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ANALYSIS OF CURRENT LEM POWERED-DESCENT TRAJECTORIES

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SUMMARY

The design powered-descent trajectory for the lunar landing mission of the Lunar Excursion Module (LEM) is divided into three operational phases: an initial braking phase, a final approach phase, and a landing phase, as reported in reference 1. This paper contains an updating of the analysis reported in reference 1 on the operational tradeoffs available in these phases of the descent. Several trajectories were found that yield satisfactory operational features which allow adequate pilot control of the final approach along with visibility and consideration of lighting due to the sun angle. These trajectories at the same time satisfy the abort and fuel economy criteria.

INTRODUCTION

The powered descent and landing trajectory is perhaps the most critical phase of the lunar landing mission. Because of the increased weight of the LEM and the added constraint of a specified thrust profile during Phase I (or Braking Phase) of the LEM powered descent, a re-examination of the analysis of reference 1 is deemed necessary. Consideration is given to pilot control and pilot safety since the crew is expected to assess the landing area and monitor the automatic descent. This may result in pilot manual control of a minor or even major portion of the powered descent. In order for the crew to be able to perform these functions properly, such factors as the trajectory characteristics of the final approach, the attitude of the spacecraft, abort considerations, and the visibility limits of the spacecraft windows must be accommodated. Tradeoffs between these factors and the need for minimum fuel expenditure is discussed.

The purpose of this paper is to present a re-examination of the reference 1 analysis on the important trajectory characteristics of the lunar landing maneuver to lo-gate and to examine these maneuver characteristics in the light of assumed operational criteria.

PHASES OF POWERED DESCENT

The powered descent portion of the lunar landing missions is a continuous thrust maneuver of several minutes duration and is initiated at or near the pericynthion of the descent transfer orbit (figure 1). This maneuver may logically be described in three phases: braking phase, final approach phase and landing phase.

In the initial phase, far from the landing site, the important consideration is optimum fuel performance. This braking phase is continued to a point where a modification to the trajectory is necessary to allow the crew to assess the approach to the landing site visually. This latter point is as yet undefined and is subject to tradeoffs which are examined in this paper.

The second phase, final approach phase, succeeds the braking phase and continues down to the initiation of the landing phase. It is during this second phase that the visual assessment of the landing area is made by the crew.

The terminal phase of the descent trajectory, which is not discussed in the text of this paper, is the landing phase and extends from termination of the final approach phase to the lunar surface.

A sketch of the powered descent is given in figure 2.

SCOPE OF CALCULATIONS

Since a previous study (see reference 1) involved a wide scope of parameters, the present investigation is limited to a more desirable range of these same variables. The initial conditions of the powered descent were pericynthion conditions at 50,000 feet ($v=5583$ fps, $\gamma = 0^\circ$). The axis system is shown in figure 3.

BRAKING PHASE

The braking phase of this descent is based on the calculus of variations technique reported in reference 2 for two-dimensional motion, a circular gravitational body, and a specified thrust profile as shown in figure 4. The specific impulse for this analysis was also varied linearly. The final conditions for the braking phase are specified by the desired conditions at hi-gate for the final approach phase.

FINAL APPROACH PHASE

For the final approach phase, the three major parameters were varied in the following manner. Two values for hi-gate, h_t, were considered: $h_t = 6000$ ft and $h_t = 8000$ ft. The attitude, θ, was varied from 120° to 140°. The throttle setting, TR, was varied from 0.6 to 0.4 of the maximum thrust level of 10,500 lbs. The terminal conditions of the final approach phase were a velocity of 62 fps with a flight path angle of -14 deg at an altitude of 700 ft. The landing site was assumed to be 2800 ft downrange since that would constitute a constant flight path of -14 deg to touchdown. The equations of motion for this phase are based on the same assumptions that were used in the braking phase.

RESULTS AND DISCUSSION

The primary objective of this analysis is to present the variations in pertinent parameters of the powered lunar descent due to the varying of the attitude, θ, and throttle ratio, TR, of the final approach phase. Tradeoffs are examined to determine trajectories that have desirable operational features, but also, meet the fuel requirements of the descent. Few of the cases considered have a total characteristic velocity, V_c, of over 6100 fps; (see figure 5) therefore falling outside the reasonable limits as far as fuel economy is concerned. The higher the attitude (i.e., closer to the optimum) and throttle ratio (optimum value would be 1.0) the lower the characteristic velocity. But these cases destroy visibility and increase the approach velocity near the surface.

The minimum desirable look angle is 35 deg, which is 10 deg above the lower widow limit. As shown in figure 6 this constraint eliminates an attitude of 140 deg for both the hi-gates of 8000 ft and 6000 ft. All other attitudes will satisfy this constraint.

Since the flight path angle is restricted to a maximum of 20 deg., figure 7 will eliminate an attitude of 120 deg except at a very low throttle ratio. But, even then the fuel expenditure becomes prohibitive. Also, the high throttle ratios for attitudes of 125 deg and 130 deg exceed the 20-deg flight path angle limitation.

Another operational factor to be considered is the time to assess the landing area. It can be seen from figure 8 that the time of Phase II for the cases considered varies from approximately 50 sec to 150 sec. It is assumed that a minimum time would be about 75 sec; therefore, as in the case of the flight path angle, eliminating high throttle ratios with attitudes of 120, 125, 130 and even 135 deg.

For completeness the range-to-go from hi-gate is presented in figure 9. This parameter is also a function of the attitude and throttle ratio, but operationally is reflected in the flight path angle and look angle. A short range would necessarily cause a steep flight path but may have adequate visibility because of the nearer-to-the-vertical attitude of the spacecraft required to maintain this steep flight path.

Since certain combinations of these important parameters are desired along with reasonable fuel consumption, figure 10 presents the look angle, β, and the flight path angle, γ, crossplotted versus the characteristic velocity and the pitch angle or attitude and figure 11 shows the range, R, and the time, t, crossplotted versus the same variables.

A nominal trajectory would have a flight path angle of about 15 deg and a look angle of 35 deg. Figure 10 shows that this would require a pitch angle of about 130 deg during Phase II and would cost 6025 fps characteristic velocity. To find the throttle ratio it is necessary to return to figure 5 with this attitude and characteristic velocity to ascertain the throttle ratio is about 0.48. The trajectory characteristics of this trajectory are presented in figure 12.

This method was also employed to determine a trajectory with a 20-deg flight path angle and a look angle of 35 deg (see figure 13). Although a 20-deg flight path angle is believed to be a design maximum, figure 14 represents trajectory characteristics for a trajectory with a 25-deg flight path and an improved look angle of 40 deg. Notice that the vertical descent rate remains large even at low altitude. Also, the time to assess the landing area is below 70 sec.

