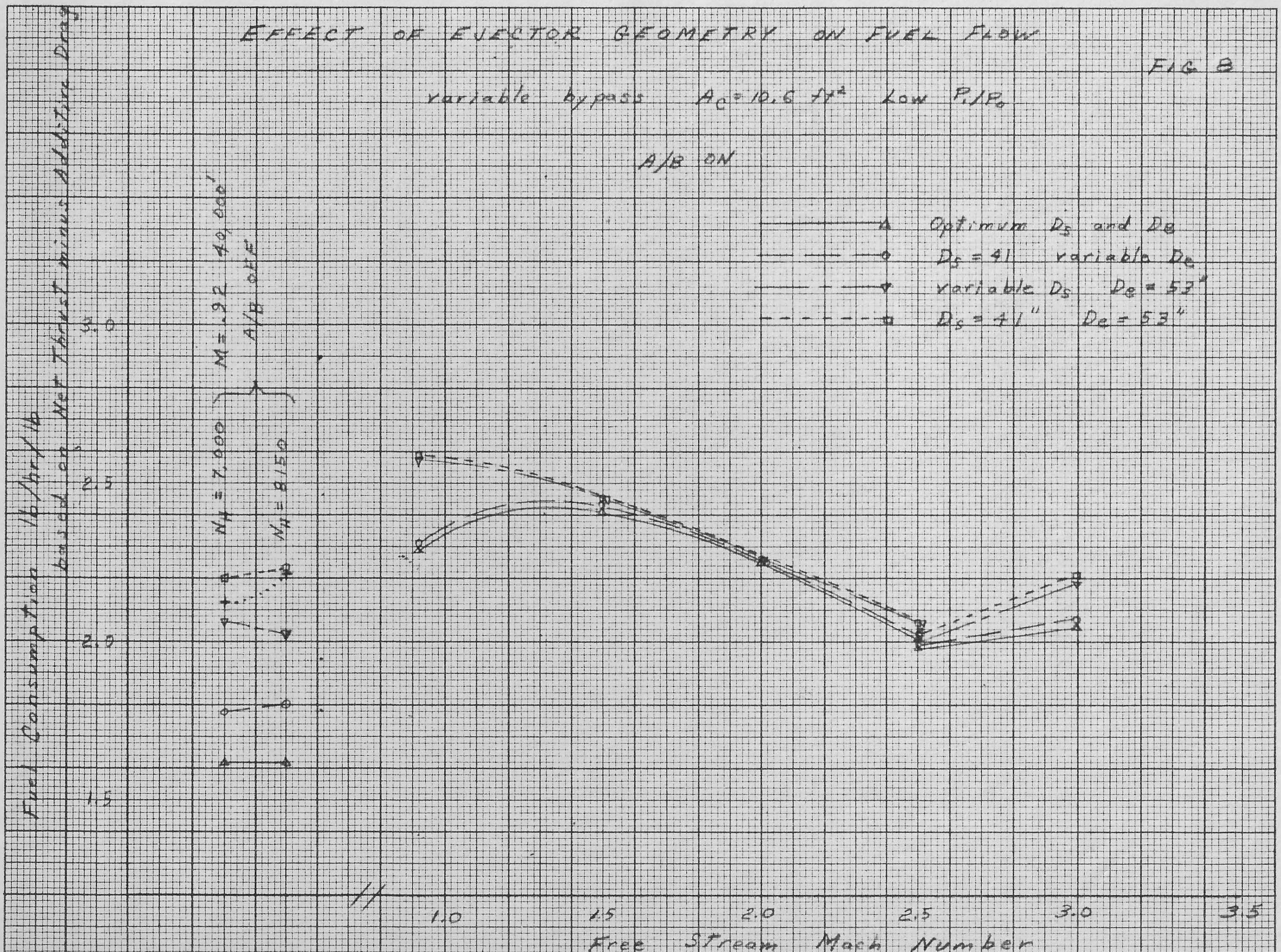


EFFECT OF EJECTOR DIAMETER "De"
M = 2.50 65,000' A/B ON Ae = 12.0 (Supercritical)
FIG 5
Fuel Consumption lb/hr/lb based on Fn'
3.0
2.0
1.0
Fuel Consumption
Net Thrust minus Additive Drag
10,000
9000
8000
7000
Thrust
Ds = 41
Theor. Max.
45
50
55
60
65
EXIT DIAMETER "De"

