OCT. 1956

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EFFECT OF N.A.C.A. WIND TUNNEL AND FREE FLIGHT TESTS ON THE ESTIMATED PERFORMANCE OF THE CF-105

AVRO AIRCRAFT LIMITED

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1.0 INTRODUCTION

The supersonic performance of the CF-105 which has been given previously has been largely based on estimates and extrapolations from transonic wind tunnel data. Recently, however, the results of the supersonic wind tunnel and free flight tests which were conducted at the Langley Laboratories of the N.A.C.A. have become available, and have been used to revise the estimated performance. These new data have unfortunately, resulted in some deterioration. On the other hand, some recent configuration changes have resulted in improvements which, in part, offset the reductions. The complete revised performance will be reported in the regular Performance Reports. However, since these reports do not fully explain the data presented, it was felt necessary to prepare this supplementary report to discuss in detail the new data in relation to the previous estimates.

2.0 PRESENT PERFORMANCE

The effect of the new data on the performance can be conveniently summarized by giving the values for three items which describe the supersonic performance, namely, the 'g' in a turn at M= 1.5 at 50,000, operational ceiling at M= 1.5, and maximum level speed. Table I lists the new and the old figures and gives a breakdown showing the effect each of the main factors has had in contributing to the change. The detailed discussion of the changes in each of these factors is then given.

TABLE I

	'g' at M= 1.5 at 50,000		OP. CEILING		MAXIMUM SPEED	
	J 75	PS 13	J 75	PS 13	J 75	PS 13
From Monthly Perf. Report No. 8	1.46	1.88	56,400	62,500	1.88	>2.0
Alteration due to:-						
Weight	1.43	1.79	56,000	61,500	1.87	>2.0
$C_{D_{Min}}$	1.30	1.69	54,400	60,200	1.80	>2.0
Lift	1.22	1.58	53,400	59,000	1.80	>2.0
Trim	1.23	1.57	53,500	58,900	1.80	>2.0
Up Aileron	1.28	1.65	54,000	59,800	1.80	>2.0
Revised Value	1.28	1.65	54,000	59,800	1.80	2.0

New P.S. 13 Combat Weight = 51,050 Lb.

J 75 Combat Weight = 54,100 Lb.

3.1 Weight

The combat weight has increased due to both an increase in the empty weight and in the fuel for the mission.

The empty weight increase can be divided into structure and equipment. The structural items were mainly due to re-estimation based on detailed drawings while the equipment items had to do in a large measure with the installation of the Astra 1 system.

The increase in the mission fuel is due to the increase in empty weight and to the increases in drag which are described below. Some numerical errors in previous calculations have also been corrected.

The extra weights for the PS 13 version are roughly as follows:-

Increase in Empty Weight	
- Structure	850
- Equipment	1250
Increase in Combat Fuel	250
Total	2350

3.2 Induced Drag

The discrepancies in the induced drag are relatively large, and are mainly concerned with the estimation of the effect of leading edge camber. This is often found to move the drag polar over so that its minimum is at some value of the lift coefficient other than zero as shown in Figure 1. The displaced drag curve can be dealt with in the normal way if the value of C_L - C_L for $C_{D_{Min}}$ is used in place of the true value of C_L in defining e.

3.2.1 C_L for $C_{D_{Min}}$

The values of C_L for $C_{D_{Min}}$ are shown in Figure 2. It can be seen that there is a large discrepancy between the extrapolation of the Cornell results and the Langley results. No reason can be given for this. It is very difficult to investigate this matter further because the quantities under discussion are not appreciably greater than balance thresholds. Although the Langley results will be used for the supersonic region to which they apply, there is no really sound reason for assuming that they invalidate the Cornell results with which they disagree. This is very much the largest factor in the increase in induced drag. Unfortunately, there is still some uncertainty about this matter that has very small chance of resolution.

3.2.2 e

The values of e are given on Figure 3. The previous estimate was based on joining the last Cornell point with the theoretical value at $M = 2.0$. This is because at $M = 2.0$, there is no leading edge suction, hence there is little uncertainty in the estimation at

3.2.2 _e_ (Cont'd)

this Mach number. At lower Mach numbers, the true value is somewhere between that corresponding to full and zero leading edge suction. The exact amount of suction could not be estimated. Accordingly, the method of estimation used was as reasonable as was possible under the circumstances. The agreement is reasonable. The discrepancies are unfortunately in the wrong direction, and accordingly contribute to the overall degradation.

The model was also tested in the N.A.C.A. wind tunnel without the leading edge droop. The values of e for this configuration are given on Figure 3 for comparison. It can be seen that the improvement due to camber vanishes at M = 2.0 as would be expected.

3.2.3 Effect of Leading Edge Camber

Although the leading edge camber has some effect in reducing the induced drag at M= 1.5, the effect of the camber is to increase the profile drag as shown in Figure 4. The drag polars for the notched and extended leading edge wing with and without drooped leading edge are compared for M= 1.5 in Figure 5. It can be seen that there is very little difference in drag at C_L = .18 which corresponds to the maximum acceleration in steady turn under these conditions. In cruise the drag is higher. This would result in a higher fuel load if it were not for some savings in the subsonic parts of the mission where the savings in drag due to camber are quite conspicuous.

From an inspection of Figures 3 and 4 it can be seen that camber is wholly detrimental at M= 2.0. Accordingly, should it be decided to emphasize the performance of the aircraft near M= 2.0 it would be logical to use straight leading edges.

3.3 Profile Drag

For present purposes the discussion of profile drag can be confined to the minimum profile drag coefficient based on a wing area of 1225 sq. ft. at a Mach number of 1.5.

Previously used value	=	.0206
Obtained from Free Flight Drag Model No. 2	=	.0223
Addition for semi-submerged missiles	=	.0007
New Value	=	.0230

It is evident from Figure 4 that the use of leading edge camber added about .0010 to the drag at M= 1.5. It is also clear from this figure that this result could not have been predicted from the Cornell results. For this reason allowance was not made for this in the previous estimates which were based on theory and the results of the firing of Drag Model No. 1 which did not have leading edge camber.

3.3 Profile Drag (Cont'd)

It is thus interesting to note that if leading edge camber is deleted, a drag coefficient of .0220 is appropriate: which is in reasonable agreement with the original estimate if it is corrected for the semi-submerged missile installation which was not required at the time the estimate was made.

If it is desired to optimize the performance between M= 1.5 and 2.0 instead of between M= .9 and 1.5, it is best to delete the camber as will be shown later.

3.4 Trim Drag

3.4.1 Elevator Angles to Trim

The trim drag is a function of the elevator angle to trim. The new and the old values are shown on Figure 6. In the case of the new data, some corrections have been applied that were not previously taken into account. The wind tunnel derivatives were corrected to the exact height of the c.g. below the reference axis. The effects of structural elasticity and of the thrust momentum change between model and full scale have also been included. Although there are considerable differences in the various factors which affect the trim angle, the overall values in the cases of most interest are not greatly changed. For this reason, the details of the changes are not felt to be of sufficient interest to warrant full discussion in this report.

