# SUMMARY REVIEW OF THE CONTINUATION TEST PROGRAM FOR THE AVROCAR

## INCLUDING REVIEW OF ALLIED PROGRAMS

500/PERF/411

AVRO AIRCRAFT LIMITED

# SUMMARY REVIEW OF THE
# CONTINUATION TEST PROGRAM FOR THE AVROCAR

(Including Review of Allied Programs)

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## 1.0 INTRODUCTION

This Review of the Avrocar Continuation Test Program covers the period from July 1960, when it was instituted, up to the present. The previous Avrocar program came to an end in April 1960.

Two aircraft were built under this previous program, and of these, in April 1960, one had just completed a series of wind tunnel tests in the 40 x 80 ft. subsonic wind tunnel at Ames Research Center, and the other was being used at Malton, Ontario for hovering trials.

Briefly, the wind tunnel tests were unsatisfactory, showing that the focussing ring control was not suitable as a forward flight control; but the hovering trials had proceeded quite well and the focussing ring was, on the other hand, proving successful for this regime.

Decision was therefore taken to introduce an in-flight control scheme into both aircraft. The first being re-tested at Ames, and the second to undergo a brief checkout flight test at Malton after the alterations had been incorporated.

This latter program was called the 'Avrocar Continuation Test Program' and is described in a proposal issued by Avro under this title in July 1960. The objectives of this program were then stated as follows:

(i) Static and flight test program:

To check the operation of the modified control system and ~~to determine~~ the aircraft behaviour in ground cushion ~~has not deteriorated because of modifications that have been done~~.

This does not include any development testing to improve known ground cushion critical height problems, or extension of the speed range.

(ii) Model Test Program

To assess the effects of the proposed modifications and to assist in determining the aircraft tunnel test program.

(iii) Wind Tunnel Test Program

(a) To define a forward flight performance envelope for the first Avrocar in its modified state, accepting the known thrust deficiency. To enable estimates of developed performance after thrust improvement to be made, and to assess the reasons for any deficiency between the latter and the performance originally specified (Avro/ SPG/TR 254).

(b) To establish the ability of the aircraft to accelerate in the ground cushion and if possible find a maximum ground cushion speed.

(c) To show that transition is feasible.

It will be appreciated that these objectives are limited and were not set up with the idea that a flight test program could follow immediately upon completion of this continuation test program.

Avro Aircraft Limited had come in (April) with a proposal to improve the thrust towards the original figures, and to enable VTO to be achieved. However, in view of the disappointing in-flight performance and particularly since the range and endurance capability for the Avrocar even after thrust improvement appeared to be minimal; the decision was taken to halt ground cushion development and institute this program for flight control development first, before considering thrust improvement. At the same time the Canadian Government instituted a program to study the design development of the Avrocar so that at the end of the Continuation Test Program the ultimate potential of the concept could be more clearly demonstrated.

This (Canadian) program was in two parts. In the first part the objective was to study the development of the Avrocar in its existing general form. The outcome of this phase of the program was to be a proposal for a tip turbine driven fan type aircraft of circular planform employing an annular jet. The general characteristics of the aircraft were to be as follows:

(i) A speed capability of hovering to 300 knots

(ii) Endurance to the maximum possible, and aimed at four hours

(iii) Load capability for two men, and 1000 lb. of useful load at 10 lb/cu.ft.

WHO (?)

The objective of the second part was to conduct a parametric design study of a GETOL subsonic aircraft to determine the merits of this concept. This study was to be made against a logistics supply mission involving the transportation of personnel, supplies and equipment from airhead to divisional area.

In this report a review will first be made of the in-flight control system modifications and the major significant test results from the wind tunnel program, with performance prediction for the present Avrocar, with and without thrust improvement. A brief review is then given of the Avrocar design development carried out under Part 1 of the Canadian Government Study Program.

## 2.0 FULL SCALE TUNNEL TEST RESULTS AND PERFORMANCE PREDICTIONS

Fig. 1 is a diagram which illustrates the jet flow in forward flight both for the first test series in which the focussed jet was attempted for forward speed as well as hovering, and after the new transition modifications in which a jet flap configuration with wing tip blowing were adopted for the in-flight configuration with internal transition from a focussed hovering condition.

This was achieved by the structural modifications illustrated in Fig. 2, which involved re-building the wing tip over about 2/3rds of the periphery so that the jet flow could exhaust directly through it, and fitting a series of transition doors which would direct the flow either through the focussing ring as before for hovering, or through the new passage through the wing tip for forward flight. A series of cascades was then fitted around the wing tip to direct the jet aft. An in-flight control was added around the rear 120° of jet exhausting from the wing tip in the form of in-flight pitch and roll control vanes. These were coupled to the focussing ring which was hung by modified hangar rods in order to allow a simple connection. The twelve transition doors were controlled by electric screwjacks, four jacks being driven by each of three electric motors. Finally, the yaw vanes were moved to a sector further forward and the collective control incorporated so that they would all be deflected backwards for in-flight and thus reflect the jet off the focussing ring in an aft direction. No change was made to the 90° sector at the front.

The effects of the new in-flight jet deployment on the aerodynamic characteristics was striking, as had been expected, and are shown up directly by measurements of lift, drag and moment at the same speed for the first and second series of wind tunnel tests, as plotted in Fig. 3.

From this Figure it will be seen that the lift curve slope has been enormously increased in fact, from a $\delta C_L/\delta\alpha$ of approximately 1.0 to a $\delta C_L/\delta\alpha$ of approximately 3.0. At the same time a considerable nose-down moment was created, so that for this control position the aircraft now has close to zero pitching moment at $\alpha = 0$ at this engine rpm. Now, if we consider the two cases at the angle of attack for which the pitching moment is zero, we see first that the usable lift has increased from about 2500 lb. to nearly 3000 lb., and second, that at the same time a drag of about 900 lb. has become a slight thrust. It will also be noticed from this Figure that although the lift curve slope has increased by a factor of 3, the moment curve slope is unchanged. The effect of this is to greatly increase the static in-flight stability, as is shown on Fig. 4 in which pitching moment coefficient is plotted against lift coefficient. The slope of this line indicates the proportion of the chord by which the neutral point, or aerodynamic center, is forward of the c.g. (0.5 chord) and it will be seen that this point has moved aft no less than 22% to a position 34% from the leading edge. Due to the jet deployment this position is now further aft than would be expected or has been obtained without the jet blowing. On the other hand the aerodynamic center of jet lift remains in the same chordwise position as indicated in the diagram to the right hand side of this Figure.

These in-flight results have been interpreted in terms of forward speed performance in Fig. 4. In this, thrust and drag are plotted against forward speed and a speed range for the second Avrocar as tested in the tunnel of approximately 50 to 100 knots is shown, with a small climb margin in the middle of this range. This marginal performance applies to a (by now) skimpy test weight of 4500 lb. and is due to the extraordinarily poor thrust which the powerplant is producing. In fact the static thrust appears to be some 30% below its value during the previous tests. However, during the time that this tunnel program was going on, other tests were being conducted under the Canadian program in order to further investigate the losses in the ducted fan system. Three tests are of special importance to the performance; first is the duct loss test, of Ref. 1, in which a segment of Avrocar duct with uniform entry profile, without simulated turbine exhaust, and with a much improved final bend arrangement, was tested for pressure loss and a loss coefficient in accordance with the original thrust estimates was obtained. The second involved tests of a small model to establish the free air focussing efficiency. These tests are reported in Ref. 2, and show once more, a loss due to focussing commensurate with original assumptions. We think, therefore, that the low static thrust level encountered in the full scale tests must be ascribed to high losses through the tip turbine (which are known to be present, tip clearances of as much as 25% of the turbine blade span having been observed), turbine exhaust flow mixing on the first bend in the flow beneath the fan (which is believed to cause an extremely uneven flow distribution), and a possibly very large corner loss for the final nozzle (which has inherited a narrow neck from the spoiler control, upstream of the last 180$^{o}$ of flow deflection, which involves taking this final corner at jet exhaust velocity).

The third test involved the measurement of intake pressure recovery in terms which include the effect of crossflow upon the efficiency of a flat fan-in-wing. In these tests it was found that the addition of a large cockpit bubble as a fairing in front of the intake reduced the pressure losses expressed in this way considerably; however, even with this fairing the overall air intake pressure loss was greater than had been originally assumed in performance calculations.