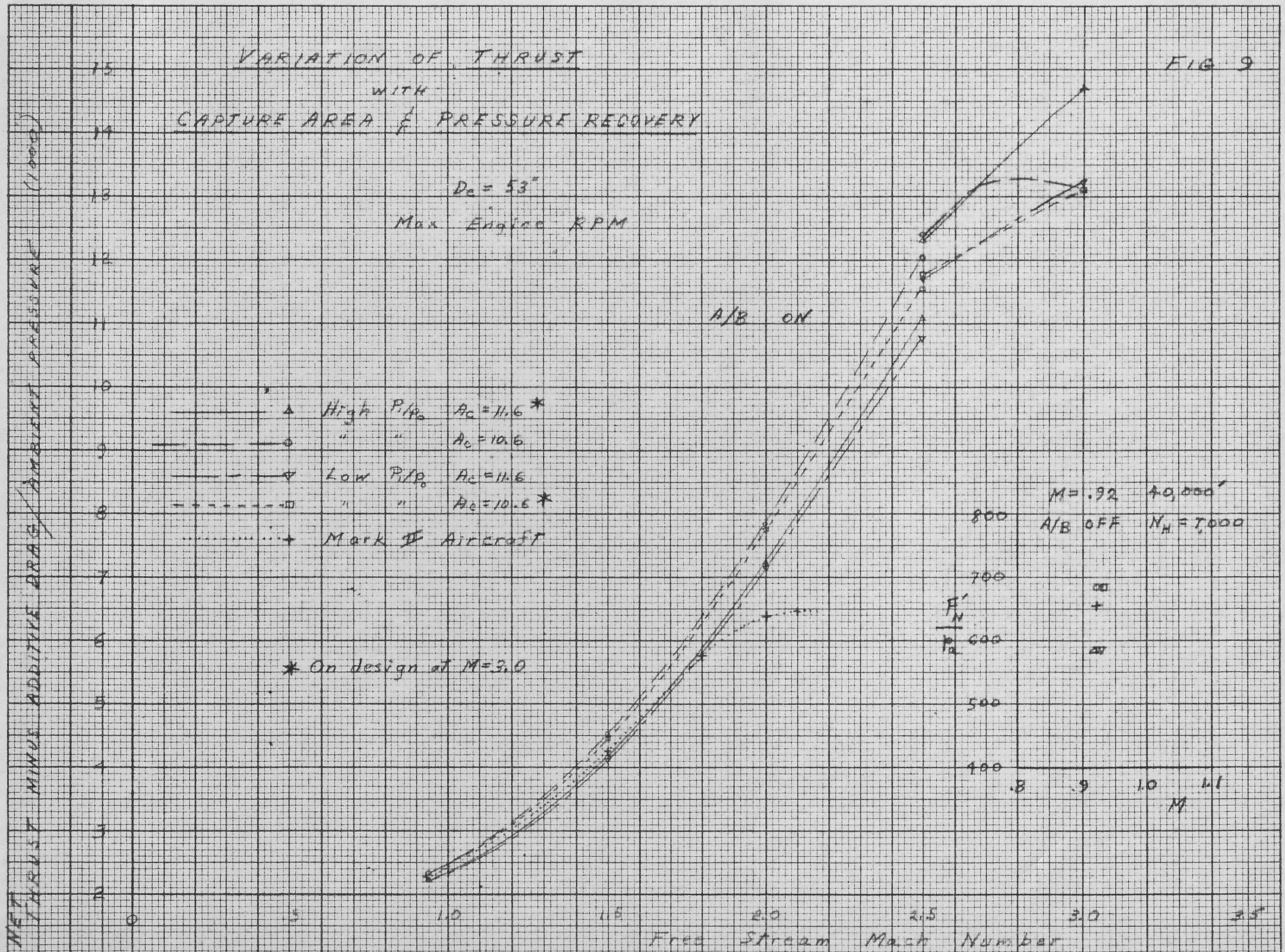

EFFECT OF EJECTOR DIAMETER
M = 3.00 70,000' A/B ON A_c = 12.0
FIG 6
Fuel Consumption lb/hr/lb based on F_N'
4.0
3.0
2.0
Fuel Consumption
D_S = 38.5
9000
8000
7000
6000
5000
Thrust
Net Thrust minus Additive Drag F_N'
Theor.
Max.
45
50
55
60
65
EXIT DIAMETER "D_e"