3.4.2 Drag due to Elevator

The drag due to a given elevator deflection as obtained from the Langley tests is identical with what had previously been assumed as shown in Figure 7.

3.4.3 Aileron Up-Trim

The trim drag of the elevator is proportional to the square of the deflection. Hence, if some assistance is given to the elevator by the aileron in producing a trimming moment, there will be a net reduction in drag. It is accordingly proposed to trim the ailerons symmetrically up to accomplish this. There is not sufficient authority available at high q to permit this, due to hinge moment limitations. However, this difficulty can be avoided if the up trim is only activated above 40,000 ft. This is not difficult to do, and will be quite analogous to the system being installed in CF-100 Mk. 5's for drooping the flaps 9° at high altitudes. The most convenient way to accomplish this is to divide the central quadrant from which cables command both ailerons, so that one-half drives each aileron. It is then easy to provide the required up-trim by rotating one-half quadrant with respect to the other. This system secures most of the advantages of an elevon system with none of its disadvantages, and hence should be incorporated on production aircraft.

3.4.3 Aileron Up-Trim (Cont'd)

The gain from this may be as high as 25 drag counts in the conditions of interest.

4.0 ENERGY CONSIDERATIONS

Reports on the flight testing of the F 104 have emphasized the importance of energy in determining the ability of the airplane to execute a command. Thus, even though the aircraft might be near its static ceiling, pulling back on the stick will cause it to ascend several thousand feet without difficulty, though with some loss in speed. It has apparently been found very difficult for the pilot to sort out what part of the performance is due to the use of energy and what is due to steady state capability.

Because of this, some indication of these effects are given in Figures 9 and 10. In Figure 9, energy climbs are considered, and in Figure 10, the ability of the aircraft to execute 2'g' manoeuvres using energy where necessary is depicted.

It is of some interest to note that the envelope which can be flown on this basis exceeds that where missiles such as the Sparrows are effective.

5.0 POSSIBLE IMPROVEMENT

Up to this point, the discussion has been concentrated on the basic performance at M= 1.5. There are, however, possibilities of improvements at this and higher Mach numbers which are sufficiently attractive to deserve mention.

5.1 Engine

A sizeable gain can be achieved with relative ease at M= 2.0. At present, the specification provides no incentive for making improvements at this speed, and for this reason, this area has not been fully exploited. However, it is felt that in the time period when production aircraft will be available, performance at M= 2.0 will be regarded as much more important than it is now.

At Mach numbers over 1.5, the engine as presently conceived does not swallow all the air available from the intake. Accordingly, it is obvious that if the engine could be made to swallow the air required to fill the intake, there would be a sizeable gain in thrust. Hence, a modification to the engine is proposed that will permit it to swallow 11% more mass flow at M= 2.0 than at present.

With the existing ejector configuration, which has been optimized for M= 1.5, it has been found that the net installed thrust increase is only 12% with this increase in mass flow. However, the thrust can be increased at least 20% by using a more suitable ejector configuration for M= 2.0. In general, it may be difficult to achieve

5.1 Engine (Cont'd)

this performance at M= 2.0 without undue sacrifices at M= .9 unless a variable geometry is used.

From this, it can be seen that there may be considerable advantage in going to a variable geometry, if it is desired to achieve optimum performance at M= 2.0 without appreciable sacrifices elsewhere. It is accordingly proposed to fit variable geometry ejectors to the Mk. 2 aircraft should further study show that this is necessary to achieve the desired results. This would be very similar to the engine nozzle in construction but would be attached to the airframe outside and behind the engine nozzle as shown in Fig. 8. The experience gained by Orenda on the engine nozzle would be of great value in minimizing the design and development time.

The weight change caused by fitting variable geometry ejectors has been estimated as follows:-

Present Combat Weight	51,050
Weight of Variable Ejectors	550
New Combat Weight	51,600

It has been found by Area Rule calculations that an enlarged nozzle size which is very near optimum at supersonic speeds gives rise to a considerable reduction in wave drag. Making due allowance for the fact that only part of the calculated savings have been achieved in recent tests, and for the previous allowance for incomplete expansion of the jet, a net saving of 10 counts would still seem reasonable. However, this will not be used in performance calculations until it can be ascertained whether the mechanical design of the new nozzle will permit sufficiently fair lines to be obtained.

The engine modifications required are under study by Orenda, and appear to be of a sufficiently minor character to be capable of being worked into their present development program.

The method of doing this is roughly as follows. The present L.P. compressor is not running up to its limiting speed at M= 2.0 and accordingly can swallow more air if its speed is allowed to rise. This can only be done by increasing the flow through the H.P. compressor, at its maximum design speed. This can be accomplished aerodynamically by changing the matching of the two compressors. In this way, the H.P. compressor swallows more air at a slightly lower speed, so that the limiting speed is not reached until near M= 2.0 instead of M= 1.5, as at present. The recent incorporation of moveable 3rd stage stator blades is expected to relieve the surge problems to a sufficient extent to permit the necessary modification to the 4th stage blading, which is critical in this respect and thus makes this proposal possible, and in fact relatively easy considering the gain to be had. Only minor adjustments in the final nozzle appear at present to be necessary.

5.1 Engine (Cont'd)

This modification will improve the thrust at M= 2.0 while leaving it virtually unchanged below M= 1.5. The improvements are summarized in Table 2.

TABLE 2

	PRESENT ENGINE	IMPROVED ENGINE
Operational Ceiling at M= 2.0	57,800	63,900
'g' at 50,000 at M = 2.0	1.48	2.00

The improvement in dynamic performance is shown in Figure 9.

5.2 Leading Edge Modifications

It is evident from the paragraph 3.2.3 that if more emphasis were placed on the performance over M= 1.5 the leading edge camber would be deleted with resulting improvements at higher speeds. It is appropriate to note, at this point, that a considerable improvement in the directional stability was observed in the transonic region when leading edge camber was resorted to. It is felt that this effect mainly emanates from the wing to fuselage junction. The camber at this point is very small. Accordingly, it is believed that if the root camber is retained and washed out towards the tip instead of increasing as at present, the beneficial effects would not be seriously altered. This would have to be tested. Deleting camber results in a saving of about 15 drag counts at M= 2.0.

The evidence given in Figure 4 shows that the deletion of the notch and extension may result in some improvements in drag at transonic speeds. The reason for their incorporation was to improve the transonic handling characteristics. They would not be necessary at higher speeds. If, however, the emphasis is shifted to higher speeds it may be possible to show that the characteristics are adequate without these devices or that some other expedient such as fences might be adequate, while producing less drag. A further saving might be achieved by this.