CONCLUDING REMARKS

A re-examination of the analysis reported in reference 1 concerning the powered descent portion of the landing mission of the lunar excursion module (LEM) is presented with special emphasis on the compromises imposed by various operational considerations. The design landing trajectory was divided into three operational phases. The initial braking phase is concerned primarily with fuel economy; the second phase, the final approach, emphasizes pilot control and visibility; and the final phase, the landing phase, is from the end of the final approach to termination at touchdown on the lunar surface. Flight safety, including abort considerations, and fuel economy are overriding criteria throughout all phases of the descent. This design landing technique was found to yield several trajectories with satisfactory operational features which allow the pilot adequate control of the final approach and at the same time satisfy the abort and fuel economy criteria.

The landing phase was not considered in the scope of this analysis. This re-examination confirms the selection of trajectory parameters made in reference 1, even with the current weight and throttle limits.

REFERENCES

1. Bennett, Floyd V., Price, Thomas G.: Study of Powered Descent Trajectories for Manned Lunar Landings, NASA TN D2426, 1964.

2. Miele, Angelo: General Variational Theory of the Flight Paths of Rocket-Powered Aircraft, Missiles and Satellite Carriers, AFOSR-TN-58-246 (AD-154 148).

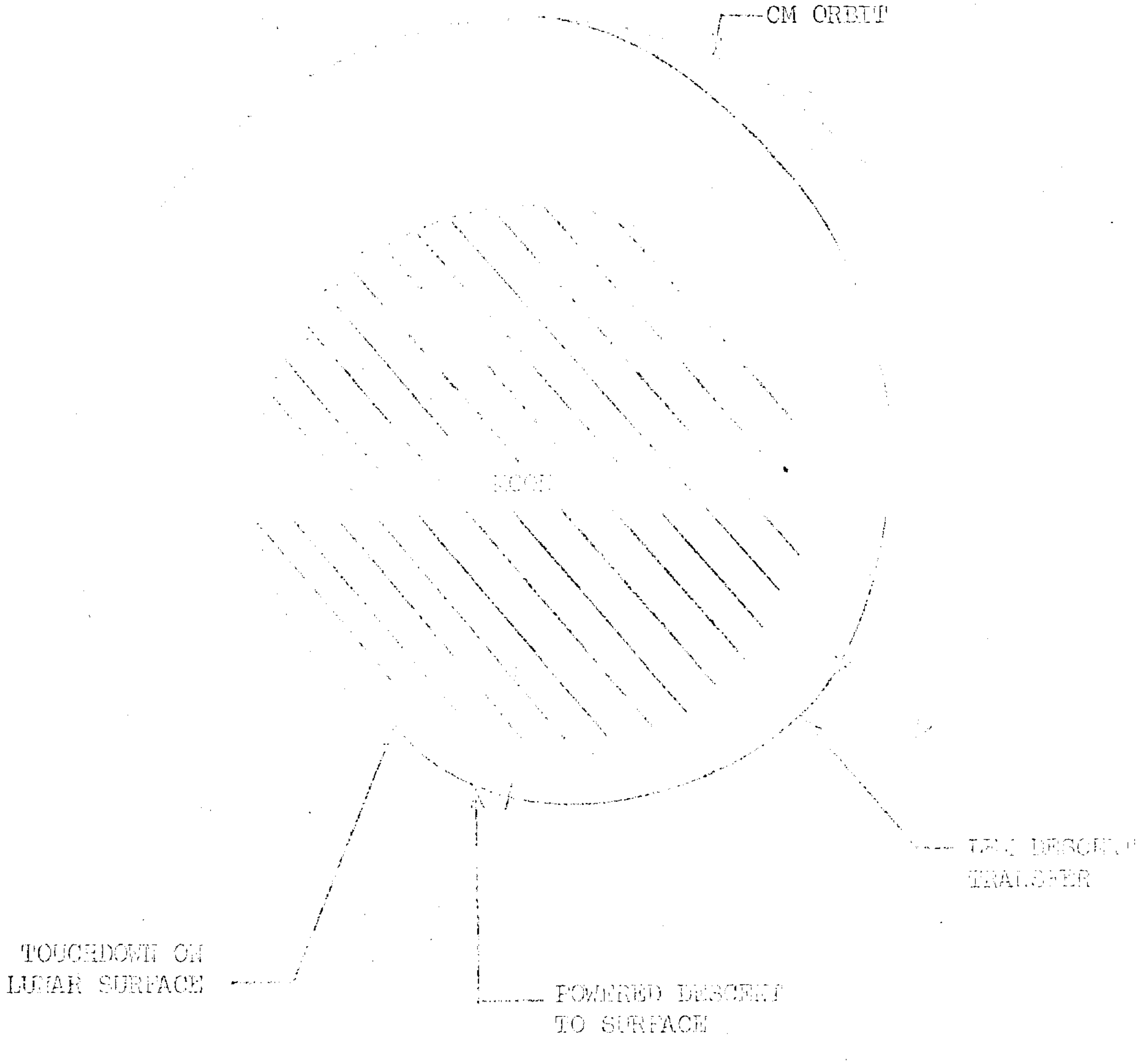

FIGURE 1.- SKETCH OF LEM DESCENT

PHASE I - BRAKING PHASE
PHASE II - FINAL APPROACH PHASE
PHASE III - LANDING PHASE

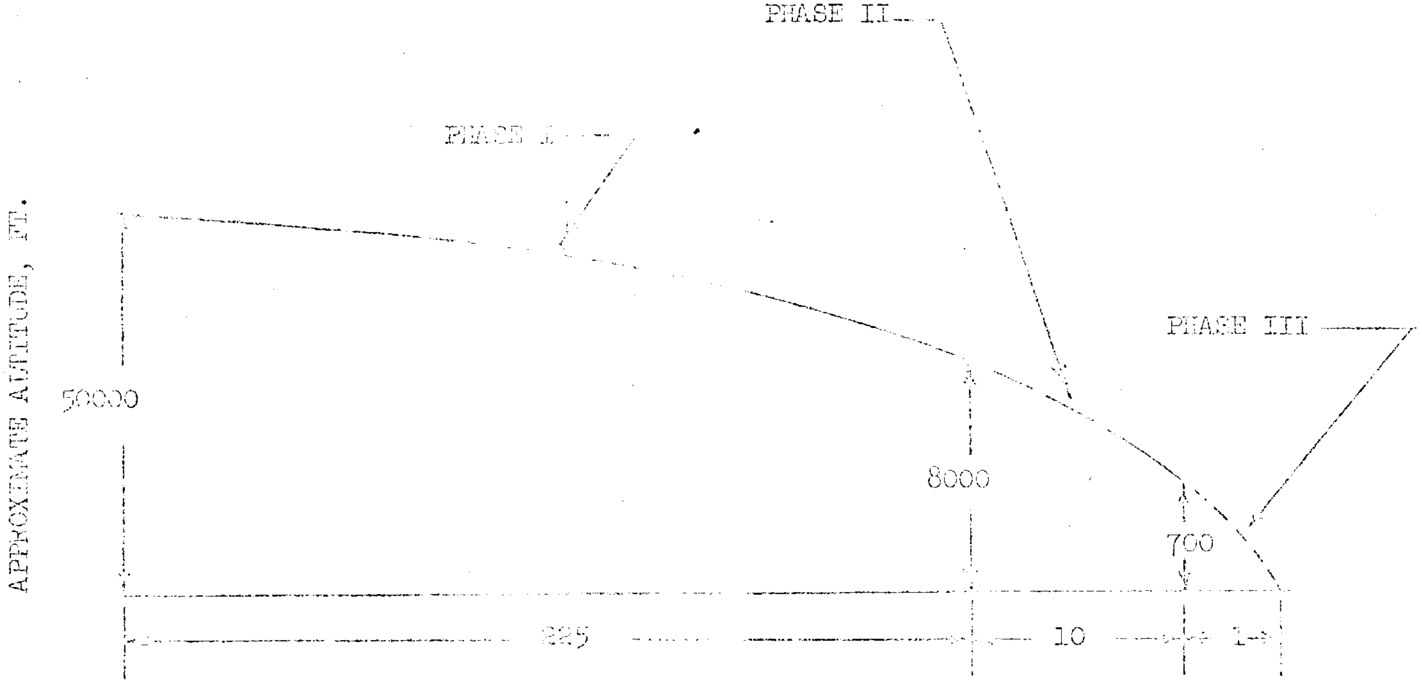

FIGURE 2.- THREE PHASES OF POWERED DESCENT

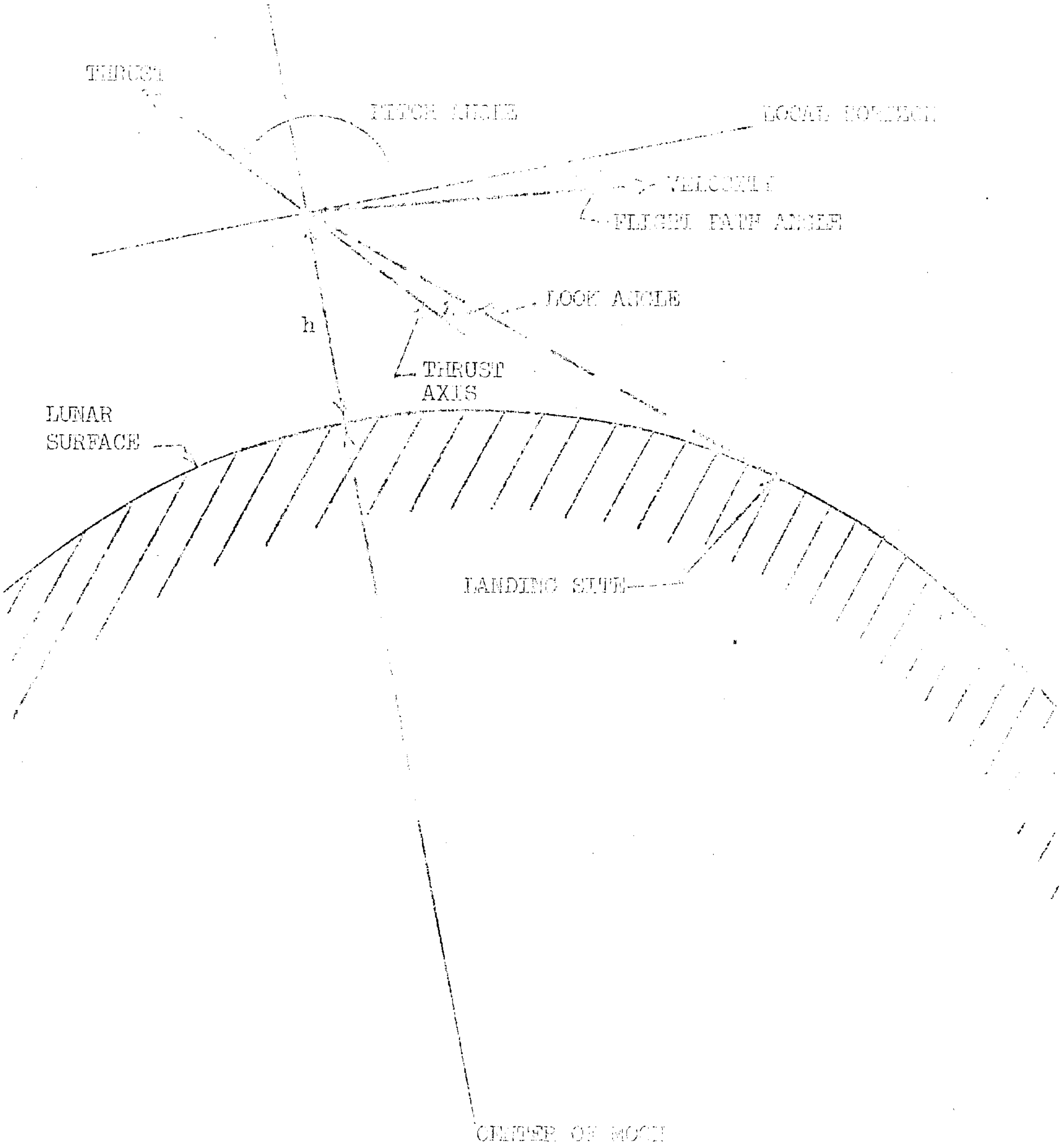

FIGURE 3.- SKETCH OF AXIS SYSTEM

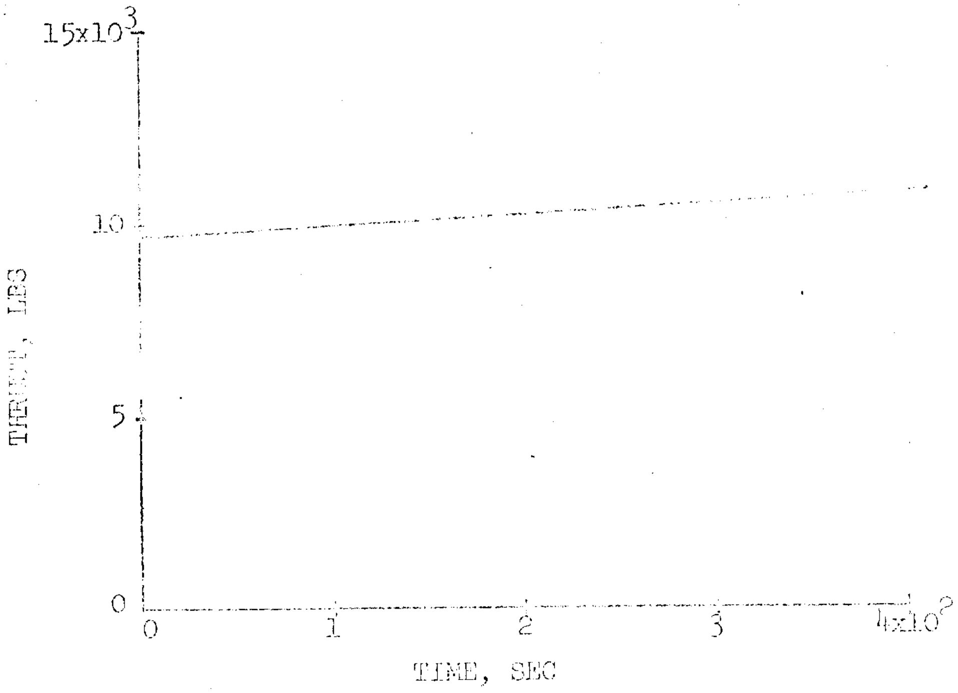