The developed performance now shown on Fig. 4 reflects the installation of modifications to re-institute the static thrust according to the original estimates and a variation of thrust with forward speed appropriate to the intake pressure loss measured with this canopy fairing. It will be seen that the speed range has now increased from 0 to 250 knots with a large climb margin. The angle of attack and control position involved for trim at maximum engine speed with the present aircraft thrust level are shown in Fig. 5. During the test the pitch control vanes were found to be much less effective in deflecting the trailing edge jet than had been hoped, and some modifications to improve the jet deflection were done. Lines for three configurations are therefore shown with a mean line drawn through representing the variations that would be achieved with a slightly modified control.

The objective of showing that transition is feasible was also achieved. This is illustrated in Fig. 7 which is a similar plot to Fig. 5 for various transition configurations at given weight. The transition procedure determined is illustrated diagrammatically on Fig. 8 which shows the freedom for transition control which was available. Either the rear transition doors could be opened, or, the port and starboard transition doors, or, both could be opened together. All these three were tried but it appeared that the only satisfactory procedure for keeping the pitch control within bounds while at constant lift was to open the side doors completely first, and then the rear. The control actions required are illustrated by the dotted line a, b, c in this Figure and it will be seen that pitch control is positive (nose-down) throughout the maneuver. On Fig. 7 two lines are drawn illustrating the variation of angle of attack and pitch control position with speed for the following two cases:

(a) equilibrium (drag = thrust)

(b) a constant accelerating force of 200 lb.

## 3.0 AVROCAR DESIGN DEVELOPMENT (Canadian Government Part 1 Study)

It was realized that in order to extend the range and duration of the Avrocar type vehicle (as appeared to be essential to increase its operational utility), two approaches were possible.

(a) to considerably increase the power, thus allowing a weight increase, and retaining VTOL capability with a considerably improved fuel load.

(b) to reduce the power and improve the cruising propulsive efficiency.

Both these approaches were tried. The design studies resulting from the second, finished up with an elliptical planform aircraft with conventional tail, with reduced capability and without VTOL. The other resulted in greatly improved capability and is illustrated here in two versions, Figs. 9 and 10. In this aircraft, the three J69 engines are replaced by two General Electric J85 engines in a different layout, and these provide approximately twice the power for no increase in powerplant weight at all. At the same time they provide a considerable improvement in specific fuel consumption. Reference to Fig. 9 shows an aircraft exactly the same size as the Avrocar with a crew of two situated in the middle in front of the main turborotor, the cockpit providing an inlet fairing to the fan. The two engines on either side of the cockpit exhaust into tusks which cover about half of the fan circumference in a partial entry turbine arrangement, similar to that adopted by General Electric, but they blow upwards through the tip turbine and exhaust rearwardly over the top of the aircraft rather than down into the duct, which was found to be unsatisfactory on the Avrocar; this arrangement is made possible by the partial entry turbine.

To absorb the increased power most effectively, the size of fan is increased from five ft. diameter to six ft. diameter, but this still leaves ample space within the vehicle for the accommodation of a standard fuel capacity of 4200 lb., plus a standard cargo capacity of 100 cu. ft.

After suitable allowances, based on the recent Avrocar and model tests, have been made the two J85's provide sufficient power to allow VTOL at a gross weight of 9700 lb. at which weight standard fuel and 1000 lb. cargo can be carried. By sacrificing some cargo capacity a maximum fuel weight of 6500 lb. can be carried allowing an improved range performance with STOL. The Avrocar focussing type hovering control and stabilizer system is proposed, with the same jet flap pitch and roll control for in-flight as have been recently tested. A single fin and retractable landing pads complete the picture.

The feasibility of this aircraft has now been very largely substantiated by the Avrocar and other tests, with one considerable exception; this is that the automatic artificial stabilizer for forward flight is still completely unproven. In an endeavour to avoid the development problems which are bound to be associated with this novel proposal, an alternative version based on a more conventional approach, albeit with a somewhat reduced performance capability, is also proposed.

This is shown in Fig. 10 and is seen to be exactly the same basic aircraft with fixed wing extensions to the rear. In this case the flow through the wing tip in the forward flight configuration is ducted through the wing extensions and exhausts through a full span slot fitted with a similar control vane for pitch and roll control in forward flight. It is clear that due to the increased moment arm of these controls that they will be more effective than the presently designed control vanes on the Avrocar. The single fin in the center is replaced by a pair of fin and rudders at the wing tip. The possible saving in development effort represented by the provision of natural stability on this design is imponderable; however, a notable advantage it possesses is that control is retained after the failure of both engines and because of the low wing loading a dead-stick landing should be quite feasible. However, because of the extra weight of the wing extensions the performance capability is markedly below that of the circular wing version.

Both versions have a greatly extended capability by comparison with the Avrocar however, as is shown by the Table, Fig. 11 which; compares the performance of the circular wing version with that of the original Avrocar according to specification. The thrust minus drag margin provided by the two J85s is adequate for a rate of climb almost three times that of the original Avrocar, in spite of the increased take-off weight, and the maximum speed is improved to 405 knots. Both range and endurance are in the order of 5 to 8 times as much as was originally available and it will be seen that the objective of four hours duration has been easily surpassed in the ground cushion, with about 3.3 hours being possible in normal cruising flight.

The performance is further illustrated in the suggested mission profiles given in Figs. 12 and 13.

Fig. 12 shows a sea level VTOL mission for both versions in which a penetration, cruising at high speed at tree top level, is visualized, with an allowance at the outward end for one hour cruising at a typical height in the ground cushion (during this time of course the ability to clear any obstacle is assured because of the VTOL capability) and return with 10% fuel reserve. Radius of action is then shown plotted against cruising speed and the advantage of the circular wing version due to its extra 850 lb. of fuel is seen to be about 30%, whereas the advantage of cruising on one engine with the other shut down is about 50%.

On this basis the maximum penetration radius of action is about 200 nautical miles in a mission lasting 2.8 hours at a cruising speed of about 220 knots, or 180 n.m. in 2.1 hours at 320 knots.

The capability is further improved in the maximum fuel case in which the take-off weight is now greater than will allow VTO. However, it is only some 20% greater and thus the distance to 50 feet is extremely short, being 350 feet with the circular wing version and 200 feet with the version with wing extensions due to its lower induced drag in the take-off phase. The increased fuel load has been apportioned to allow 1500 lb. fuel for scouting at the outward end which gives 1.5 hours in the ground cushion, and at the same time the radius of action with the circular wing version is seen to have increased to about 320 n.m. for a mission lasting 3.8 hours, cruising at about 225 knots.

## 4.0 CONCLUSION

In conclusion it is believed that the objectives of both the U.S. Army Continuation Test Program and the Canadian Government Study Program have largely been achieved.

The Continuation Test Program has shown that good aerodynamic characteristics (increased effective aspect ratio with high lift curve slope) and greatly improved static stability result from the new in-flight configuration and as far as can be seen it ought to be possible to restore the thrust to a level of the order of that originally specified. This ought to result in a forward speed performance substantially the same as that originally specified.

Under the Canadian program, the vehicle, using what one might call a bona fide VTOL engine, has been designed; which we think has a very attractive performance potential. Because of its performance improvement and particularly because of its projected high speed and low structure weight, the direct operating costs in cents/ton mile for these aircraft appear favourable, in comparison with helicopters and other light aircraft. Furthermore, the other model tests performed largely substantiate the values used in calculating the performance of these aircraft. irrelevant

The superior VTOL performance and the direct operating costs results from increased AUW, disposable load, and fuel carried, and does not reflect an improved fuel economy compared with the Avrocar, although there is in fact a small improvement because of the greater efficiency of the J85s compared with the J69s. The fuel logistics problem remains. Nevertheless this aircraft can apparently offer vertical take-off in standard conditions with considerably more than half its weight as a disposable load. It should perhaps be noted that structure weights are based on Avrocar experience and have been increased to allow for anticipated changes and slightly increased load factors.

With regard to the status of the two Avrocar machines that have been built: the first aircraft has undergone 54 hours of largely trouble-free running in the wind tunnel in a period of approximately four weeks, but has again suffered wide-spread minor damage. Without an extensive and costly repair program it could possibly be used for a short further test series, perhaps a brief investigation of the effect of wing extensions. A repair program of greater scope than that undertaken in the beginning of the last series would be necessary to restore it to its original condition and it should always be remembered that the aircraft has now been modified back to front because of the incompatability of the tunnel mount with the aircraft undercarriage, and the cockpit therefore appears at the rear with respect to the transition controls, and faces aft.

The second aircraft is in good shape and is currently being used at Malton for preliminary terrain testing, hovering at heights up to three feet. With what has become fairly routine repair and maintenance, it can probably be used for a considerable further program. In whatever areas further development is postulated it becomes fairly clear that the program will be ham-strung unless some measure of thrust improvement is attempted. Whereas it is difficult to see any reason why a static thrust in the order of that originally estimated should not be achieved, nevertheless it is also difficult to ascribe losses which can account for the deficiencies to particular areas in which no detail studies have been made.