5.3 Aft C.G. Movement

At supersonic speeds the aerodynamic centre moves aft giving a very large static margin. This causes the elevator angles required to be increased. If the c.g. is moved back, these angles can be reduced, thus reducing the trim drag. The subsonic longitudinal stability and the supersonic directional stability is made more marginal by this procedure. However, this deficiency can be made up by the damping system. Initially, it is not desired to extend the damping system requirements over what they are now. However, it is not felt that there should be any real difficulty in eventually extending the c.g. aft 2 or 3 percent in due course. After sufficient experience is built up with the present system to justify confidence

5.3 Aft C.G. Movement (Cont'd)

in it, it would be logical to attempt its extension. It ie very probable that the necessary modifications could be confined, to some minor adjustments in the gain echedules.

The method of sequencing the fuel tanks has been made adjustable so that the c.g. can be controlled in the most appropriate way, within certain basic limits. The necessary adjustments are easily made and do not represent any hardware changes. However, the best that the preeent fuel system will do is to give an aft c.g. of 33 1/2%, i.e. a shift of 2 1/2%, between aircraft weights of 56,000 and 51,000 lb. While this covers the calculated combat weights, it is not as large as might be desired. It should, however, be noted that at the lower weights, the performance is increased due to the weight reduction and so the absolute value of the performance may not be greatly affected for weights below 51,000 lb. even though the c.g. ie moving forward.

To obtain a greater range of weights at aft c.g.'s it will be necessary to add fuel to the outer wing. The basic design is not unsuitable for this. However, a fairly large number of structural details would have to be altered to permit sealing. The fuel system would have to be extended to cover the necessary tankage. The extra fuel would be about 2,700 lb. and the c.g. shift 3% for aircraft weights from 50,000 to 61,000 lb. The improvement in trim drag would be about 10% of the total drag.

It now may be of interest to examine the percentage that the trim drag forms of the total drag in a steady turn at M= 1.5 and 50,000 ft. The percentage with and without the c.g. moved aft are given in Tabel 3.

TABLE 3

Breakdown of the Drag in a Steady Turn at M= 1.5 at 50,000 Ft.

	Preeent C.G.	2 1/2% Aft C.G.
Profile	58.2	58.2
Induced	28.9	34.2
Trim	12.9	7.6

5.4 Summary of Possible Improvements

TABIE 4

	M = 1.5		M = 2.0	
	g at 50,000'	OP. ALT.	g at 50,000'	OP. ALT.
Present Design	1.65	59,800	1.48	57,800
Compressor Rematching *	1.64	59,700	2.00	63,900
Deletion of L.E. Camber *	1.64	59,700	2.09	65,000
Aft. C.G. *	1.74	61,000	2.26	66,500

* Combat Weight = 51,600 lb.

While some improvement is possible at M= 1.5, the gains are quite substantial at M= 2.0 considering the relatively small effort required to accomplish them. The engine and ejector modifications will be incorporated on production aircraft. However, the leading edge change would only be incorporated, if it is desired to improve the performance at M= 2.0 at the expense of the subsonic performance. On the other hand, the aft c.g. will automatically become available if flight experience is sufficiently favourable.