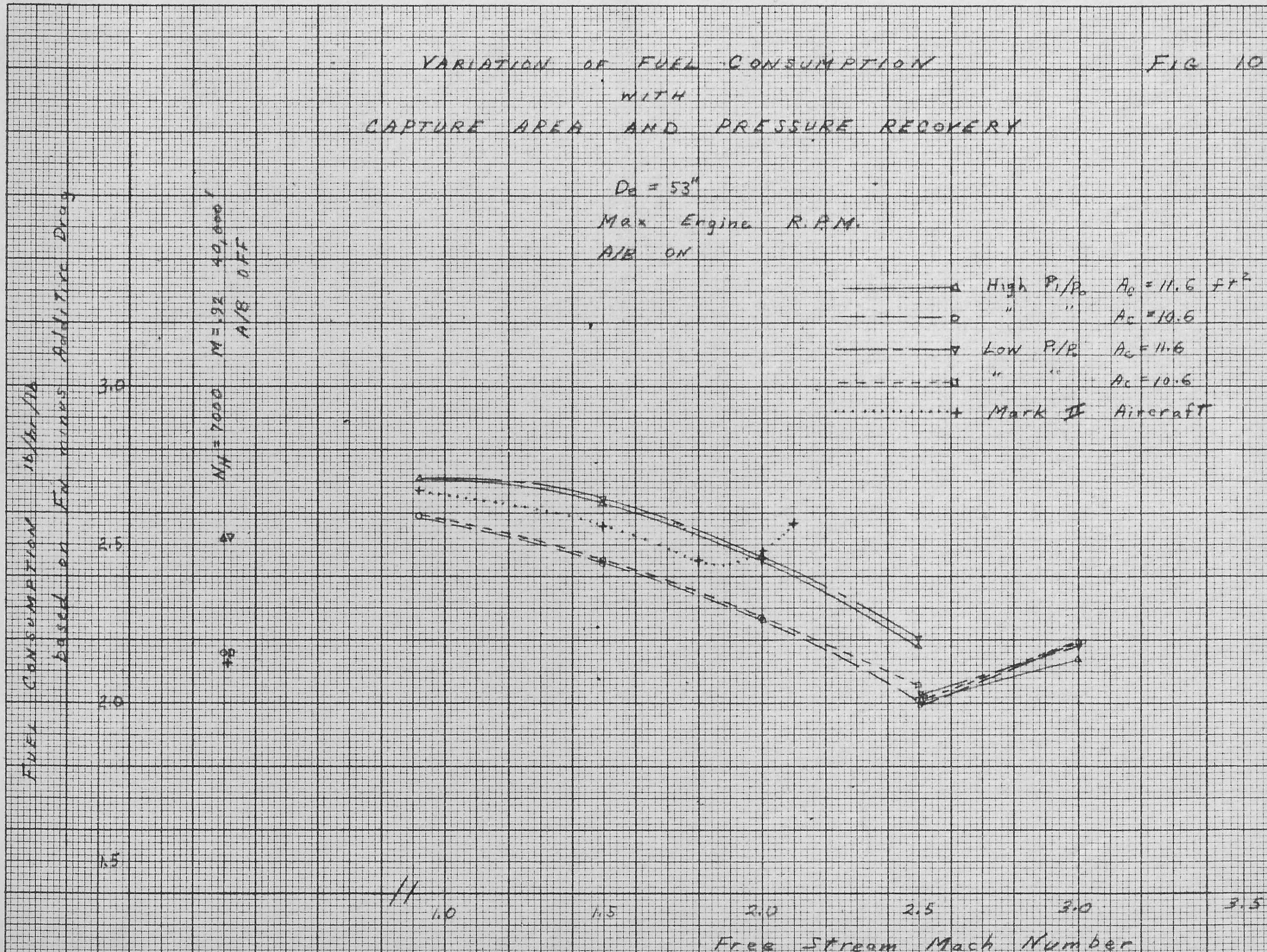


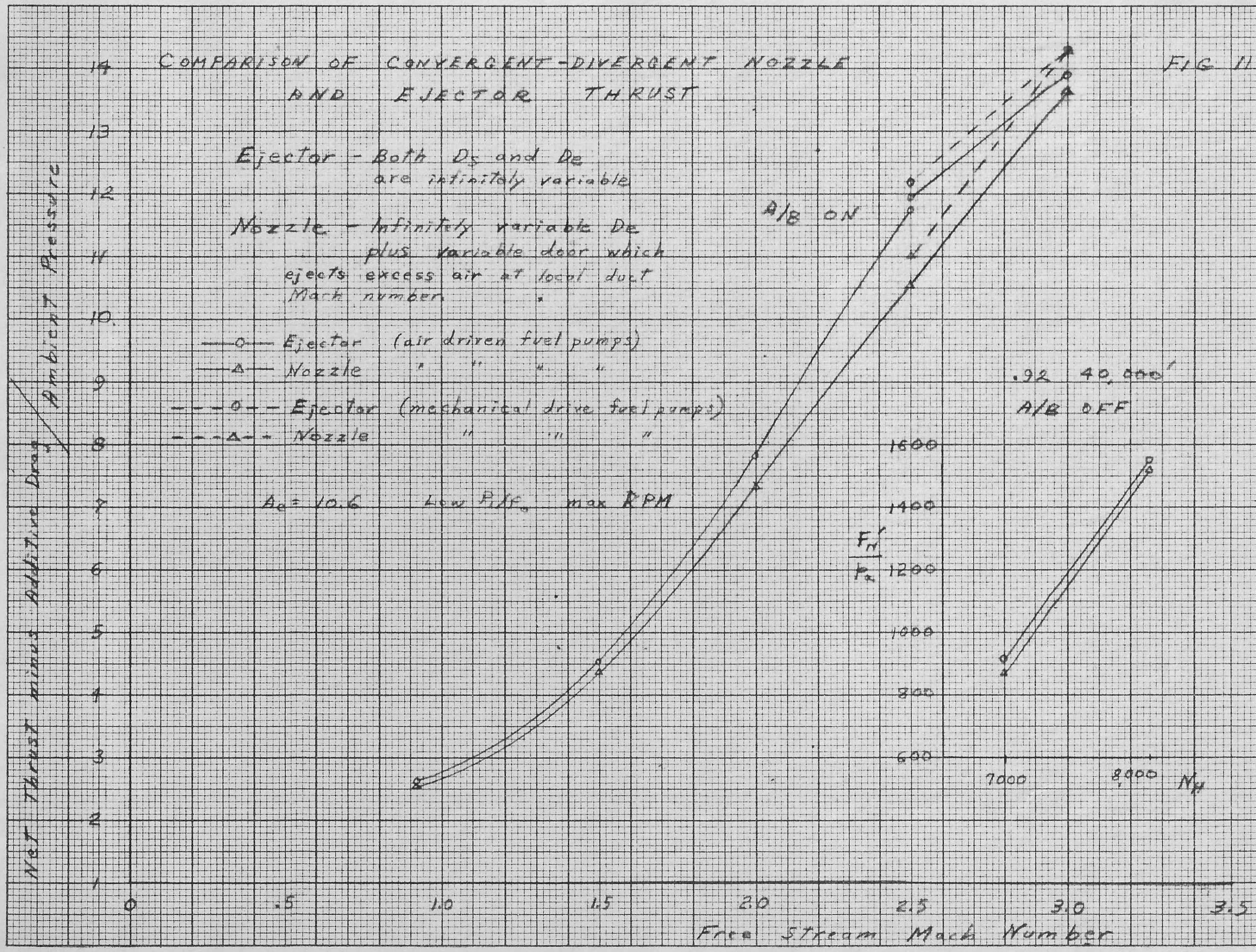
EFFECT OF EJECTOR GEOMETRY ON THRUST
FIG 7
A/B ON Acapt = 10.6 Low P/P
with variable bypass
Infinitely variable Ds and De (at optimum)
Ds = 41" variable De
variable Ds De = 53"
Ds = 41" De = 53"
Mark II Aircraft
M = .92 Cruise
A/B OFF
NH = 8150
NH = 7000
Intake Over choked
1600
1400
1200
1000
800
600
.8
.9
1.0
1.1
M
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number
NET THRUST MINUS ADDITIVE DRAG / AMBIENT PRESSURE (1000)