This report is a preliminary to a final review of these programs, which is scheduled to take place on 13th and 14th of June 1961. In view of the foregoing, it is believed that the second Avrocar now represents an invaluable research tool and it is anticipated that new proposals will be made at this review along the following lines:

(1) A short initial program to investigate thrust improvement consisting of further model tests on existing models, and one simple new model and tests on the second aircraft in the static rig at Malton. The objective of these tests being to pin-point high loss areas and estimate possible improvement accurately.

(2) A program of thrust improvement modifications to be applied to the second vehicle.

(3) A program of ground cushion development, including the provision of a hydraulic system to provide much greater actuating forces for control movement. An improved hovering control mechanism will be recommended.

(4) Vertical take-off with the second aircraft. <——

(5) Further design study of the proposed Avrocar Development Aircraft, plus a wind tunnel model for low speed wind tunnel testing at a Canadian facility. (?)

These proposals will be submitted in a formal document at the time of the review.

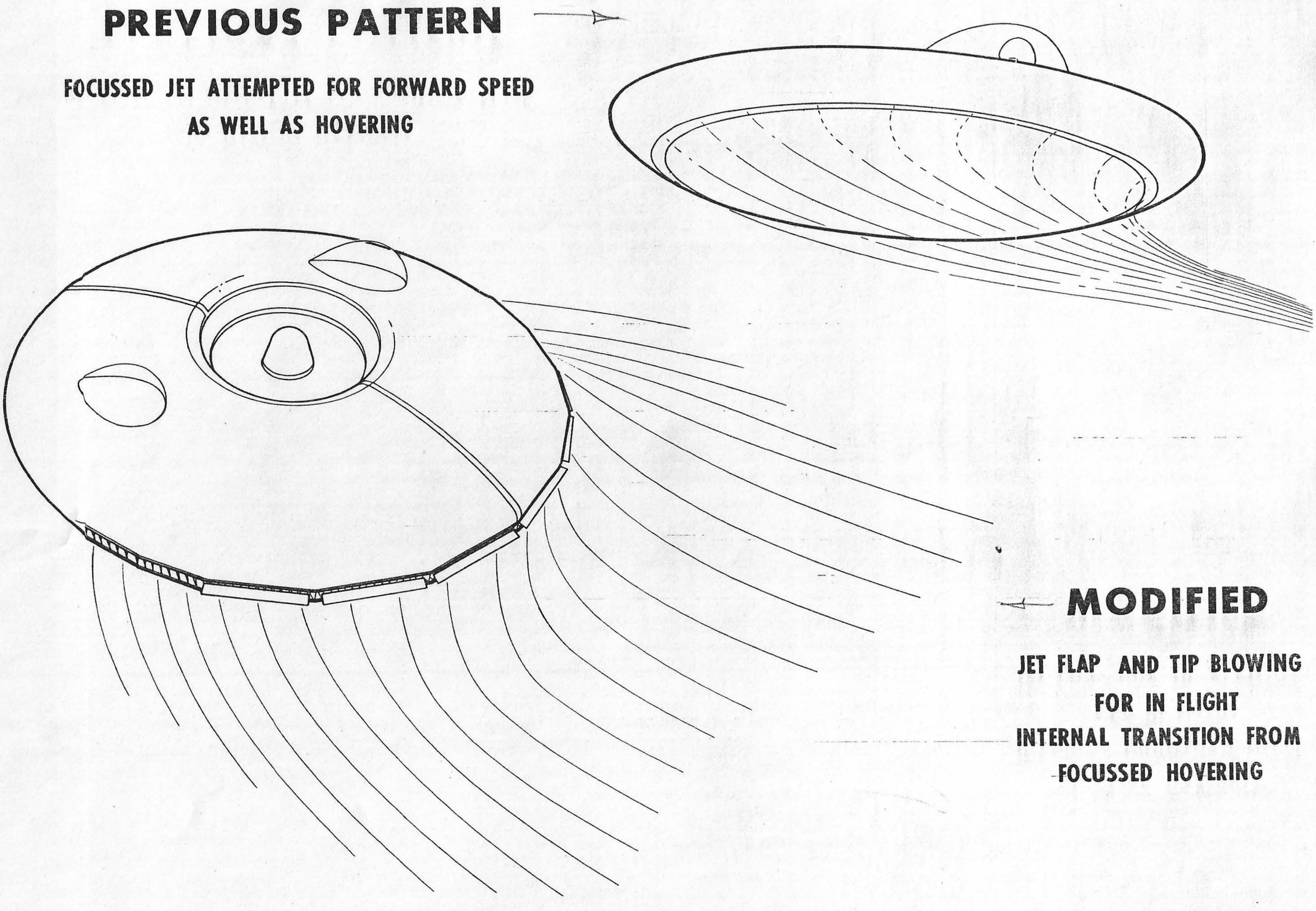