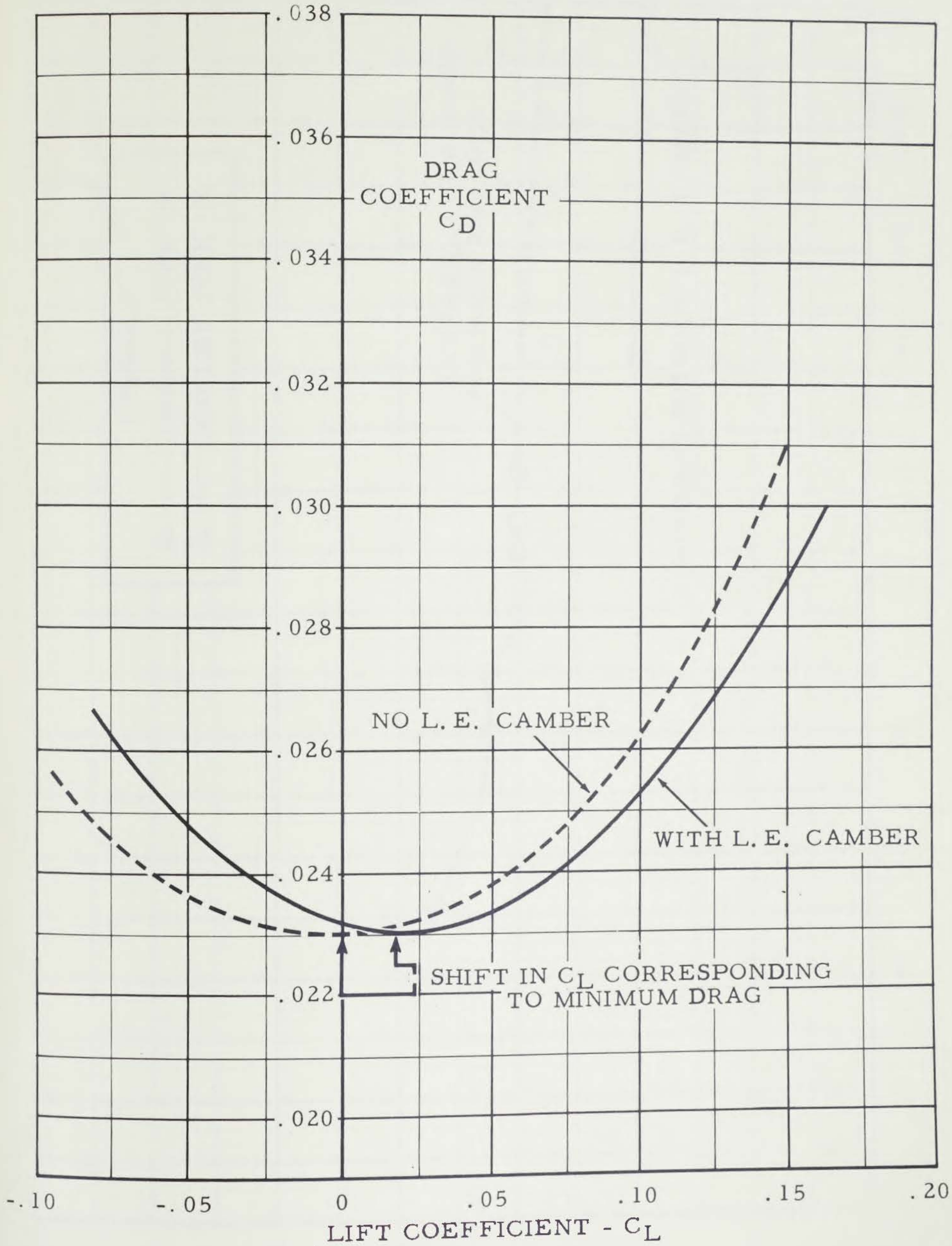

FIG. 1 EFFECT OF LEADING EDGE CAMBER

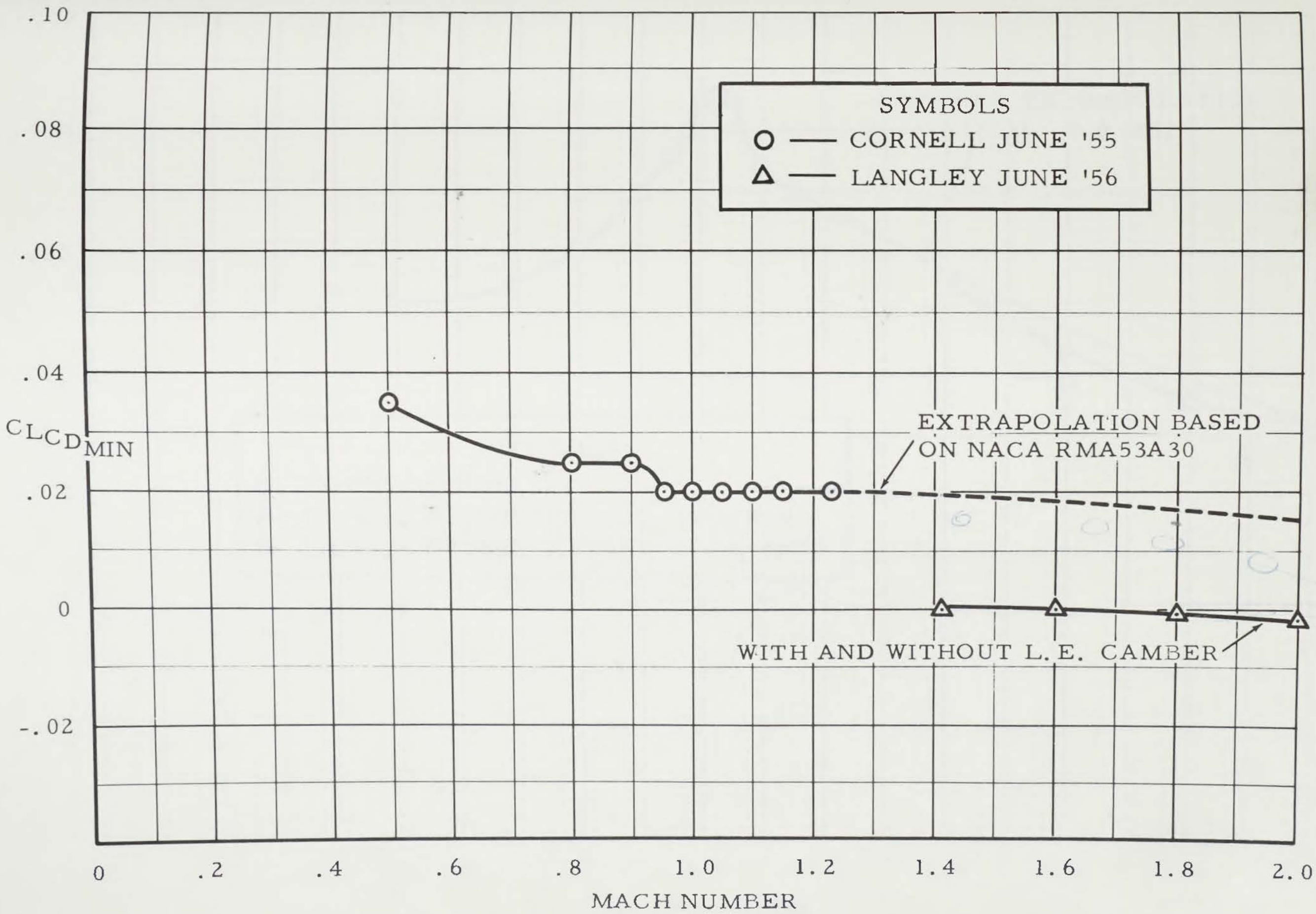

FIG. 2 VARIATION OF CF-105 LIFT COEFFICIENT AT $C_{D_{MIN}}$ WITH M. N.

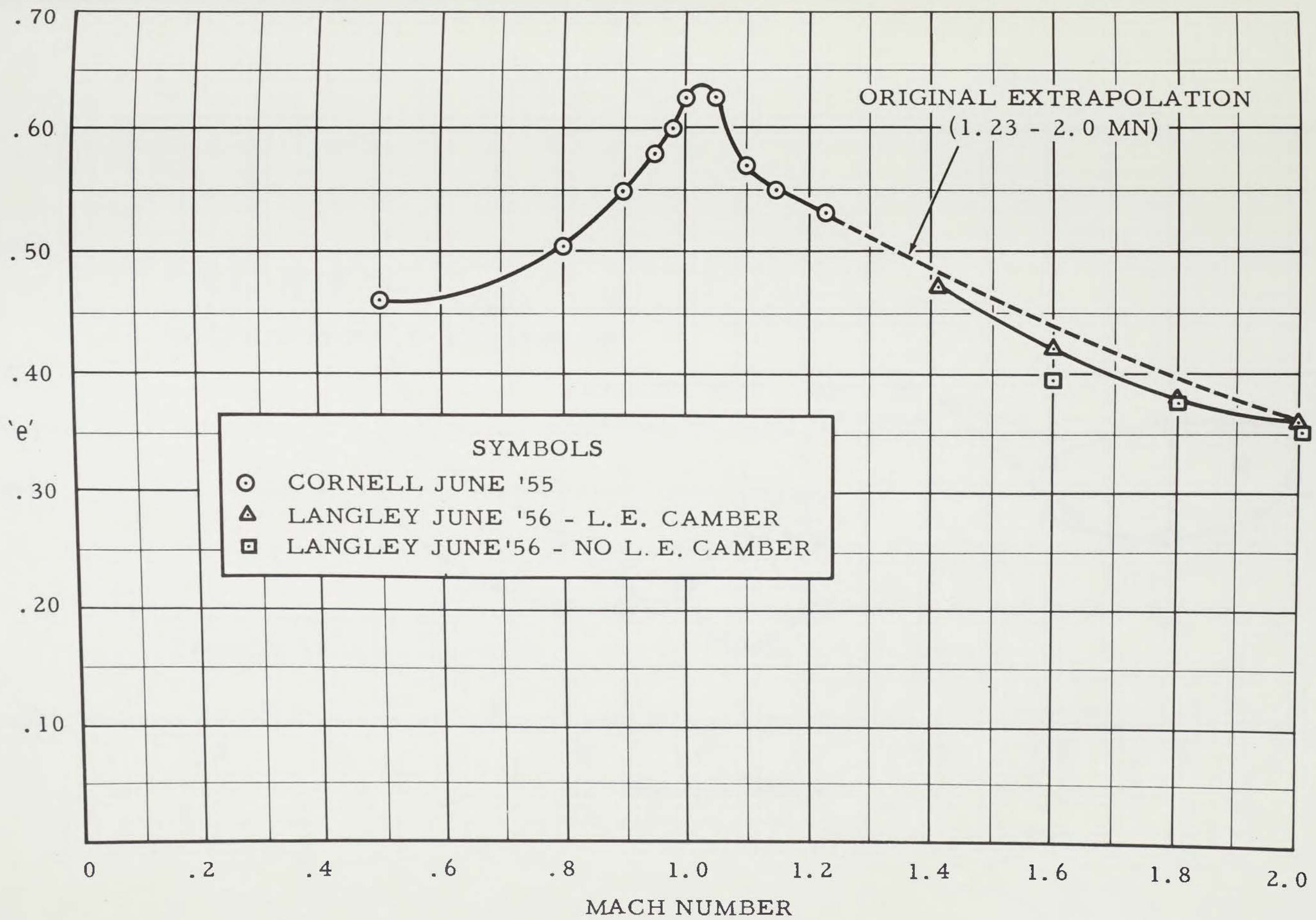

FIG. 3 VARIATION OF AERODYNAMIC EFFICIENCY OF CF-105 WITH M. N.