FIGURE 4.- THRUST PROFILE

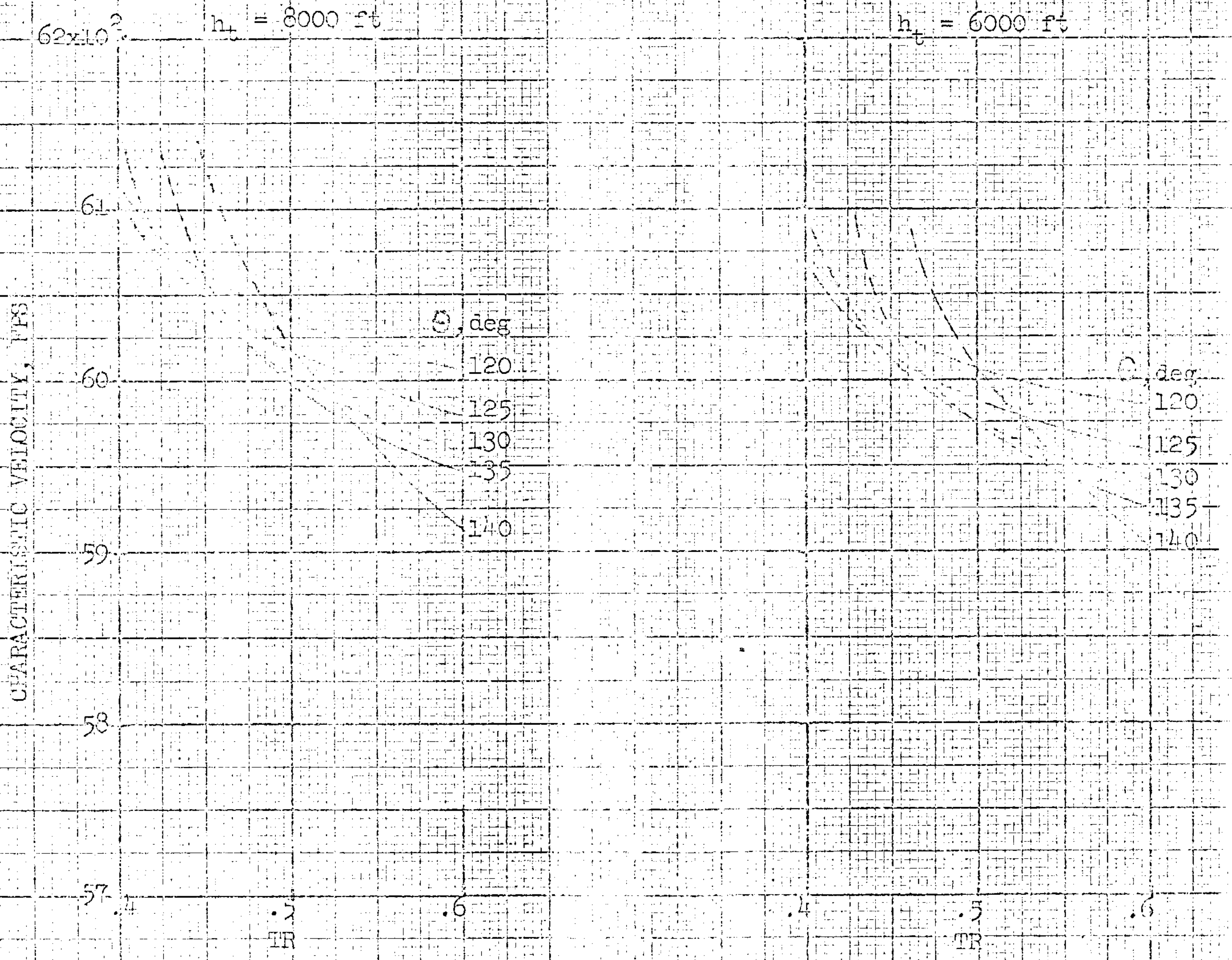

FIGURE 5.- CHARACTERISTIC VELOCITY VS THROTTLE RATIO FOR VARIOUS PITCH ANGLES DURING THE LANDING APPROACH PHASE

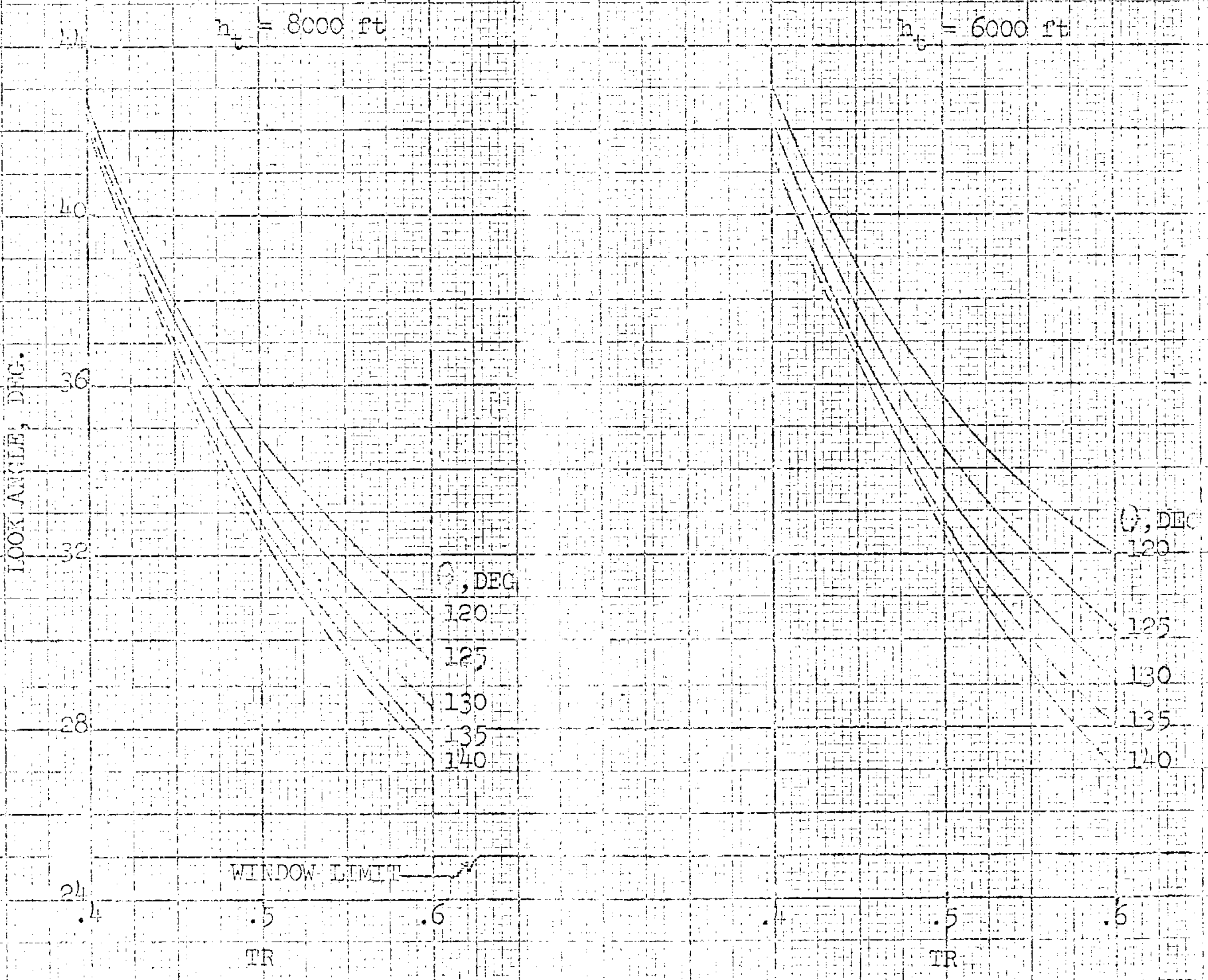

FIGURE 6.- LOOK ANGLE VS THROTTLE RATIO FOR VARIOUS PITCH ANGLES DURING THE LANDING APPROACH PHASE

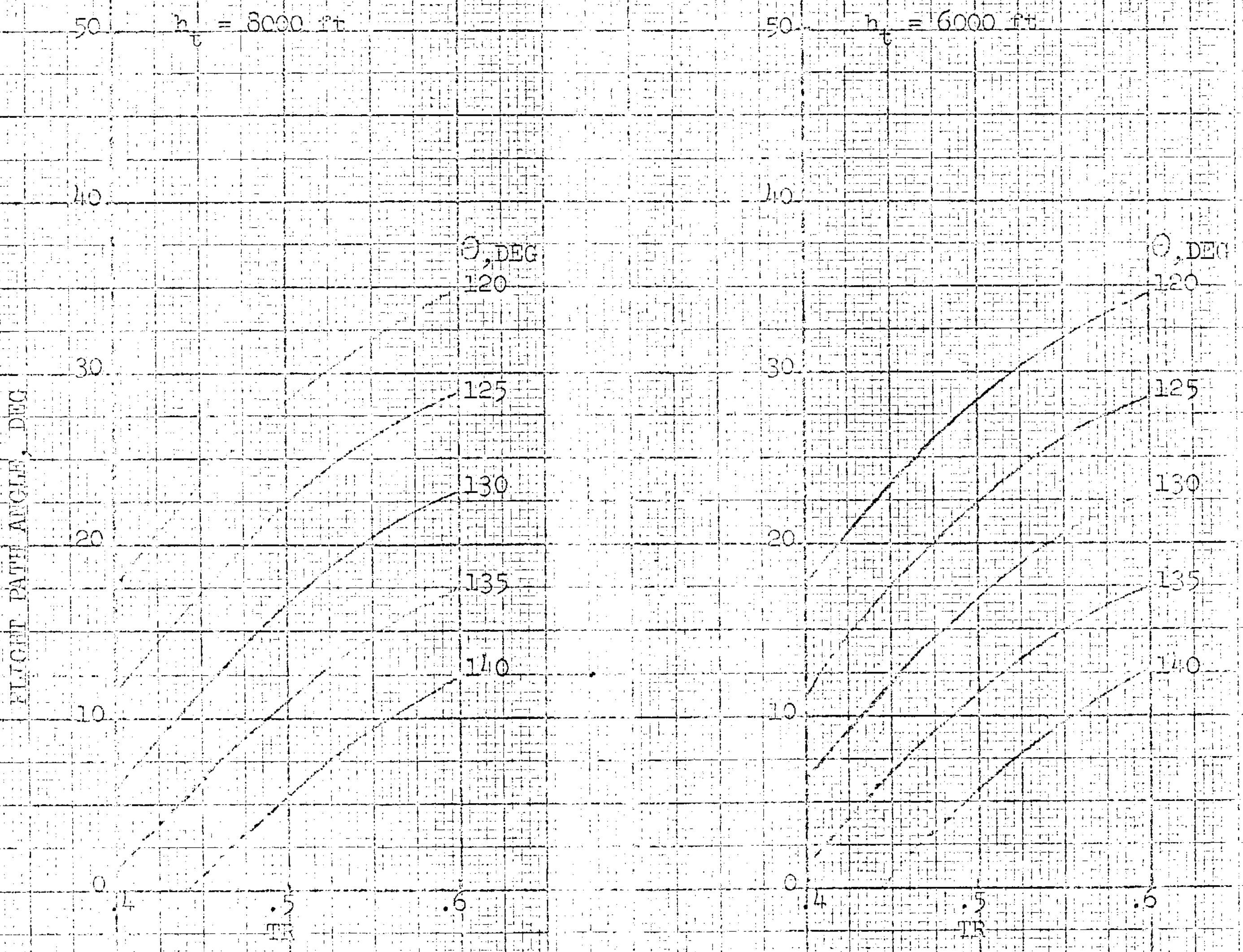

FIGURE 7.- FLIGHT PATH ANGLE VS THROTTLE RATIO FOR VARIOUS PITCH ANGLES DURING THE LANDING APPROACH PHASE