FIG 1 AVROCAR JET DEPLOYMENT

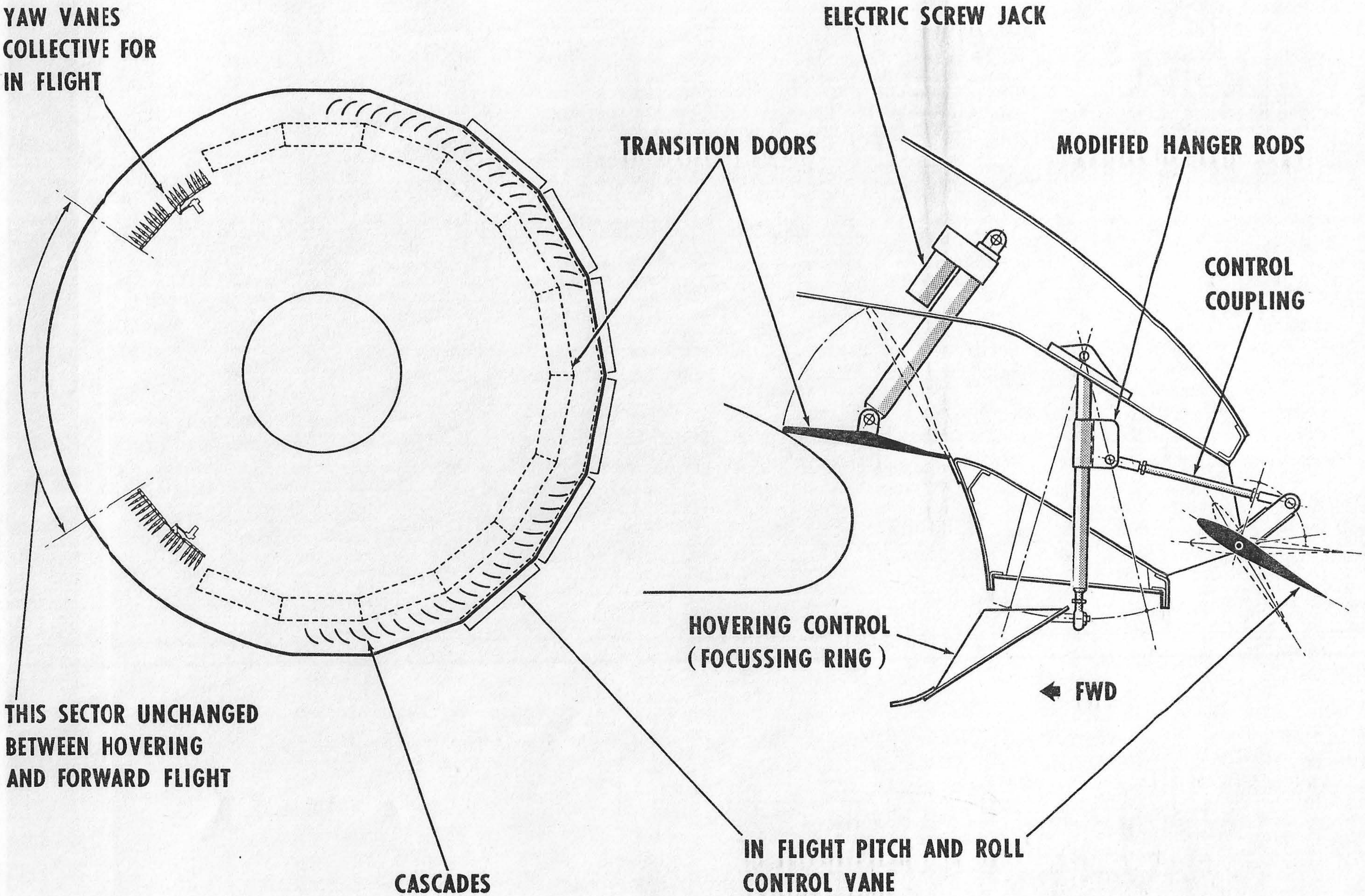



FIG 2 AVROCAR CONTROL AND PROPULSION DEVELOPMENT

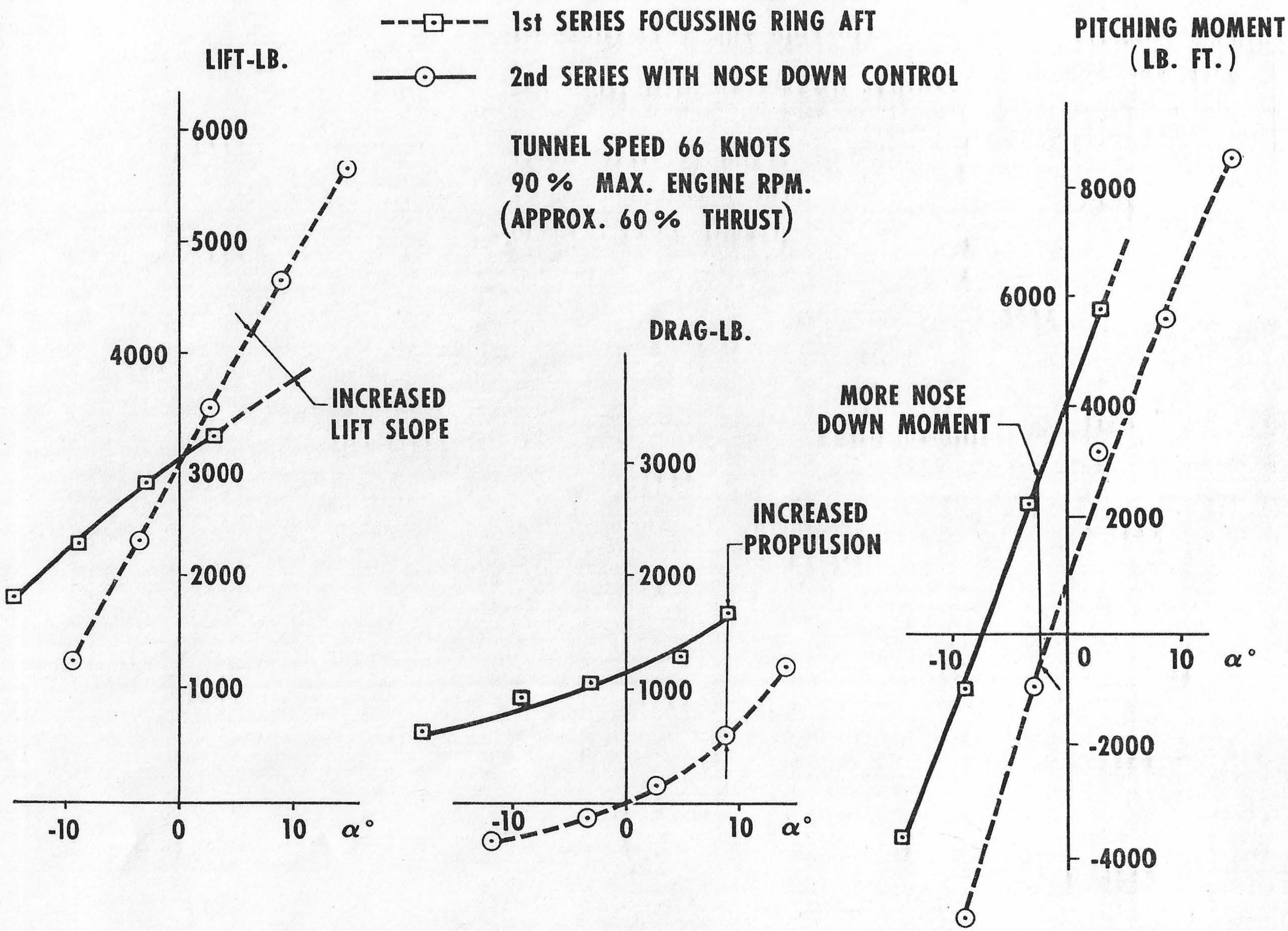



FIG 3 AVROCAR COMPARISON OF TUNNEL RESULTS AT AMES RESEARCH CENTER

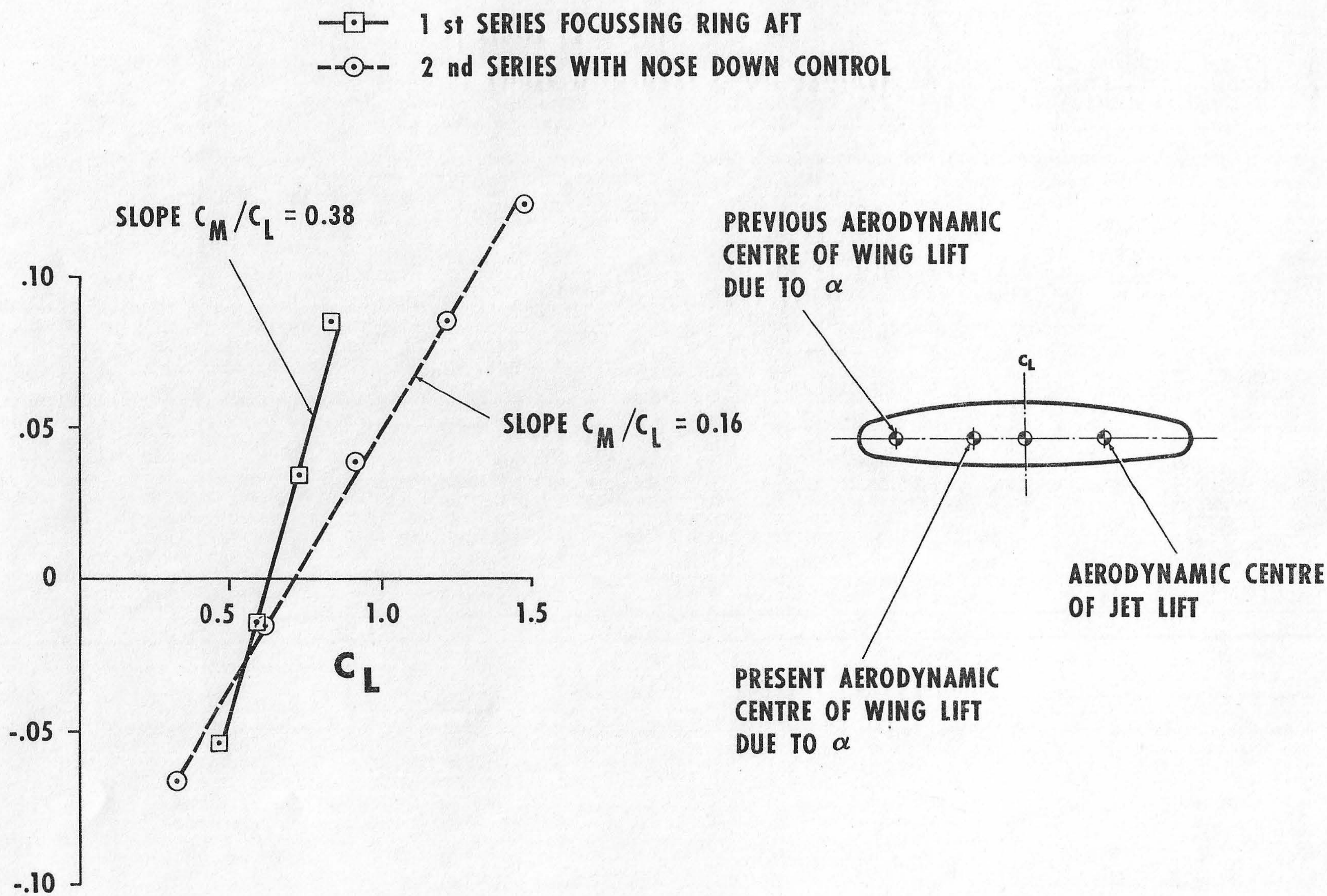



FIG 4 AVROCAR COMPARISON OF TUNNEL RESULTS AT AMES RESEARCH CENTER

DRAG-THRUST, ANGLE OF ATTACK AND PITCH CONTROL POSITION FOR TRIM VS FORWARD SPEED

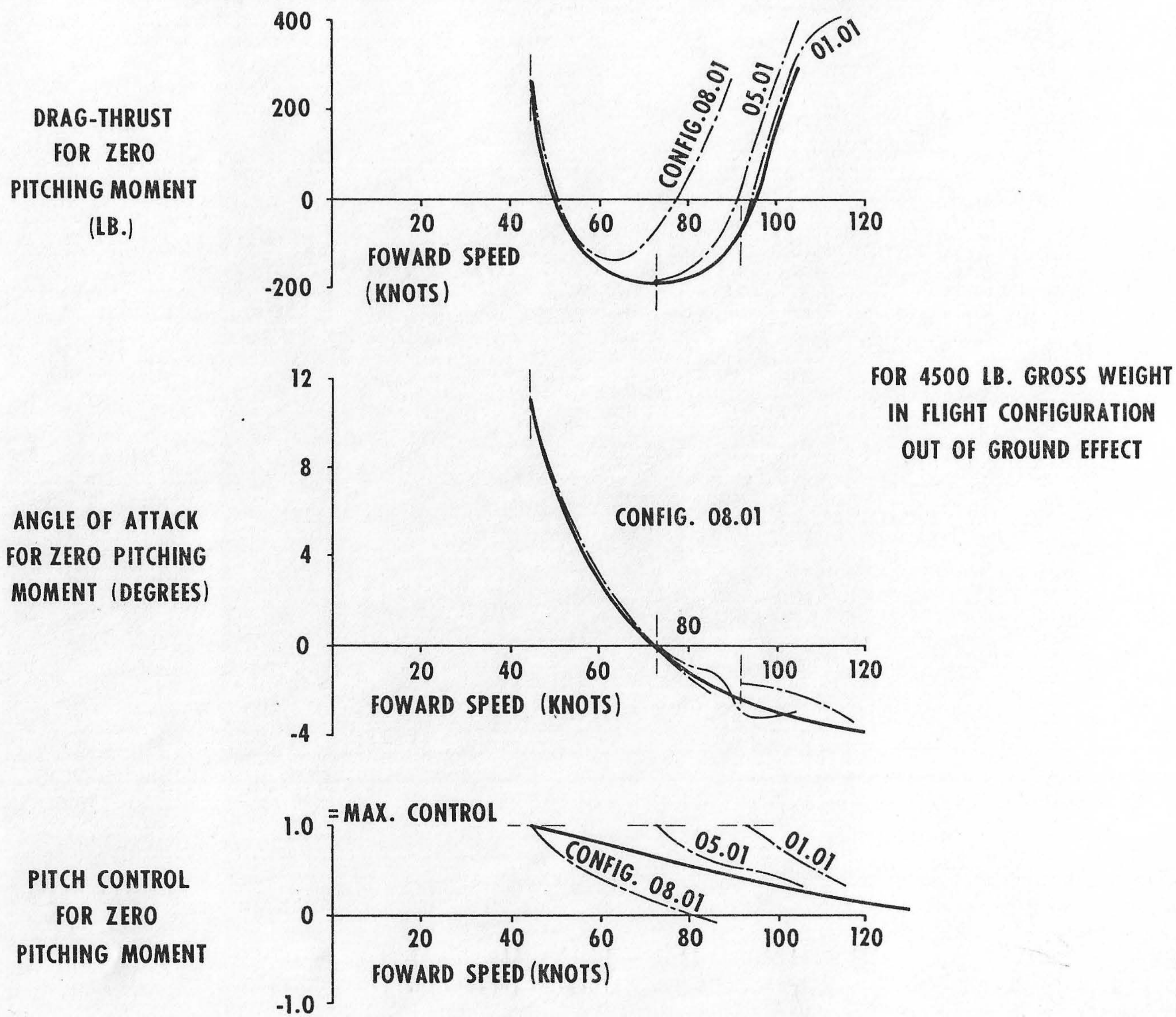



FIG 5 AVROCAR FULL SCALE TUNNEL TESTS AT AMES RESEARCH CENTER

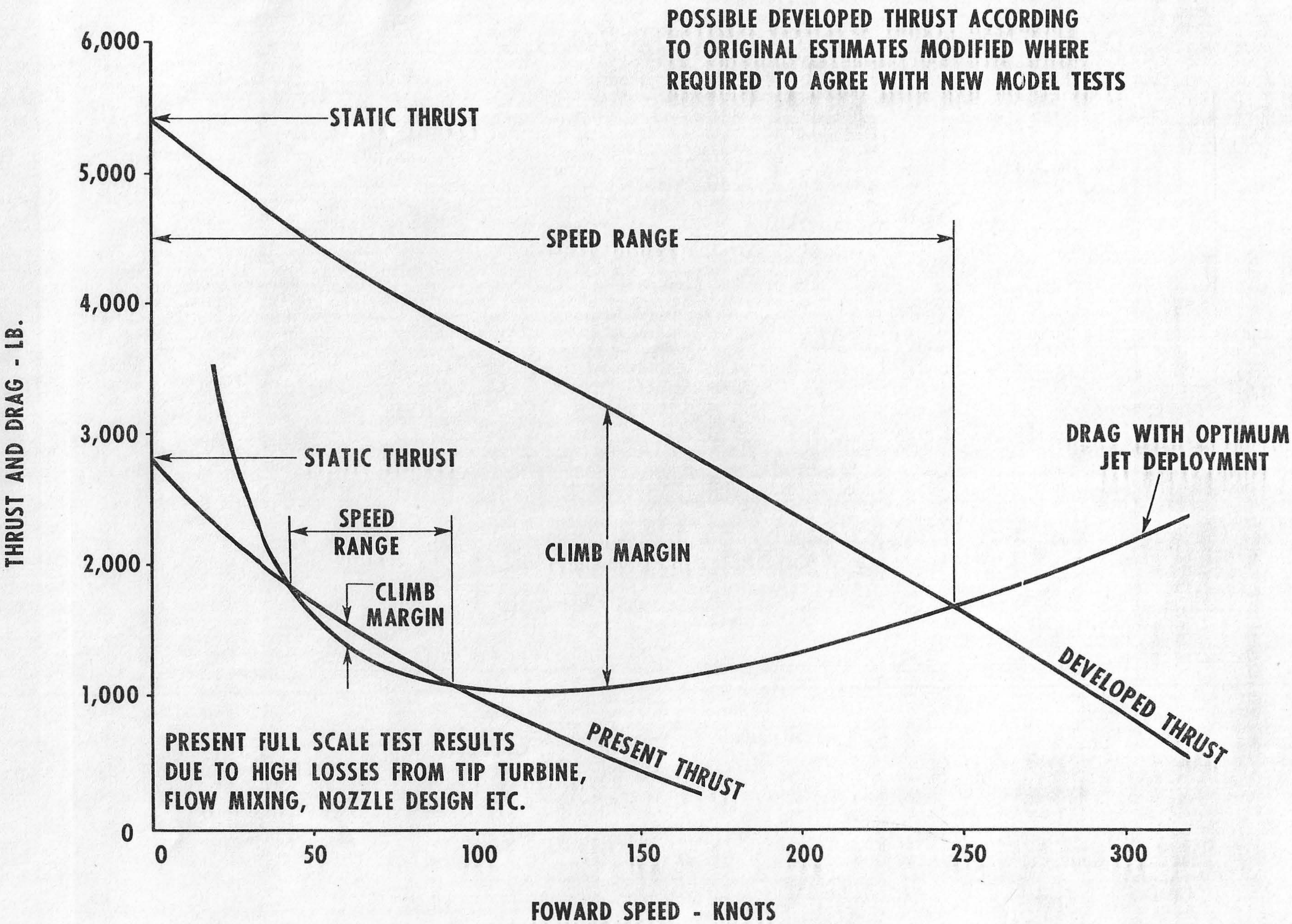
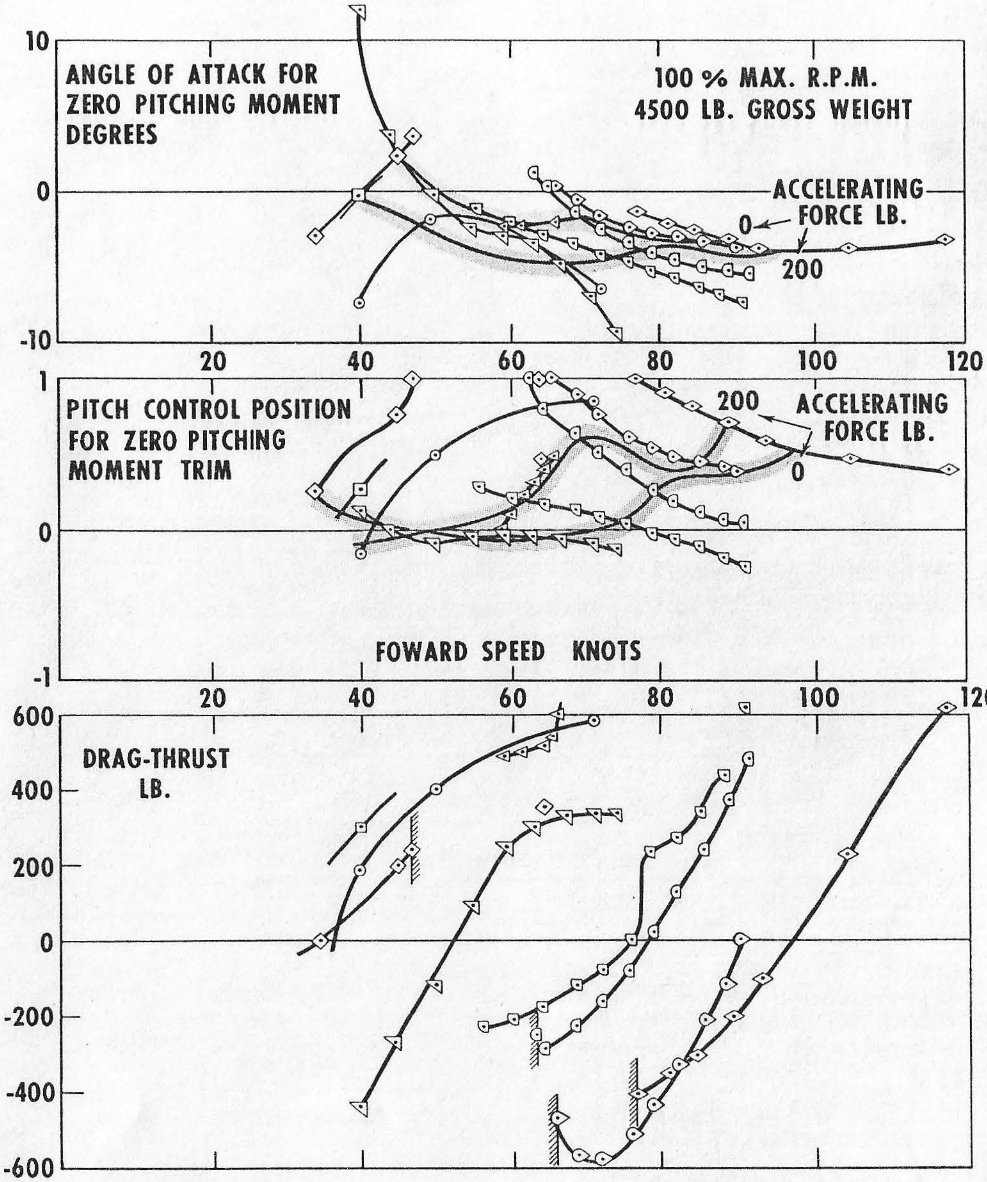