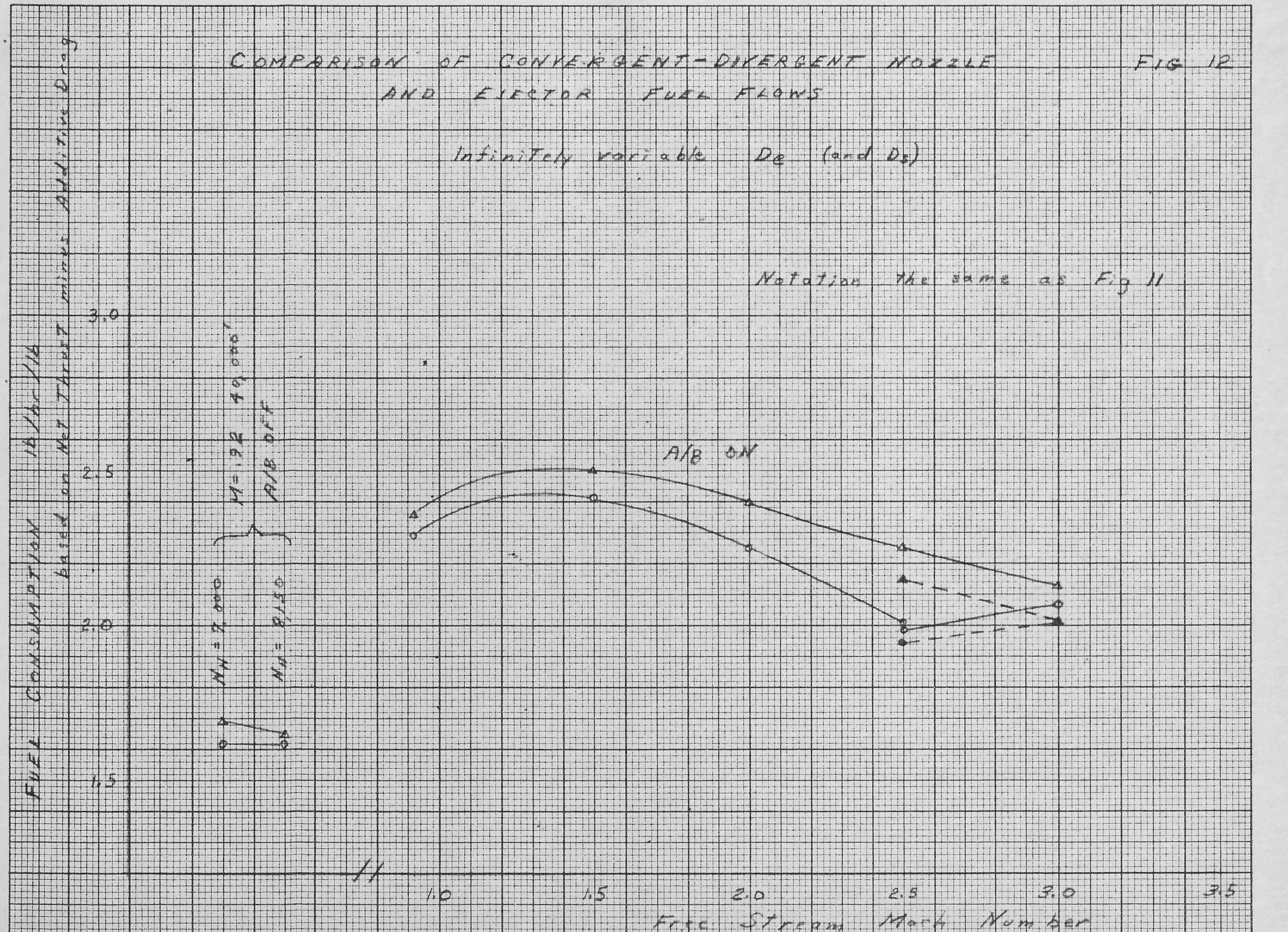


EFFECT OF EJECTOR GEOMETRY ON FUEL FLOW
FIG 8
variable bypass A_C = 10.6 ft² Low P_i/P_o
A/B ON
Optimum D_S and D_e
D_S = 41 variable D_e
variable D_S D_e = 53"
D_S = 41" D_e = 53"
M = .92 40,000'
A/B OFF
N_H = 7,000
N_H = 8150
Fuel Consumption lb/hr/lb
based on Net Thrust minus Additive Drag
3.0
2.5
2.0
1.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number