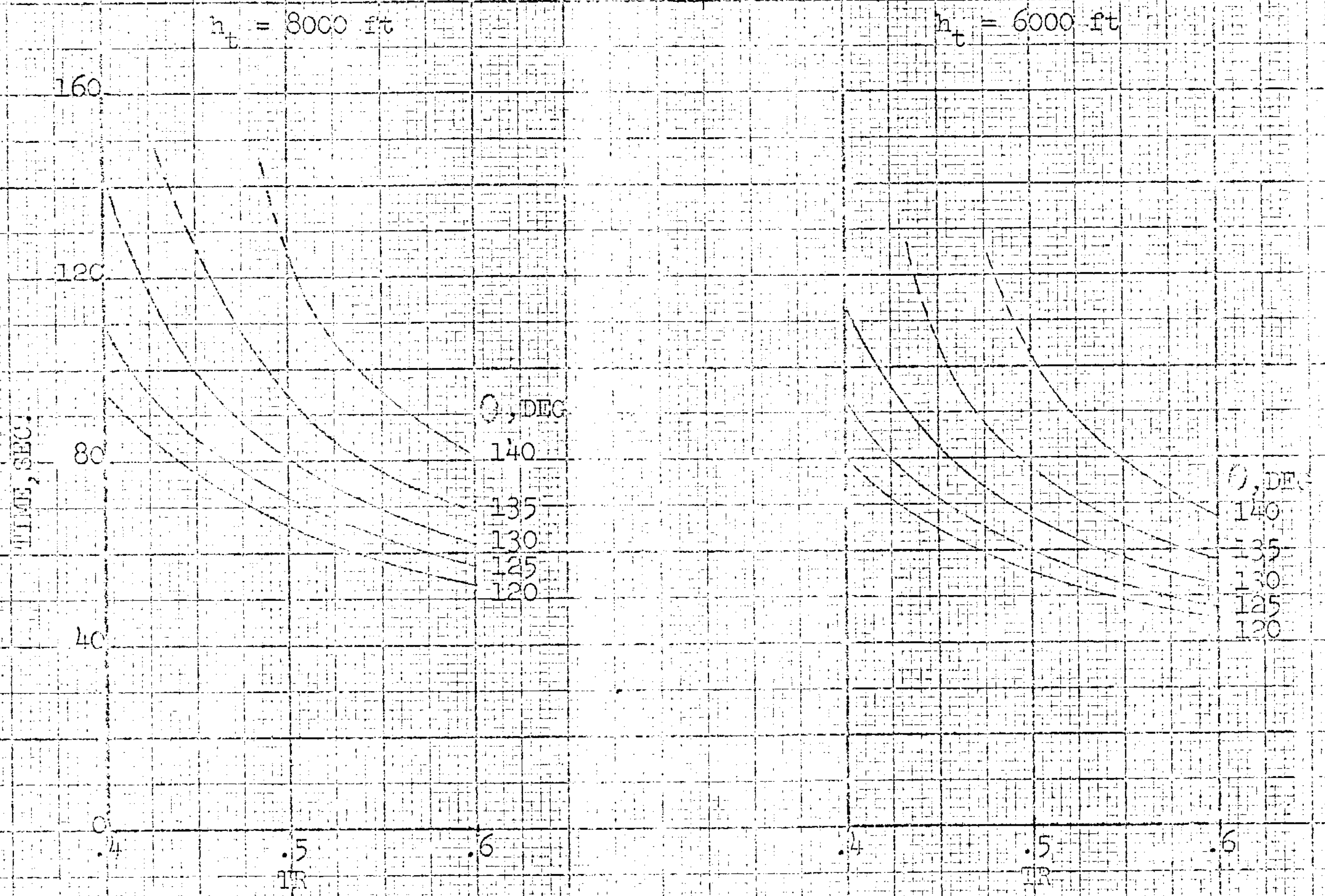

FIGURE 8.- TIME VS THROTTLE RATIO FOR VARIOUS PITCH ANGLES DURING THE LANDING APPROACH PHASE

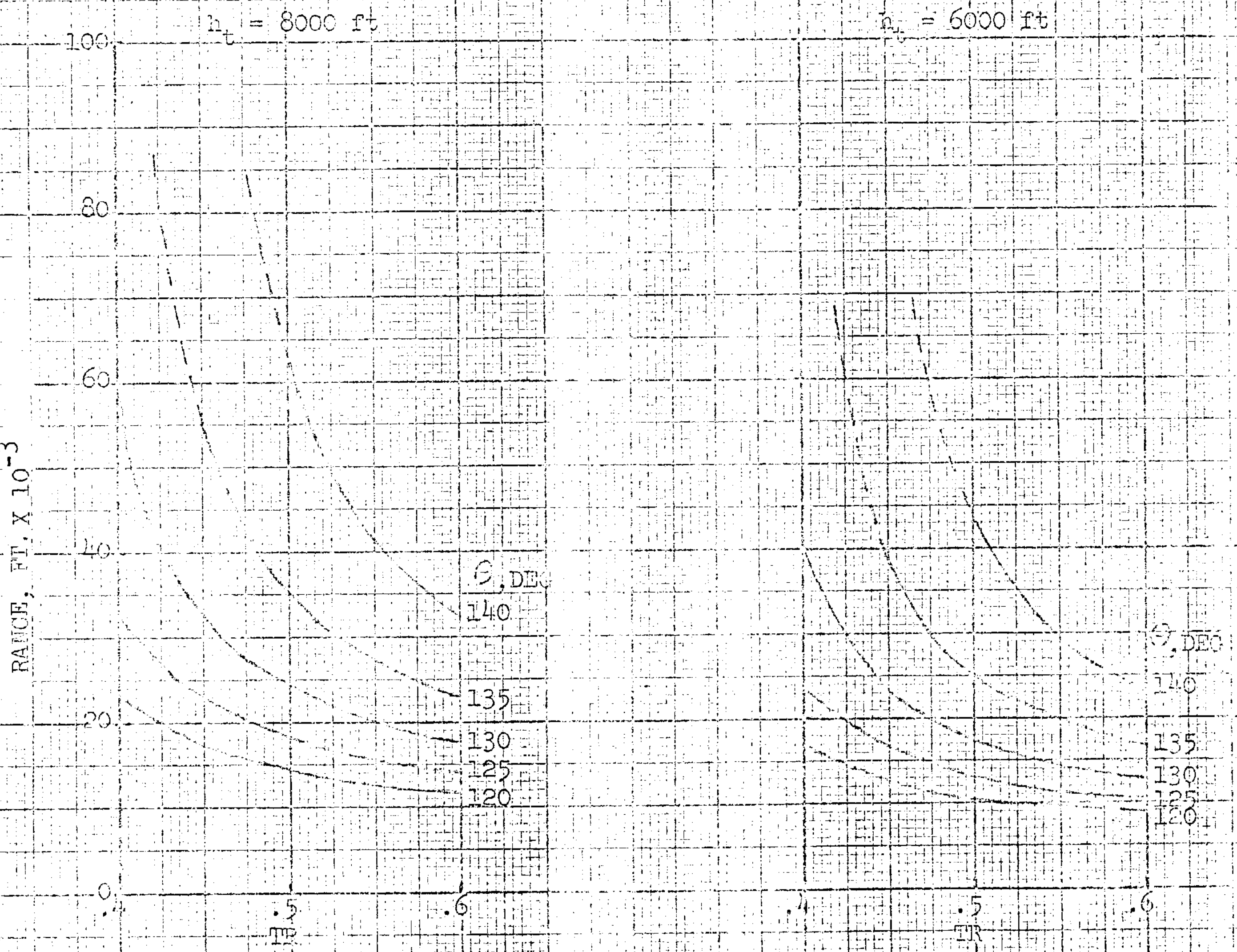

FIGURE 9.- RANGE VS THROTTLE RATIO FOR VARIOUS PITCH ANGLES DURING THE LANDING APPROACH PHASE

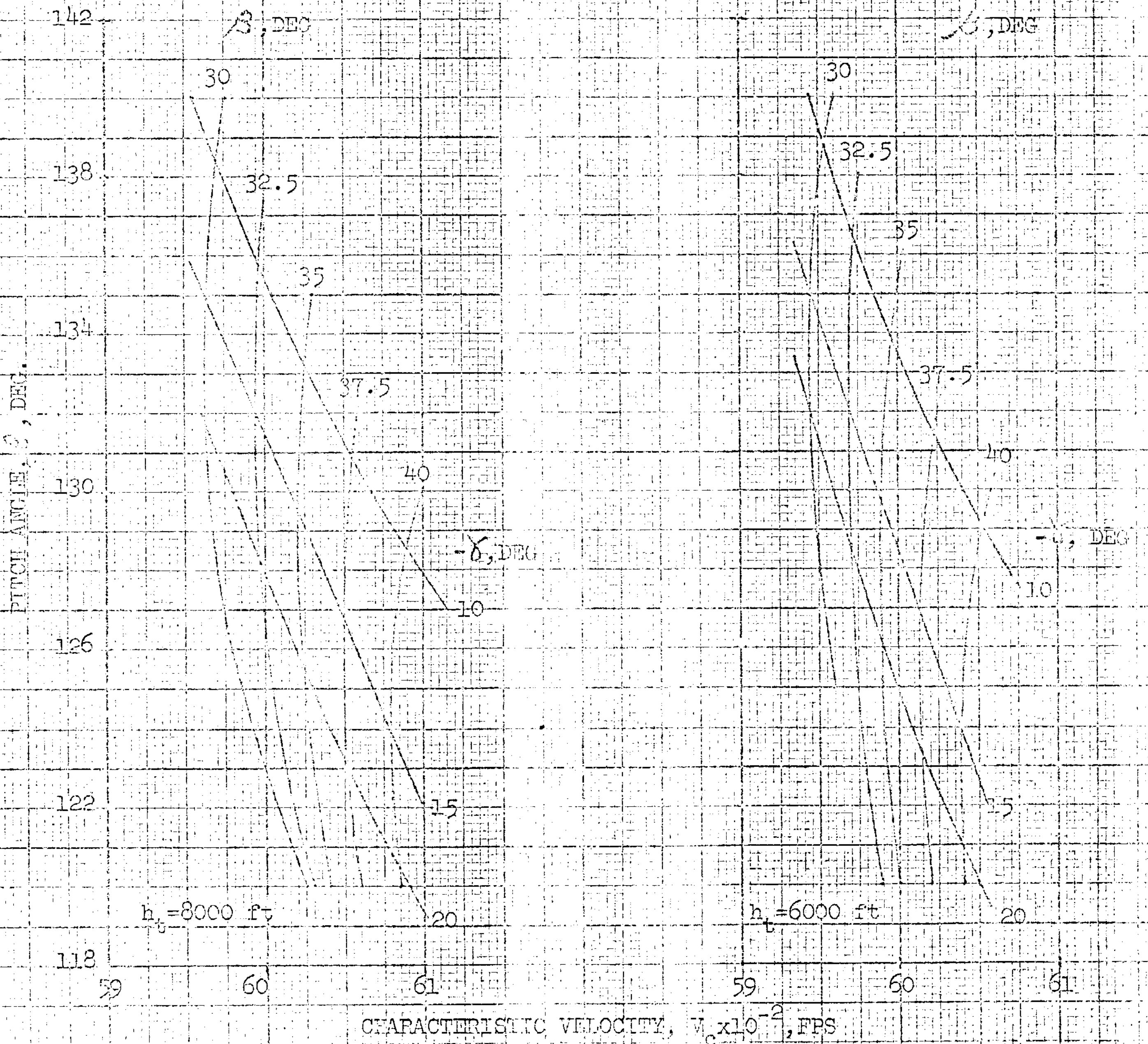

FIGURE 10.- CHARACTERISTIC VELOCITY VS PITCH ANGLE WITH LOOK ANGLE, β, AND FLIGHT PATH ANGLE, γ, CROSSPLOTTED.