FIG 6 AVROCAR FORWARD FLIGHT PERFORMANCE




**TRANSITION PERFORMANCE AT 32 INCHES ABOVE GROUND**

| SYMBOL | $J_{T1}$ | $J_{T2}$ |
|---|---|---|
| ○ | 0 | 0 |
| □ | 0 | .25 |
| ◇ | 0 | .50 |
| ◁ | 0 | .75 |
| ◸ | 0 | 1.0 |
| ◻ (flagged) | .25 | 1.0 |
| ◻ (flagged) | .50 | 1.0 |
| ◯ (flagged) | .75 | 1.0 |
| ◇ (flagged) | 1.0 | 1.0 |

FIG 7 AVROCAR FULL SCALE TUNNEL RESULTS AT AMES RESEARCH CENTER

DIAGRAM OF CONTROL MOVEMENTS DURING TRANSITION

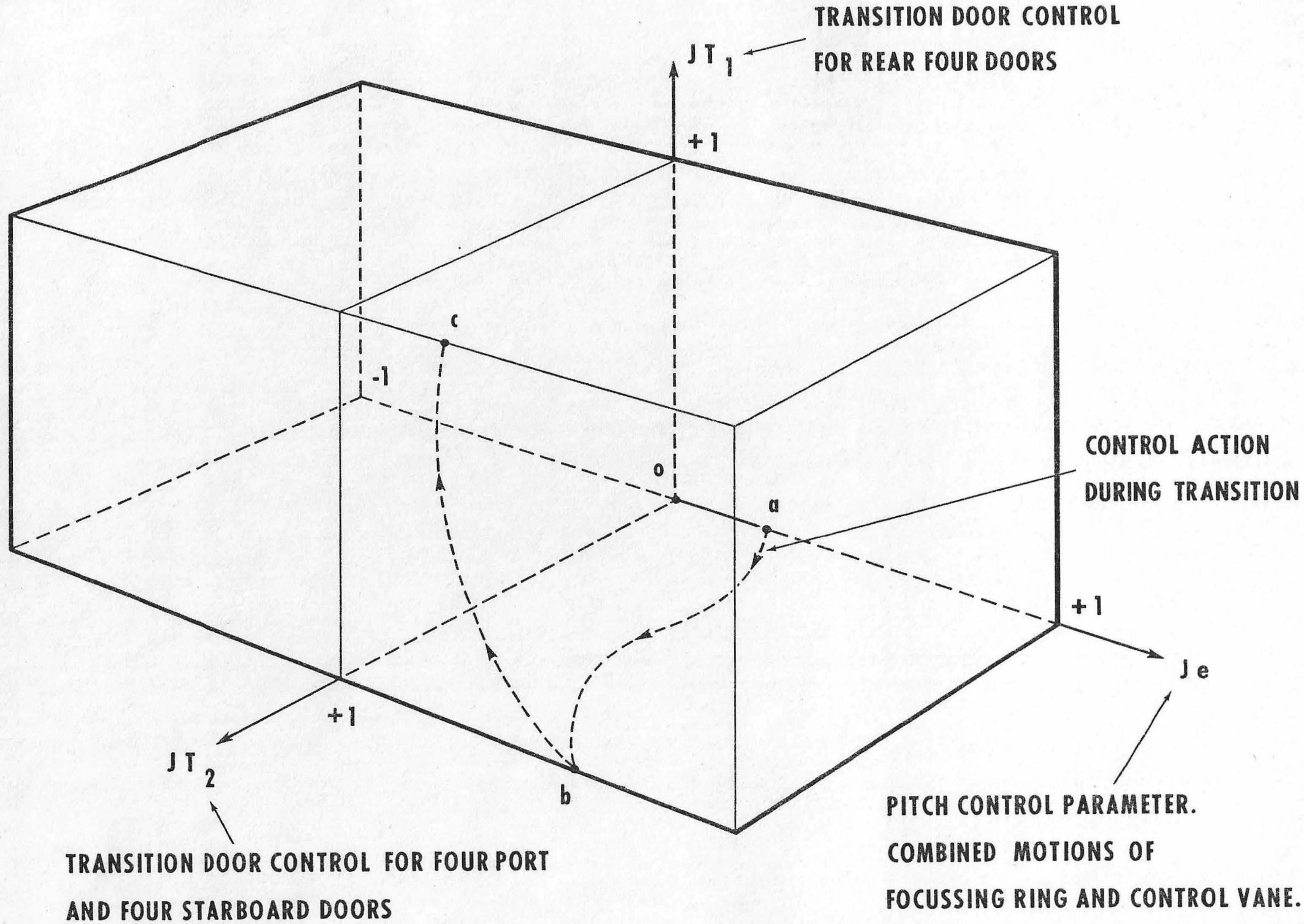



FIG 8 AVROCAR FULL SCALE TESTS AT AMES RESEARCH CENTER

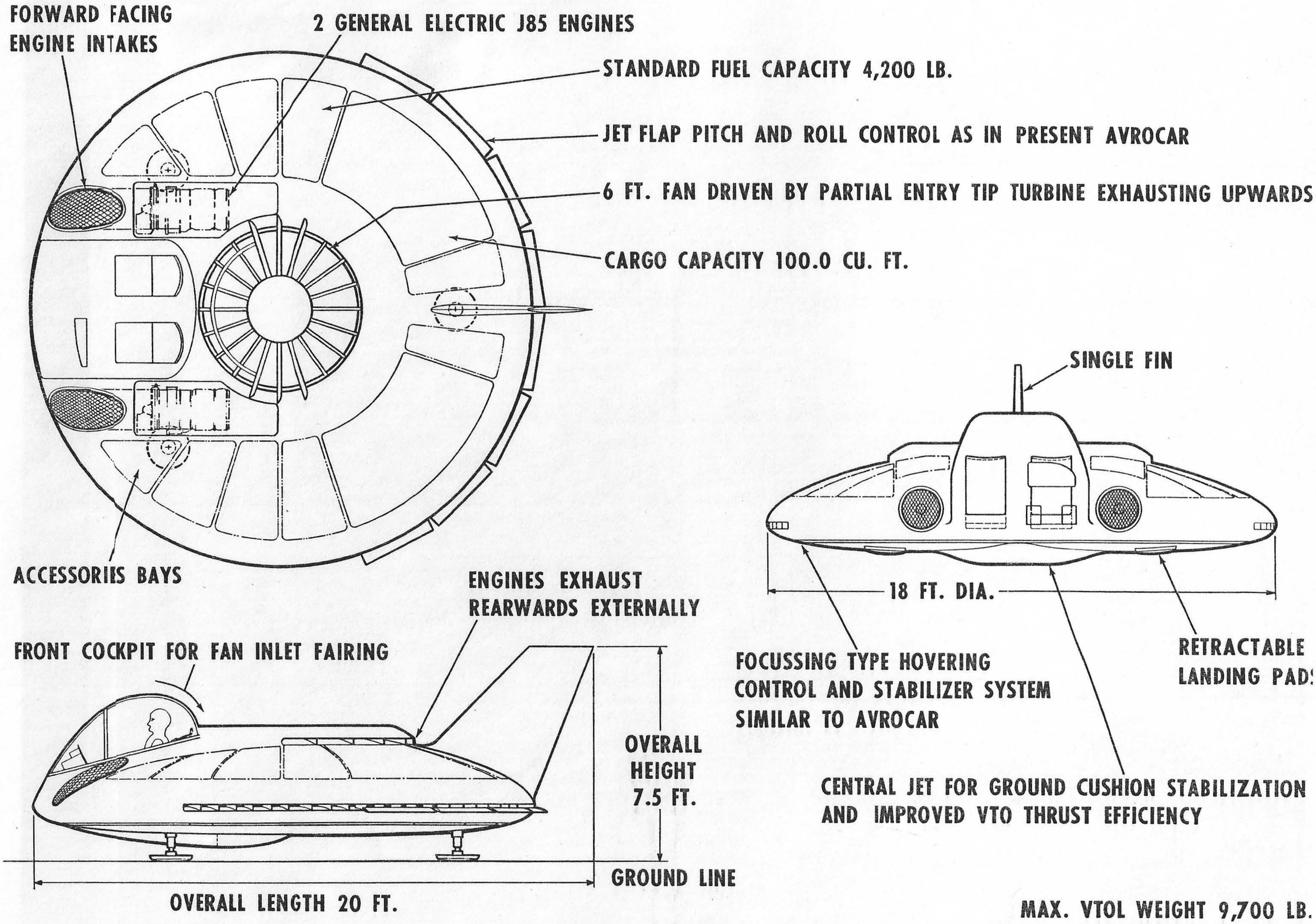





FIG 9 AVROCAR DEVELOPMENT 2 J85 ENGINES

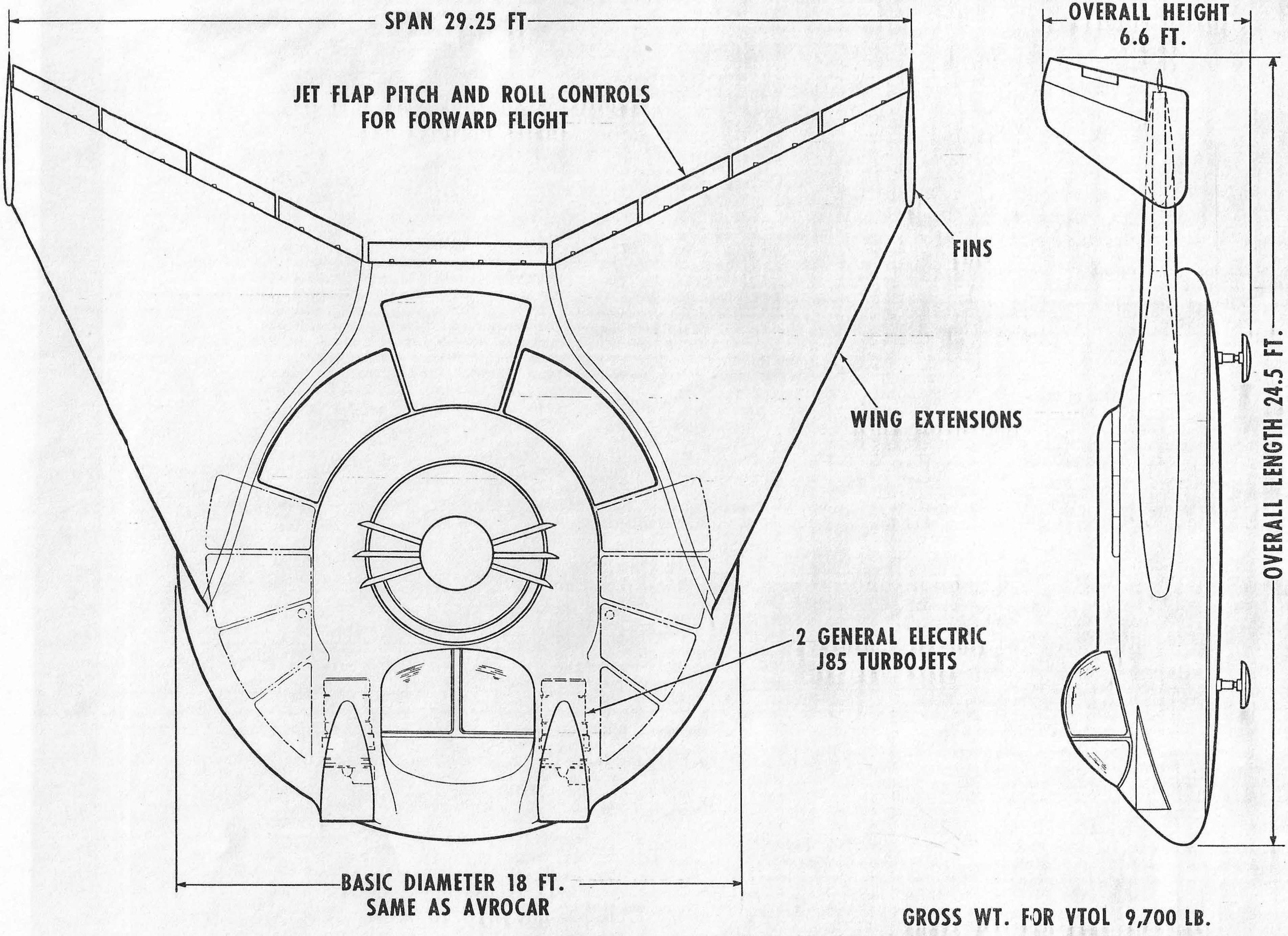



FIG 10 AVROCAR DEVELOPMENT VERSION WITH WING EXTENSIONS

| | DEVELOPED AVROCAR VERSION CIRCULAR PLANFORM WING | ORIGINAL AVROCAR | G.8 |
|---|---|---|---|
| REFERENCE | 500/PERF/427 | AVRO/SPG/TR 254 | ASR-1-6 |
| ENGINES | 2 X J85 @ 2,700 LB. | 3 X J69 @ 920 LB. | 2xPT6 14' fan |