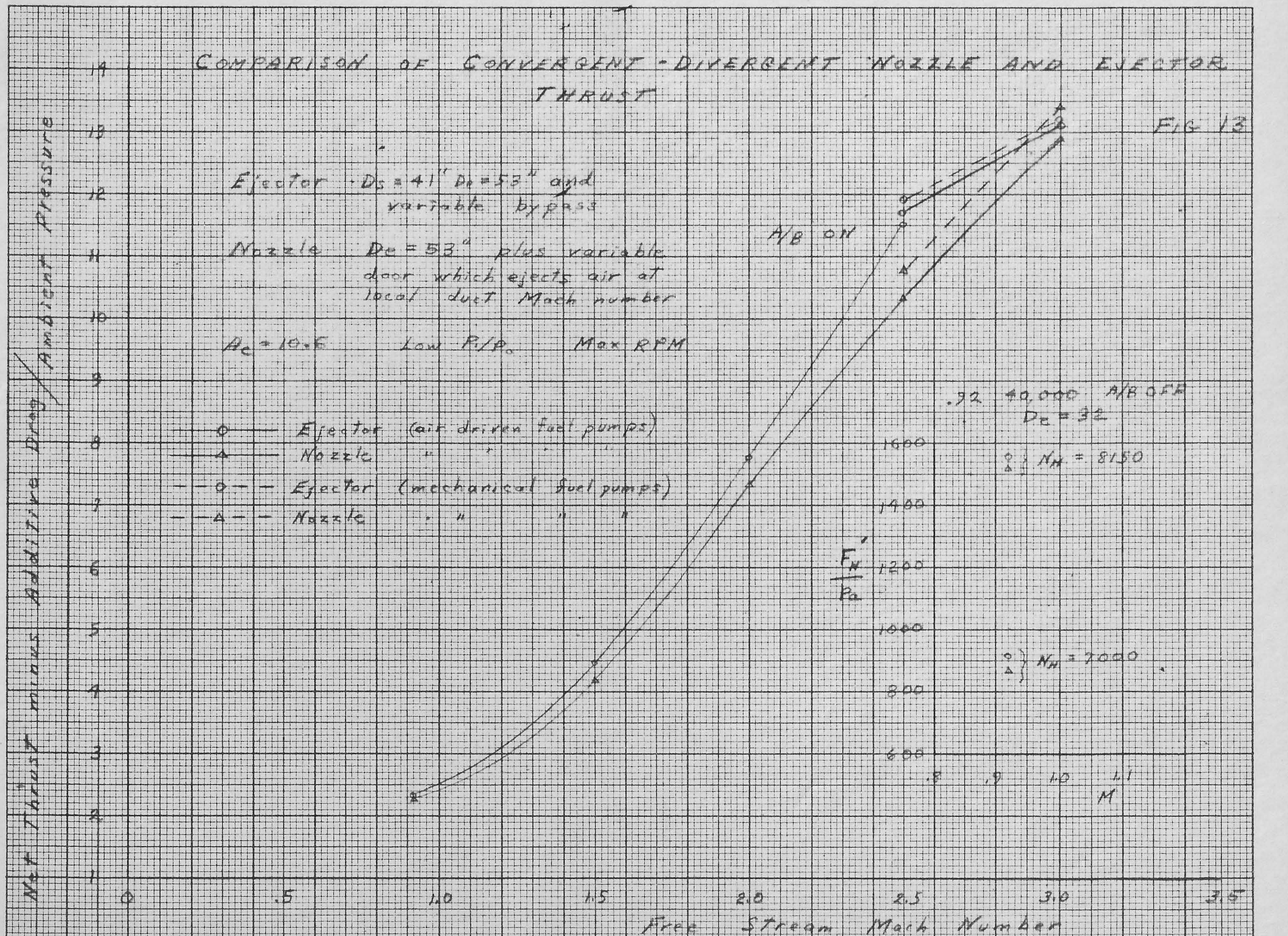

VARIATION OF THRUST
WITH
CAPTURE AREA & PRESSURE RECOVERY
FIG 9
D_c = 53"
Max Engine RPM
A/B ON
High P_1/P_0 A_c = 11.6 *
" " A_c = 10.6
Low P_1/P_0 A_c = 11.6
" " A_c = 10.6 *
Mark II Aircraft
* On design at M=3.0
M = .92 40,000'
A/B OFF N_H = 7,000
F_N' / P_a
800
700
600
500
400
.8
.9
1.0
1.1
M
NET THRUST MINUS ADDITIVE DRAG / AMBIENT PRESSURE (1000)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number


VARIATION OF FUEL CONSUMPTION
WITH
CAPTURE AREA AND PRESSURE RECOVERY
FIG 10
D_e = 53"
Max Engine R.P.M.
A/B ON
High P_1/P_0 A_c = 11.6 ft²
" " A_c = 10.6
Low P_1/P_0 A_c = 11.6
" " A_c = 10.6
Mark II Aircraft
N_H = 7000 M = .92 40,000'
A/B OFF
Fuel Consumption lb/hr/lb
based on Fn minus Additive Drag
1.5
2.0
2.5
3.0
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number


COMPARISON OF CONVERGENT-DIVERGENT NOZZLE
AND EJECTOR THRUST
FIG 11
Ejector - Both Ds and De are infinitely variable
Nozzle - Infinitely variable De plus variable door which ejects excess air at local duct Mach number
—o— Ejector (air driven fuel pumps)
—Δ— Nozzle " " " "
- - -o- - Ejector (mechanical drive fuel pumps)
- - -Δ- - Nozzle " " "
Ae = 10.6 Low Pt/Po max RPM
A/B ON
.92 40,000'
A/B OFF
Fn'/Pa
1600
1400
1200
1000
800
600
7000
8000
NH
Net Thrust minus Additive Drag / Ambient Pressure
Free Stream Mach Number
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
.5
1.0
1.5
2.0
2.5
3.0
3.5



COMPARISON OF CONVERGENT-DIVERGENT NOZZLE
AND EJECTOR FUEL FLOWS
FIG 12
Infinitely variable De (and Ds)
Notation the same as Fig 11
A/B ON
NH = 2,000
NH = 8,150
M = .92 40,000'
A/B OFF
FUEL CONSUMPTION lb/hr/lb
based on Net Thrust minus Additive Drag
3.0
2.5
2.0
1.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number