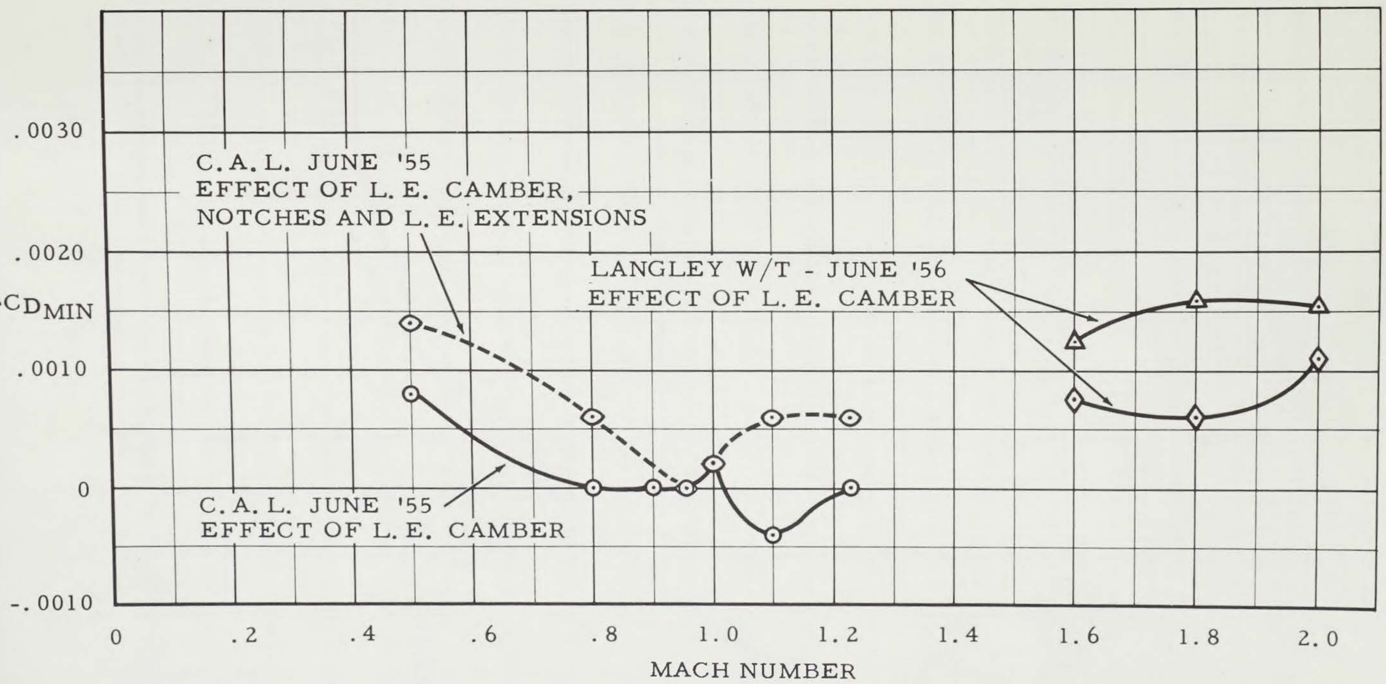

FIG. 4 CF-105 INCREASE IN $C_{D_{MIN}}$ DUE TO WING PLANFORM MODIFICATIONS

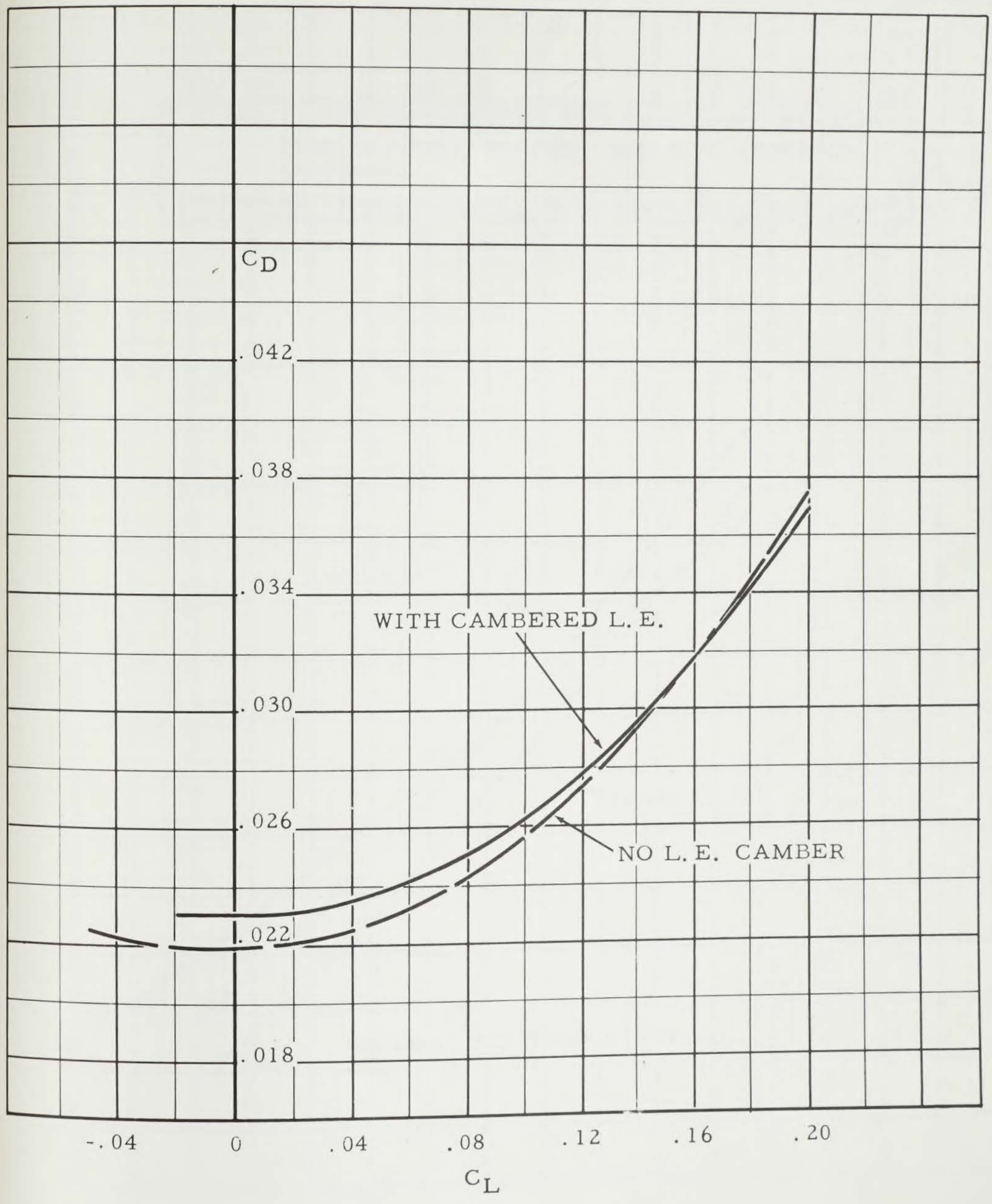

FIG. 5 DRAG COEFFICIENT VS LIFT COEFFICIENT
WITH AND WITHOUT L. E. CAMBER 1.5 M. N.