| **TAKE-OFF** | | | |
| MAX. VTO WEIGHT | 9,700 LB. | 5,650 LB. | 6500# |
| FUEL + PAYLOAD & CREW(2) | 5,600 LB. | 2,400 LB. | 2533# |
| FUEL FLOW | 4,800 LB. / HR. | 3,120 LB. / HR. | 700# |
| INITIAL RATE OF CLIMB | 11,000 FT. / MIN. | 4,300 FT. / MIN. | 1300 |
| sfc | .5 | .55 | .11 |
| **SEA LEVEL - ALL ENGINES** | | | |
| MAX. RANGE SPEED | 210 KNOTS | 235 KNOTS | 120K |
| NAMPP | .104 | .097 | .3436 |
| MAX. SPEED | 405 KNOTS | 305 KNOTS | 222 |
| MAX. RANGE - NAUTICAL MILES | 437 N. M. | 79 N.M. | 3906 |
| WITH NORMAL TANKAGE OF | 4,200 LB. | 810 LB. | 1133 |
| AND PAYLOAD + CREW OF | 1,400 LB. | 1,590 LB. | 1400 |
| MAX. DURATION IN - FLIGHT WITH NORMAL TANKAGE | 2.5 HOURS | .42 HOURS | 4.0@ |
| MAX. DURATION IN GROUND CUSHION AT 2 FT. | 3.5 HOURS | .5 HOURS | 4.0@ |
| **SEA LEVEL - ONE ENGINE SHUT DOWN** | | | |
| MAX. RANGE | 613 N.M. | 104 N.M. | |
| MAX. ENDURANCE | 3.3 HOURS | .52 HOURS | |
| MAX. ENDURANCE AT 2 FT. | 5.1 HOURS | .60 HOURS | 5.06 |