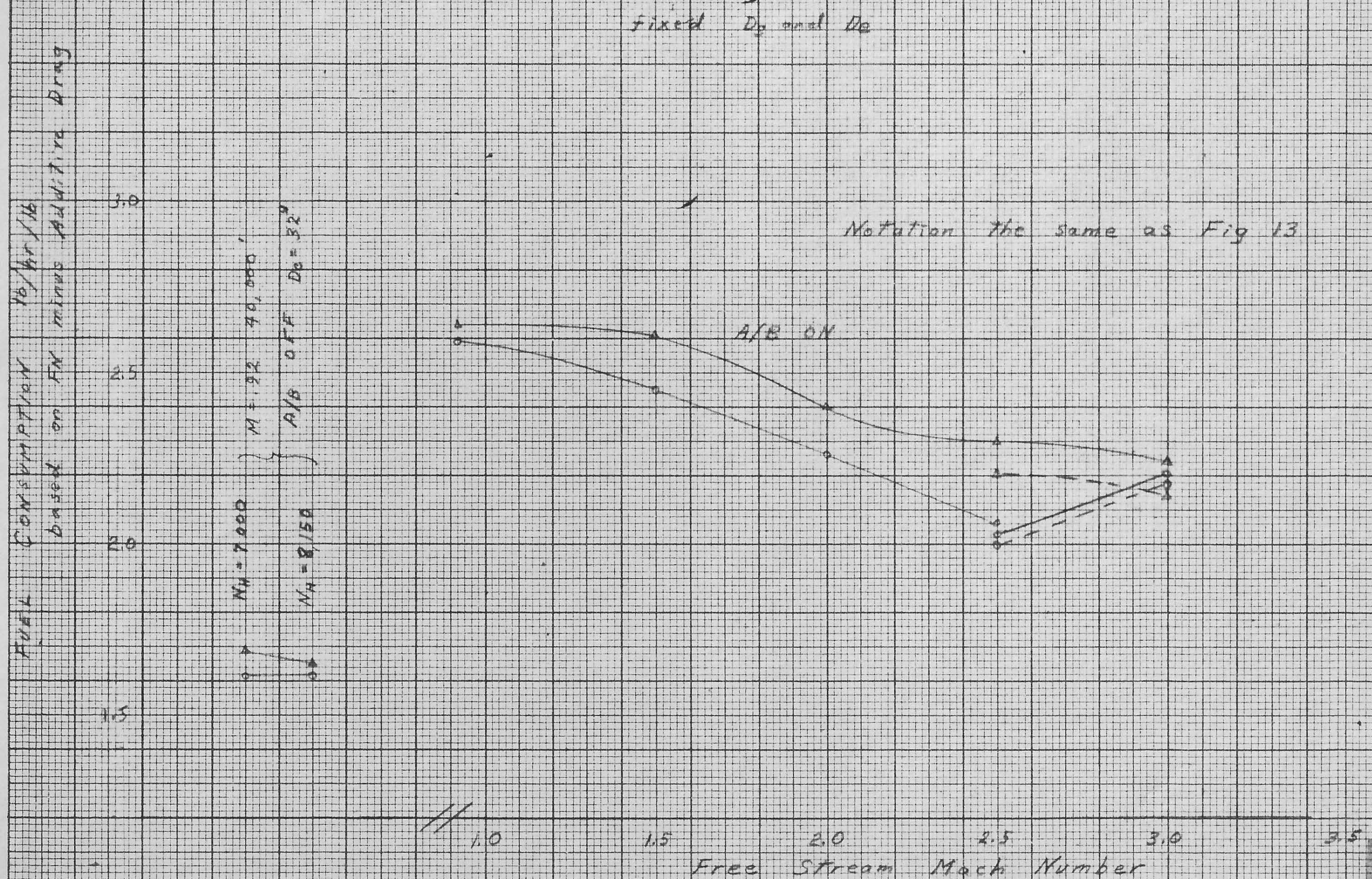


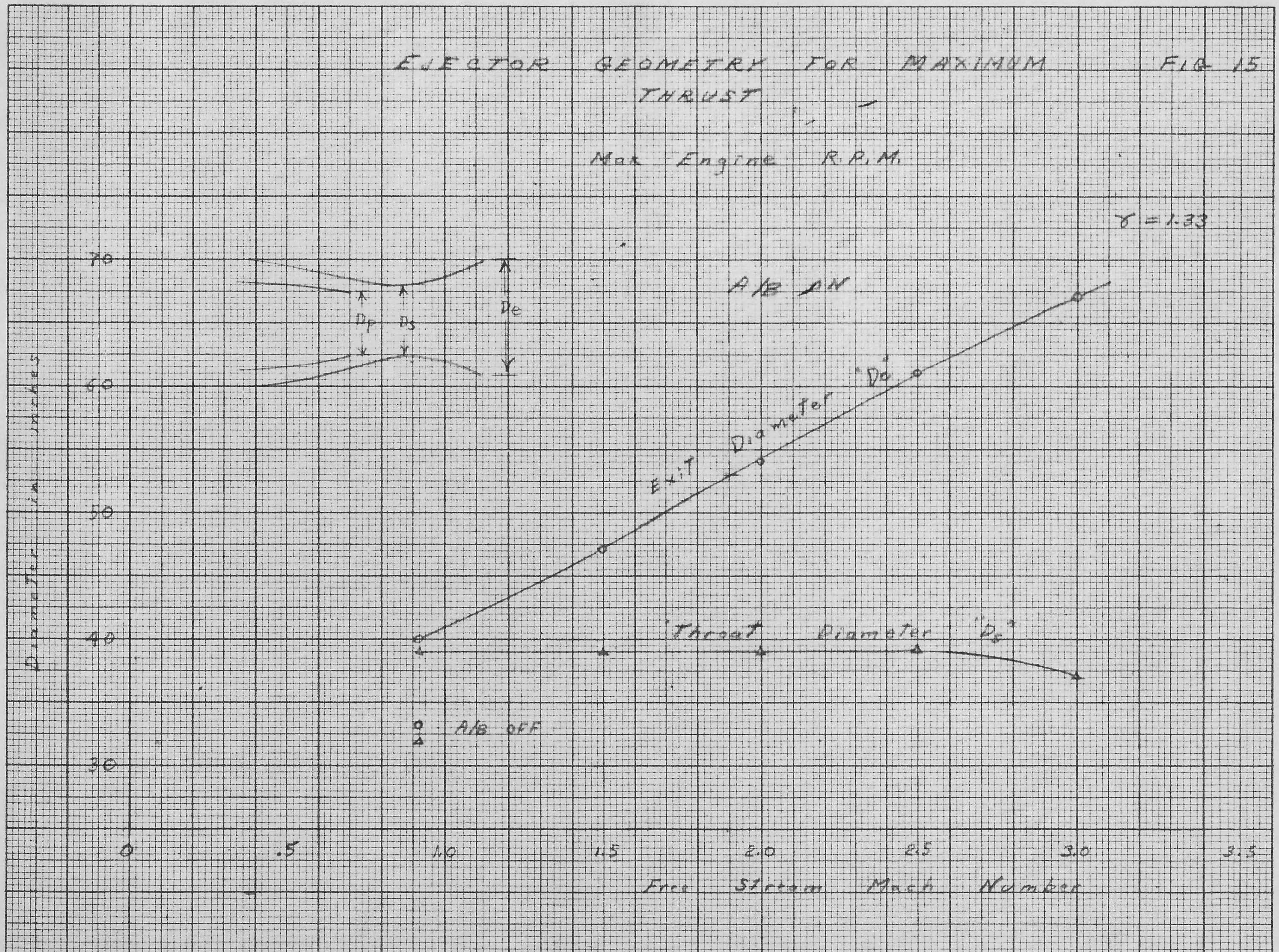
COMPARISON OF CONVERGENT - DIVERGENT NOZZLE AND EJECTOR THRUST
FIG 13
Ejector · Ds = 41" De = 53" and variable bypass
Nozzle De = 53" plus variable door which ejects air at local duct Mach number
Ae = 10.6 Low P/Po Max RPM
—o— Ejector (air driven fuel pumps)
—Δ— Nozzle " "
– –o– – Ejector (mechanical fuel pumps)
– –Δ– – Nozzle " " "
A/B ON
.92 40,000 A/B OFF
De = 32
o Δ } NH = 8150
o Δ } NH = 7000
F'N / Pa
1600
1400
1200
1000
800
600
.8
.9
1.0
1.1
M
Net Thrust minus Additive Drag / Ambient Pressure
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number

COMPARISON OF CONVERGENT-DIVERGENT NOZZLE AND EJECTOR

FUEL CONSUMPTION

Fig 14




EJECTOR GEOMETRY FOR MAXIMUM THRUST
FIG 15
Max Engine R.P.M.
γ = 1.33
A/B ON
A/B OFF
Exit Diameter "De"
Throat Diameter "Ds"
De
Dp
Ds
70
60
50
40
30
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number
Diameter in inches