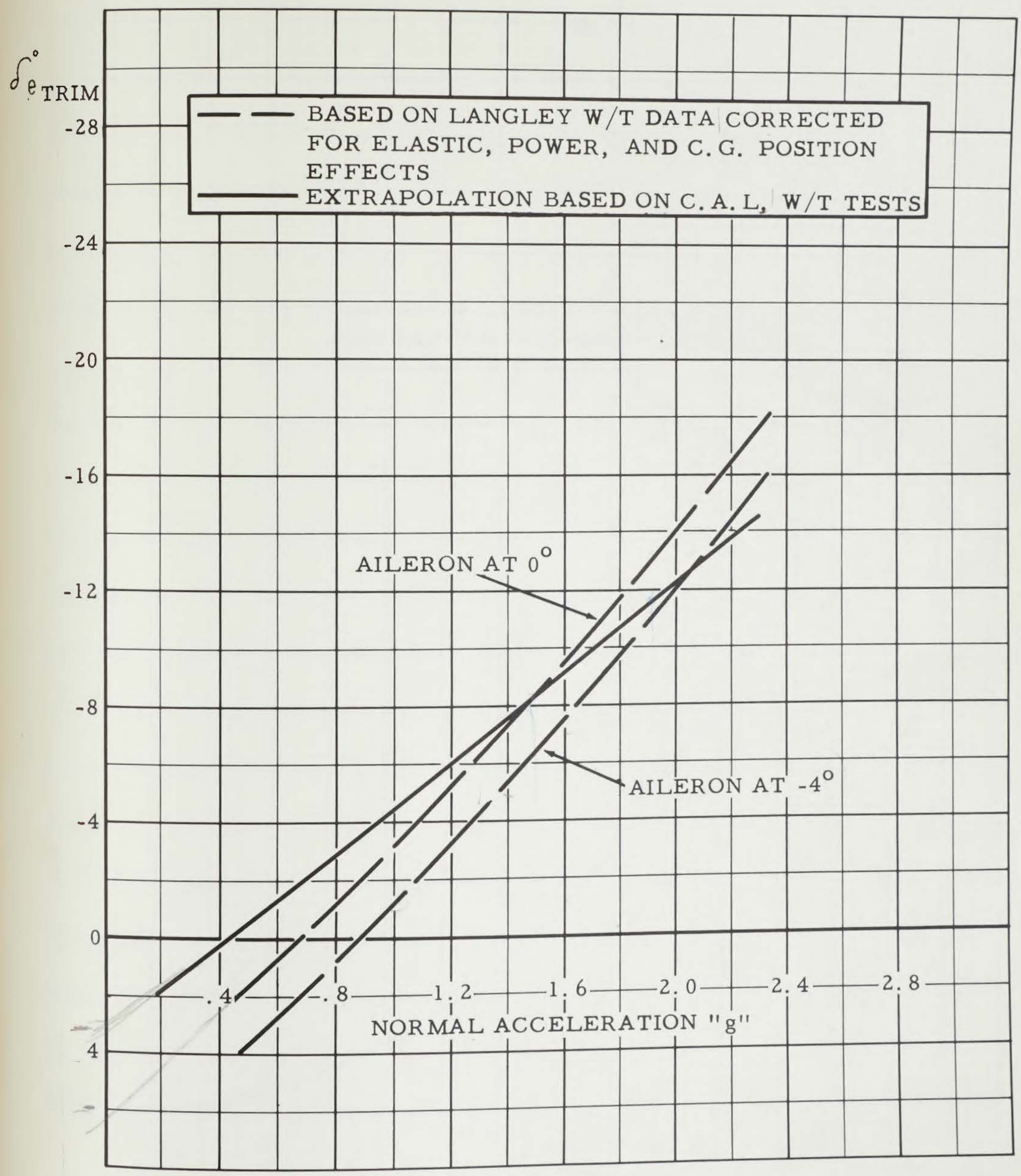

FIG. 6 CF-105 NORMAL ACCELERATION VS ELEVATOR ANGLE
MACH NO. 1.5 C.G. AT 29.5% MAC

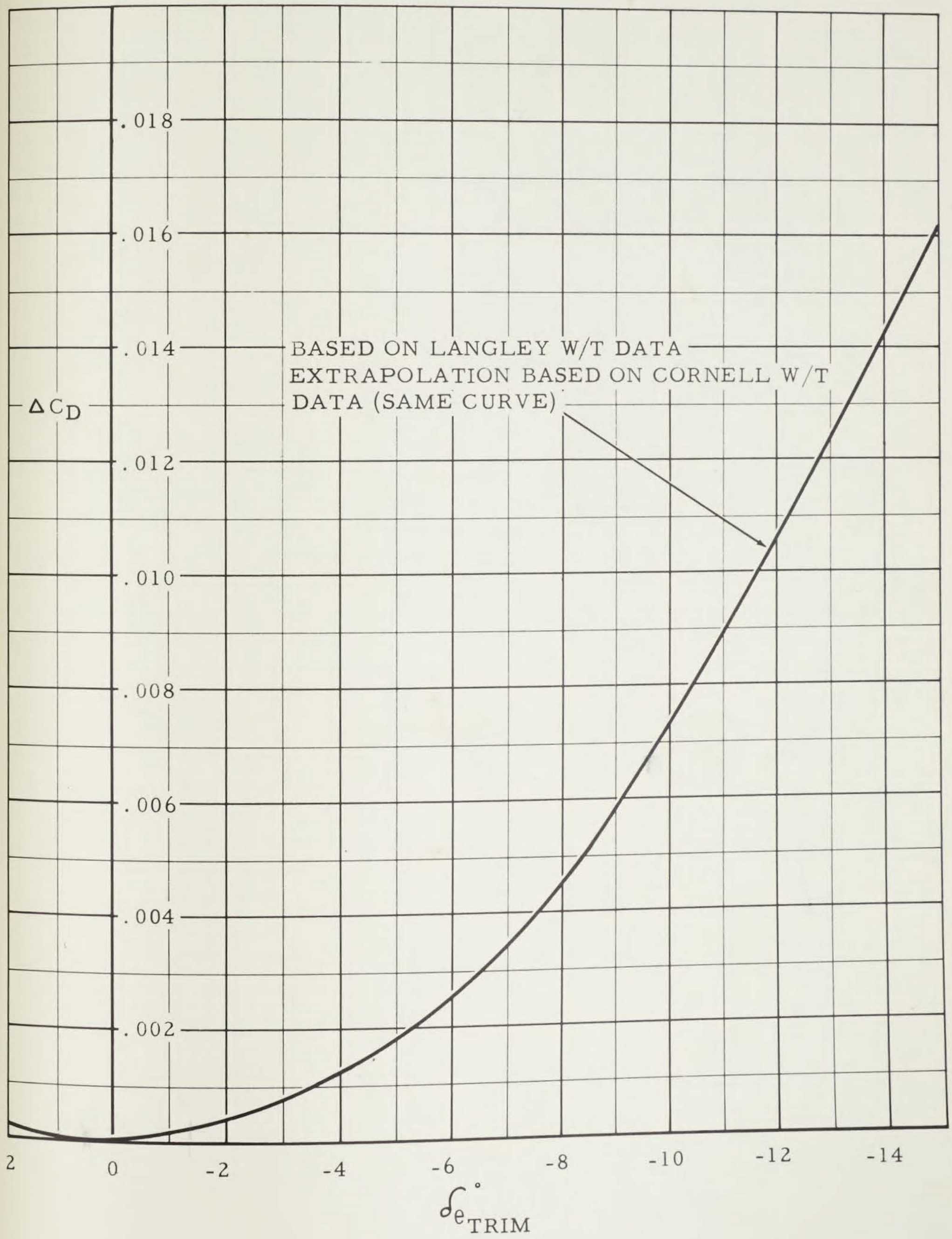

FIG. 7 CF-105 DRAG INCREMENT TO TRIM VS. ELEVATOR ANGLE 1.5 M. N.