FIG 11 VTOL PERFORMANCE COMPARISON

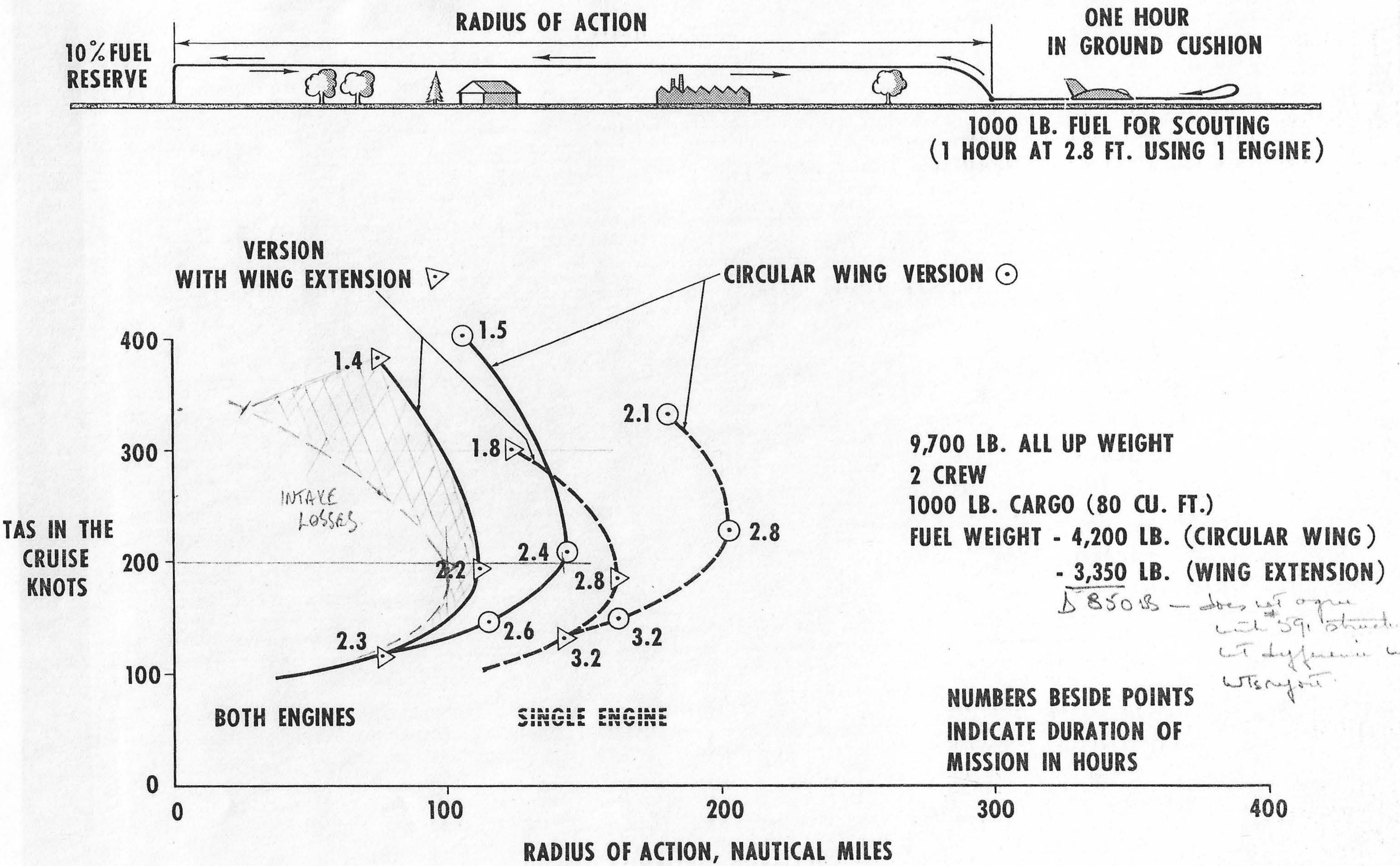



FIG 12 DEVELOPED AVROCAR - 2 J85 SEA LEVEL VTOL MISSION

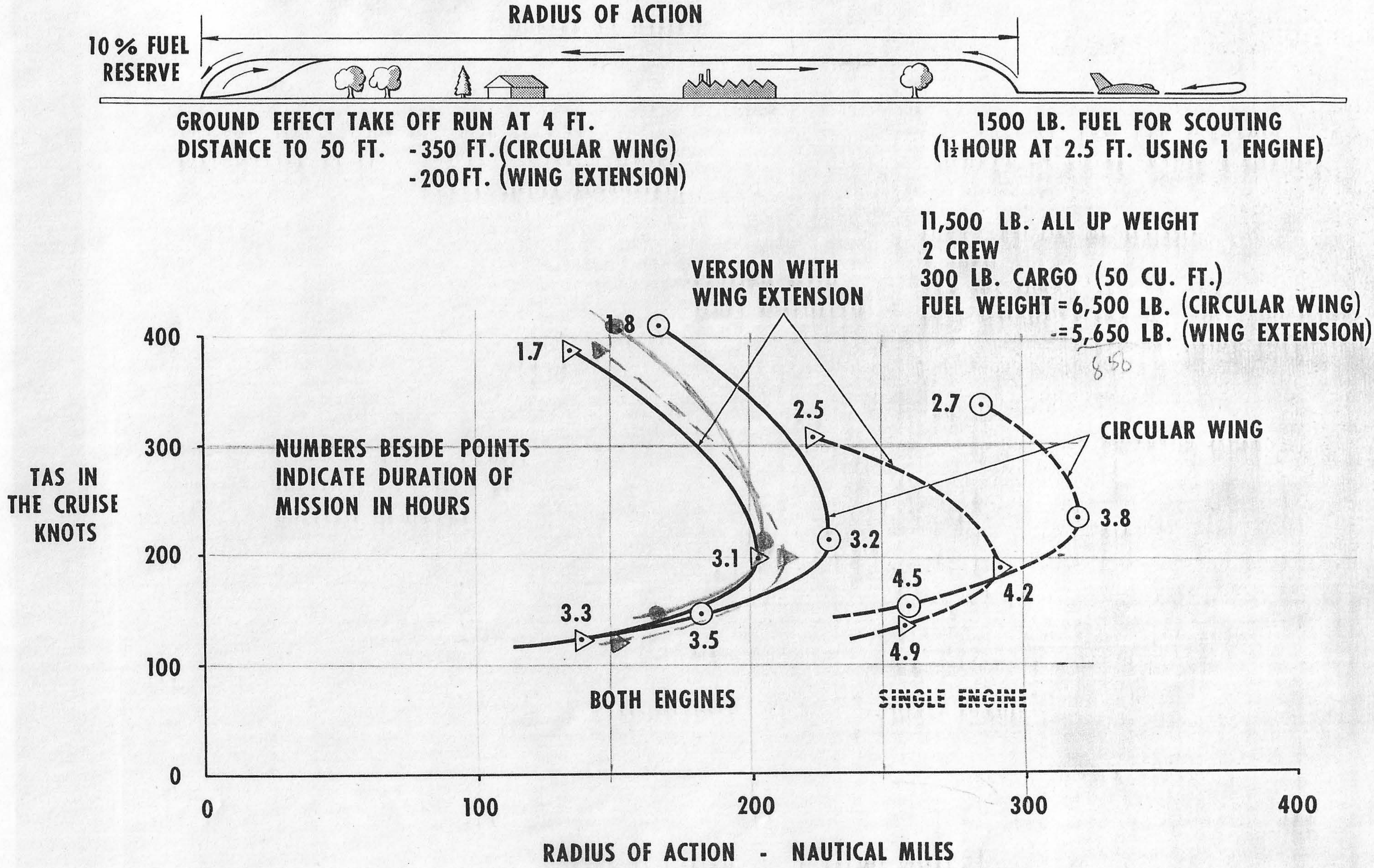



FIG 13 DEVELOPED AVROCAR - 2 J85 SEA LEVEL STOL MISSION