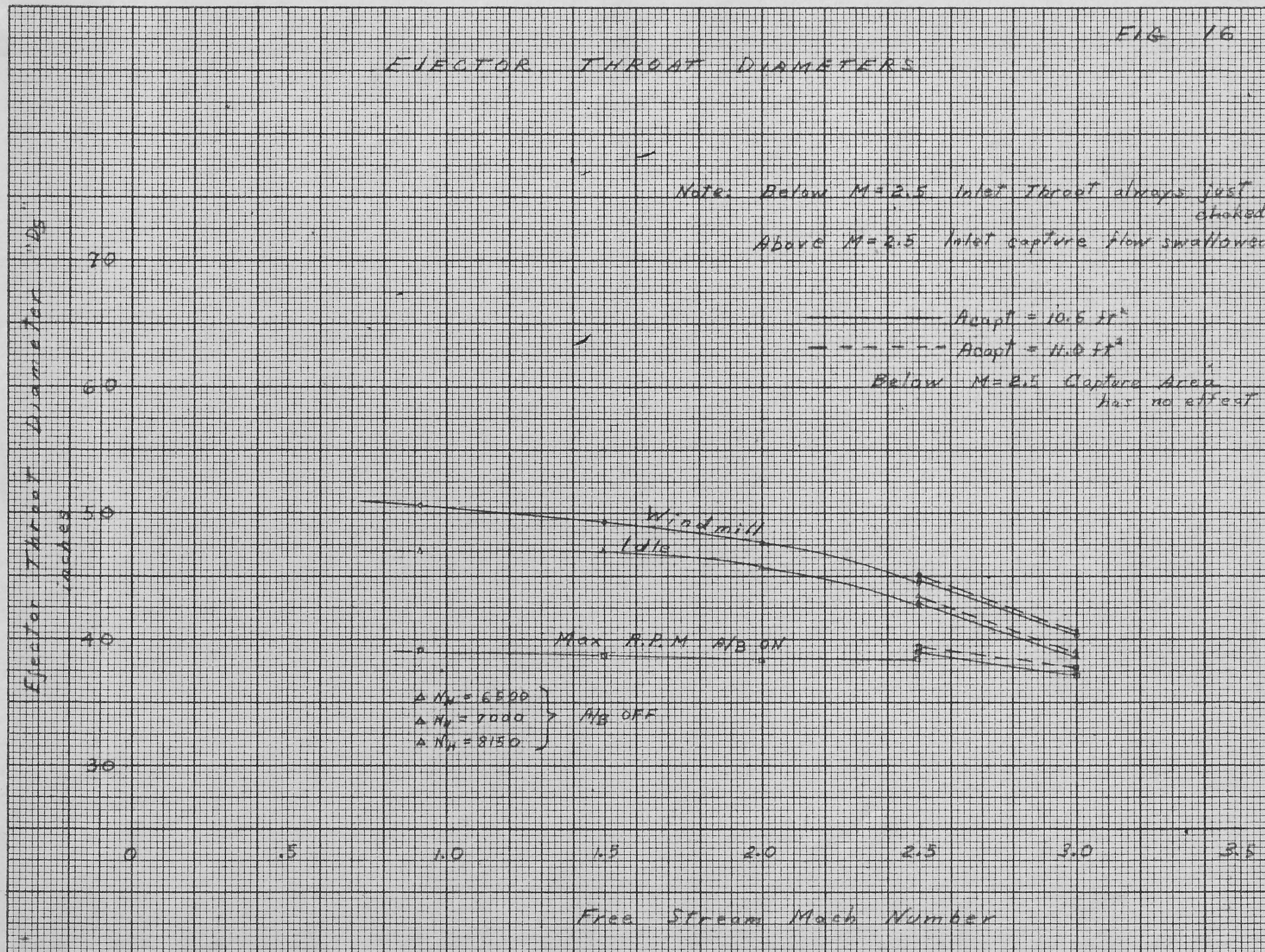


FIG 16
EJECTOR THROAT DIAMETERS
Note: Below M = 2.5 Inlet Throat always just choked
Above M = 2.5 Inlet capture flow swallowed
Acapt = 10.6 ft²
Acapt = 11.0 ft²
Below M = 2.5 Capture Area has no effect
Windmill
Idle
Max R.P.M. A/B ON
Δ N = 6500
Δ N = 7000
Δ N = 8150
A/B OFF
Ejector Throat Diameter "Dj" inches
70
60
50
40
30
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number