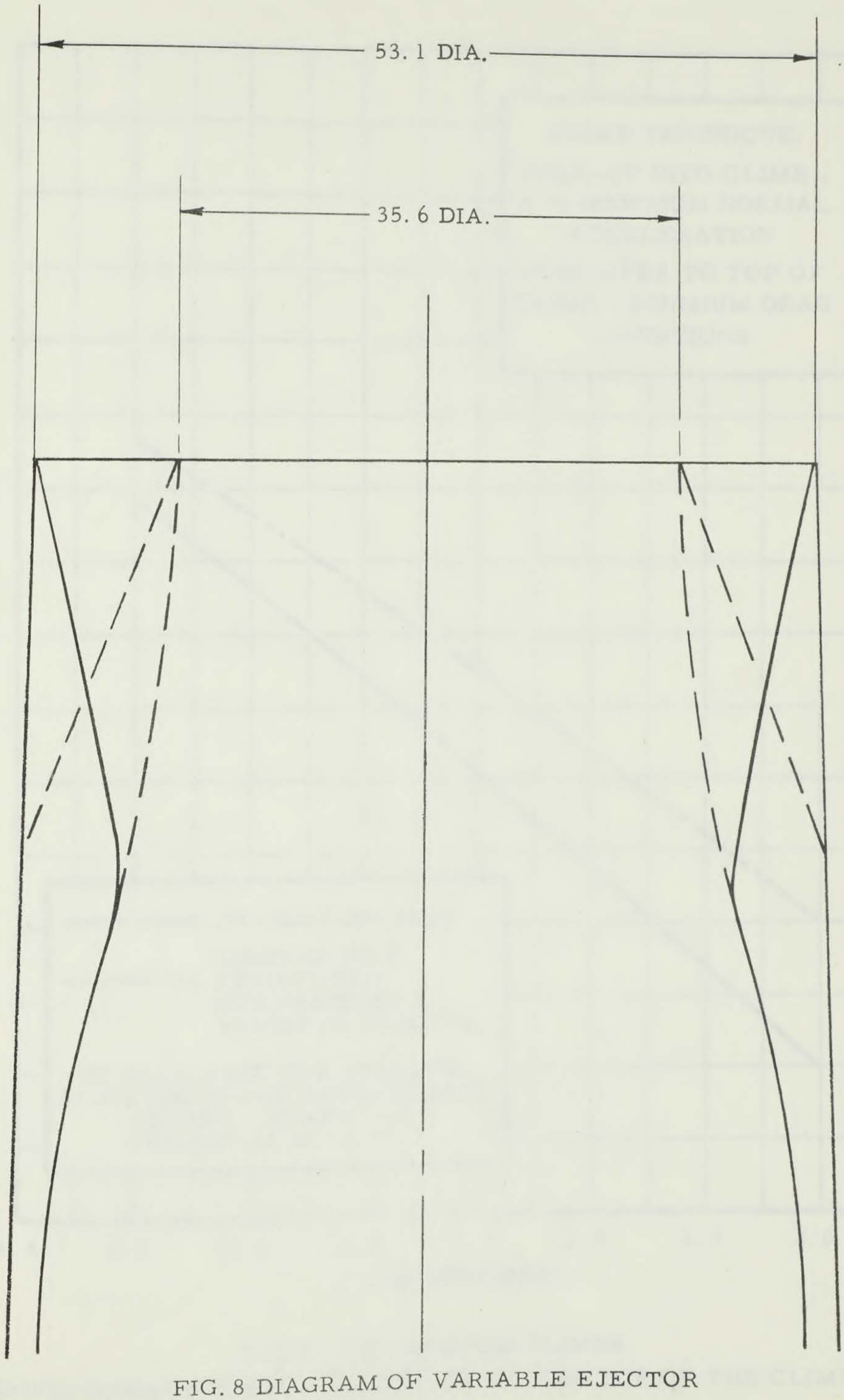

FIG. 8 DIAGRAM OF VARIABLE EJECTOR

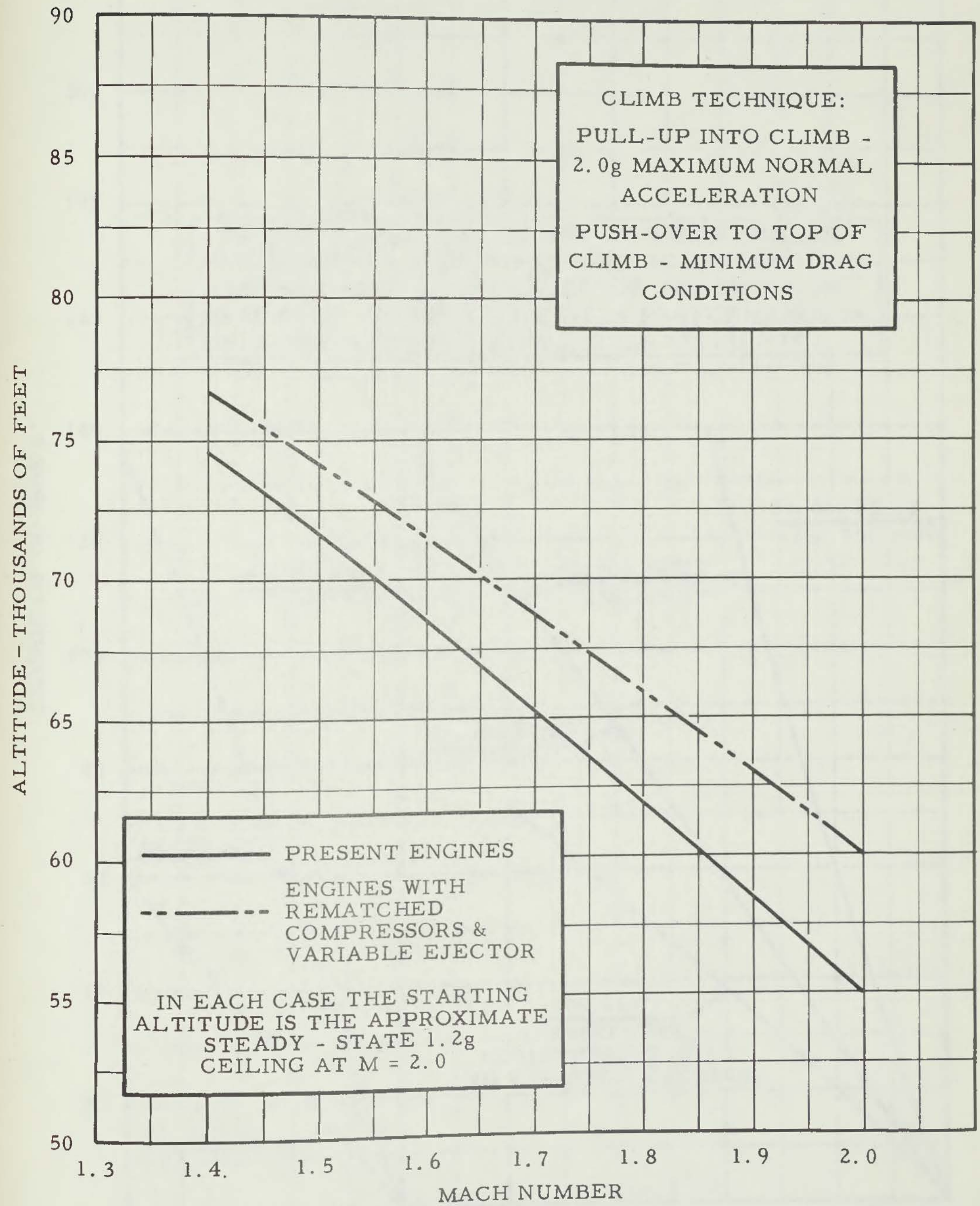

FIG. 9 CF-105 ZOOM CLIMBS
ENVELOPES OF SPEED VS ALTITUDE AT THE TOP OF THE CLIMB

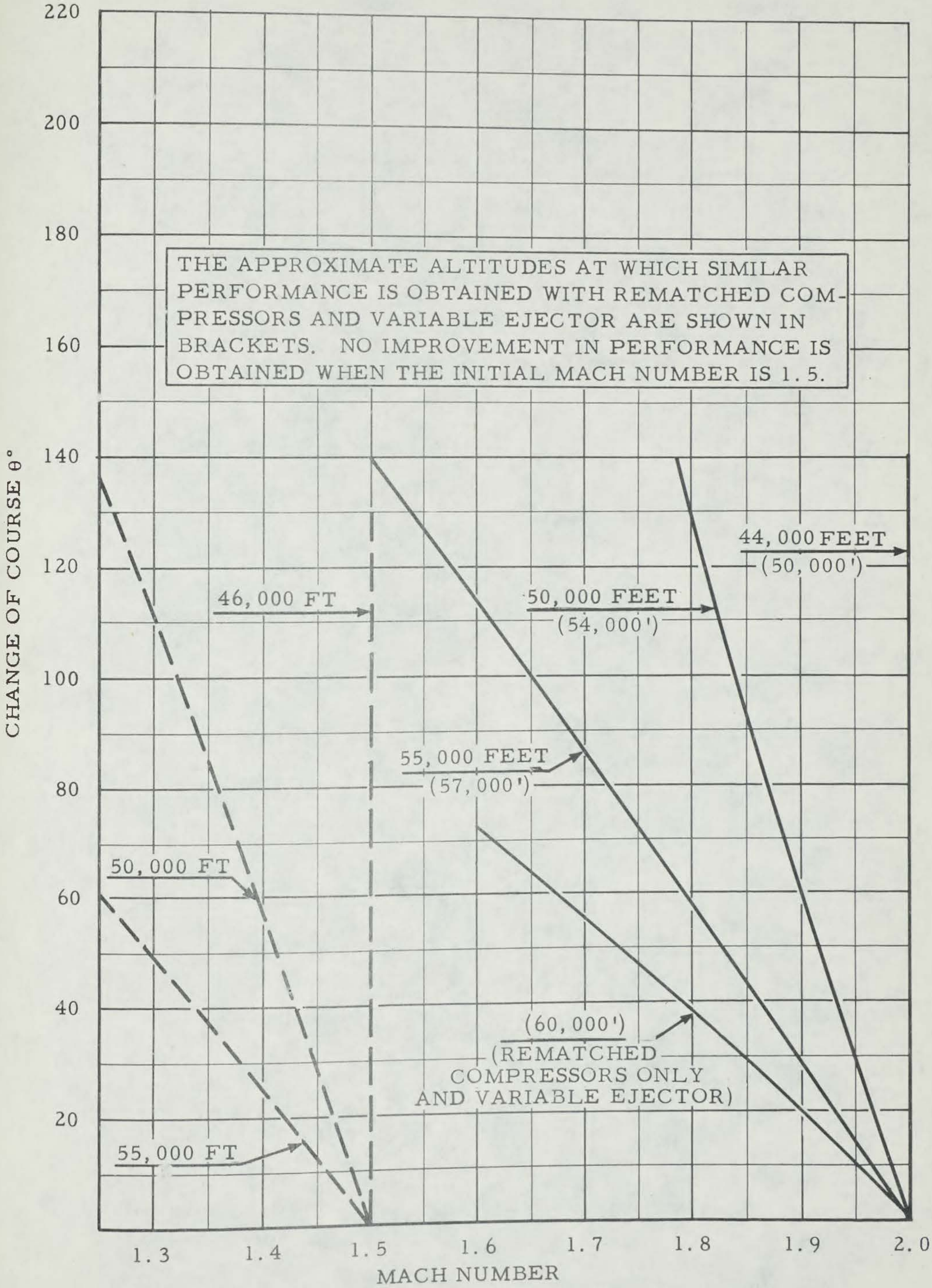

FIG. 10 CF-105 DYNAMIC TURN PERFORMANCE
CONSTANT ALTITUDE - COMBAT FACTOR 2G