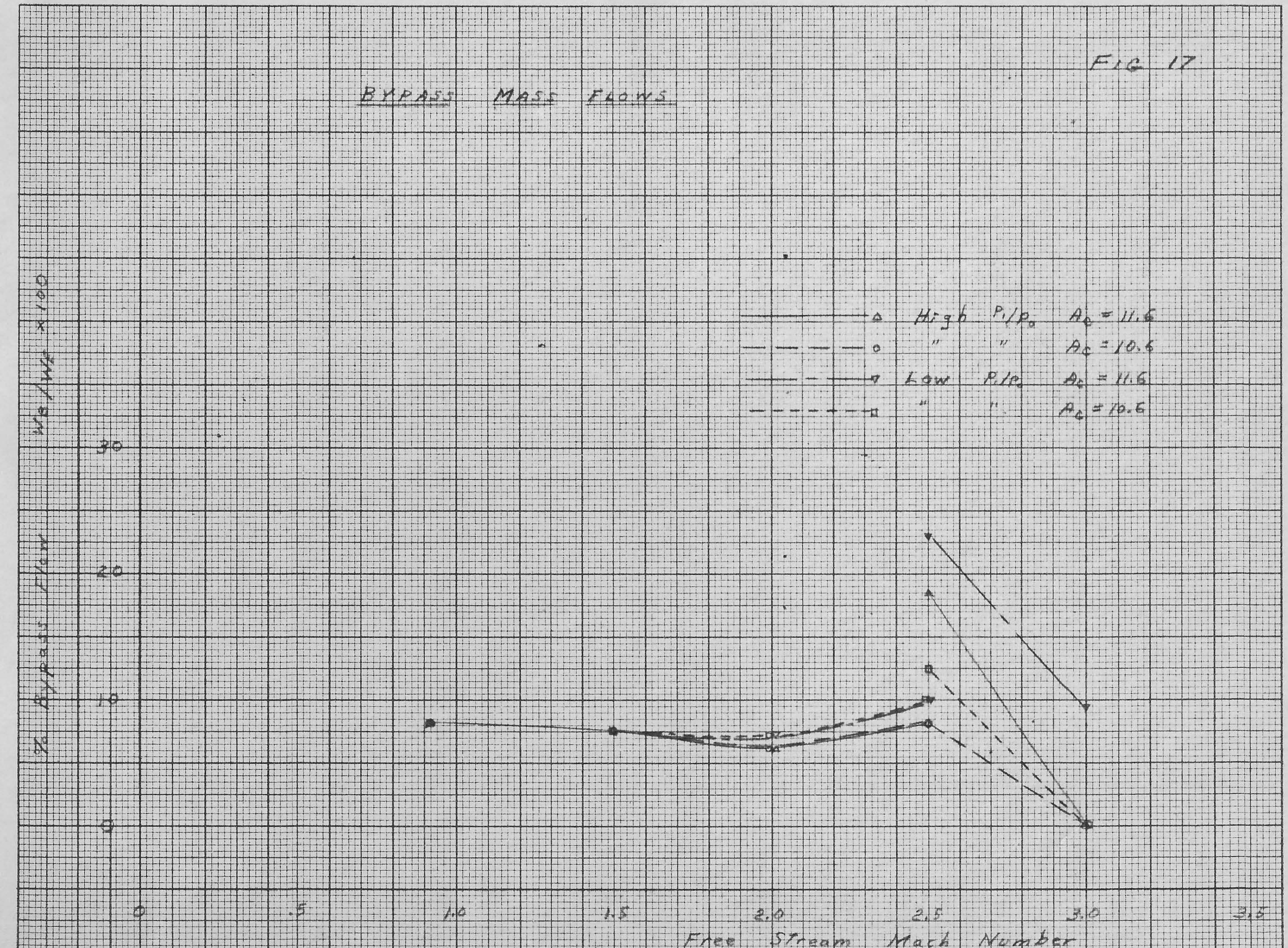
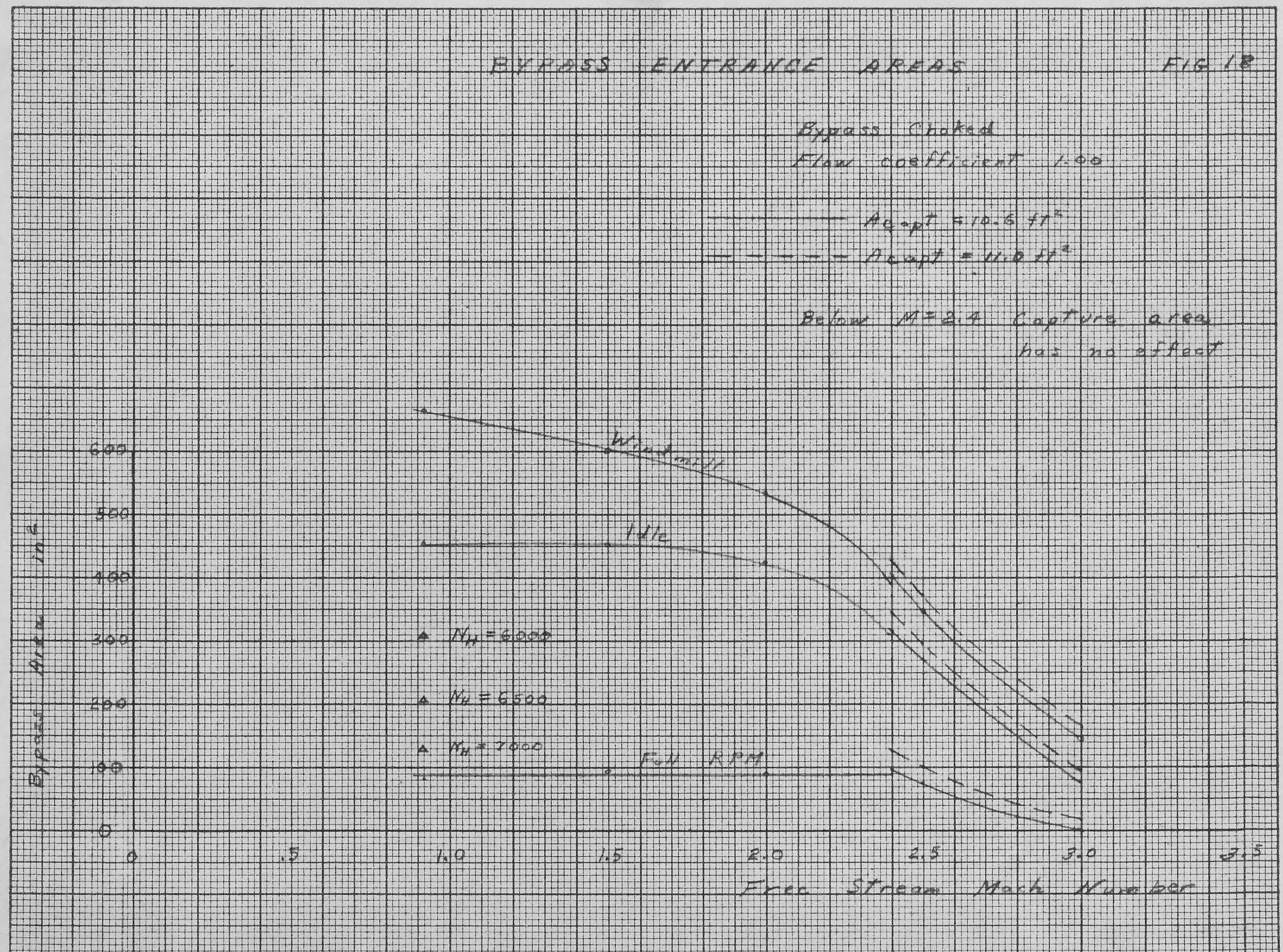


FIG 17
BYPASS MASS FLOWS
High P₁/P₀ A_c = 11.6
" " A_c = 10.6
Low P₁/P₀ A_c = 11.6
" " A_c = 10.6
% Bypass Flow Wb/Wt x100
0
10
20
30
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number


BYPASS ENTRANCE AREAS
FIG 18
Bypass Choked
Flow coefficient 1.00
Acapt = 10.6 ft²
Acapt = 11.0 ft²
Below M = 2.4 Capture area has no effect
Windmill
Idle
Full RPM
N_H = 6000
N_H = 6500
N_H = 7000
Bypass Area in²
600
500
400
300
200
100
0
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Free Stream Mach Number