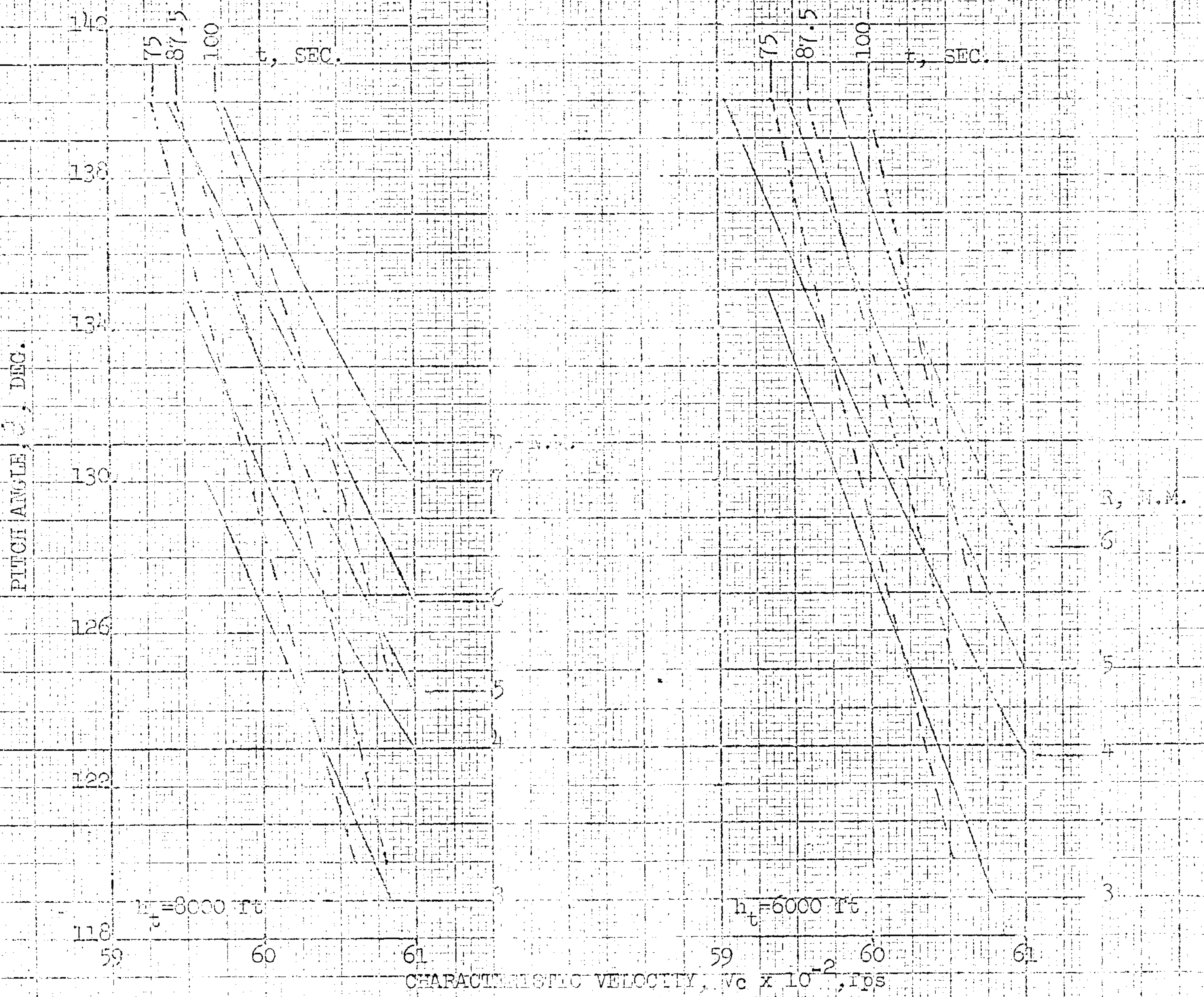

FIGURE 11.- CHARACTERISTIC VELOCITY VS PITCH ANGLE WITH RANGE, R, AND TIME, t, CROSSPLOTTED

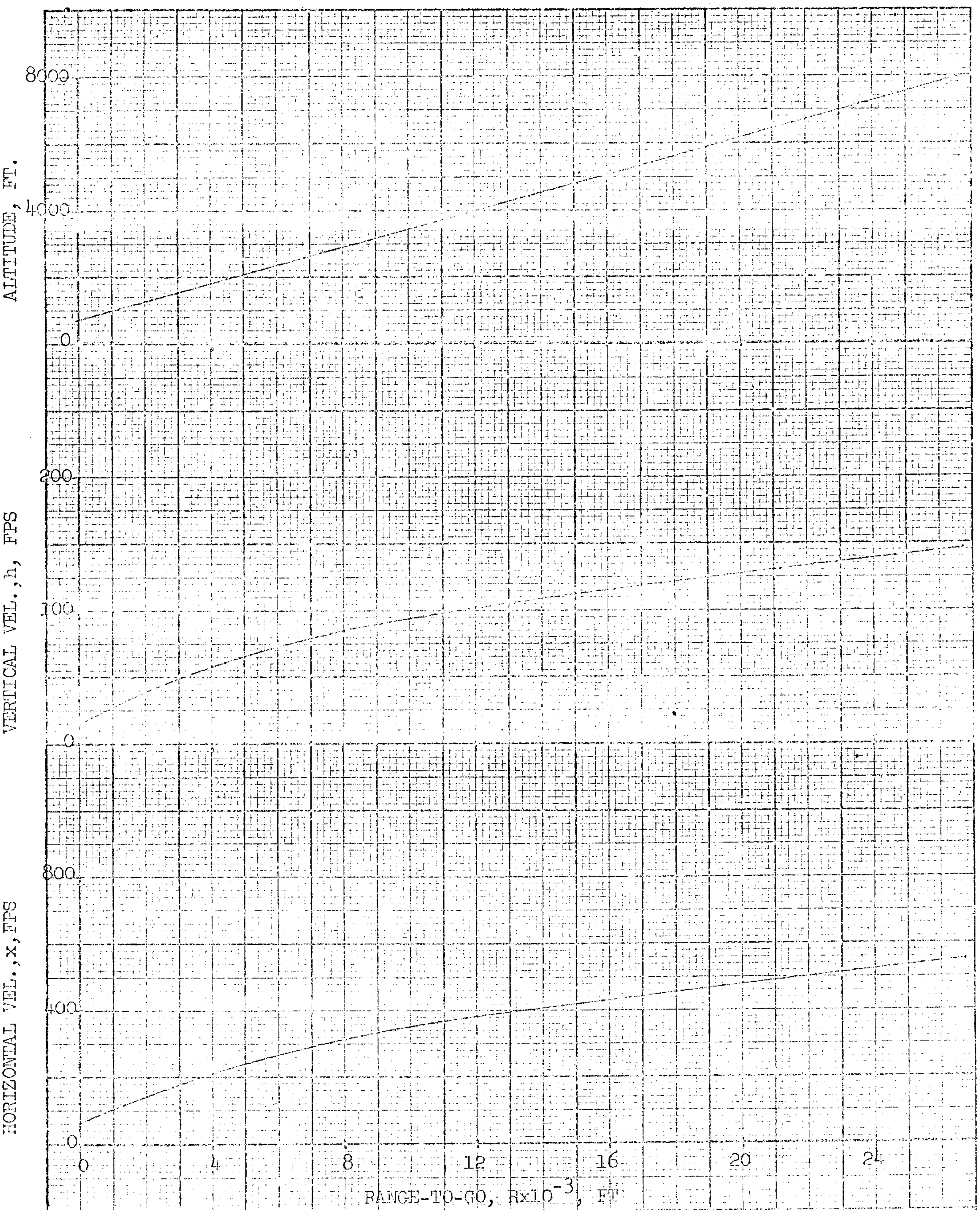

FIGURE 12.- TRAJECTORY CHARACTERISTICS FOR PHASE II LOOK ANGLE=35 DEG AND FLIGHT PATH ANGLE=15 DEG, PITCH ANGLE = 130 DEG, THRUST = 5040 LBS

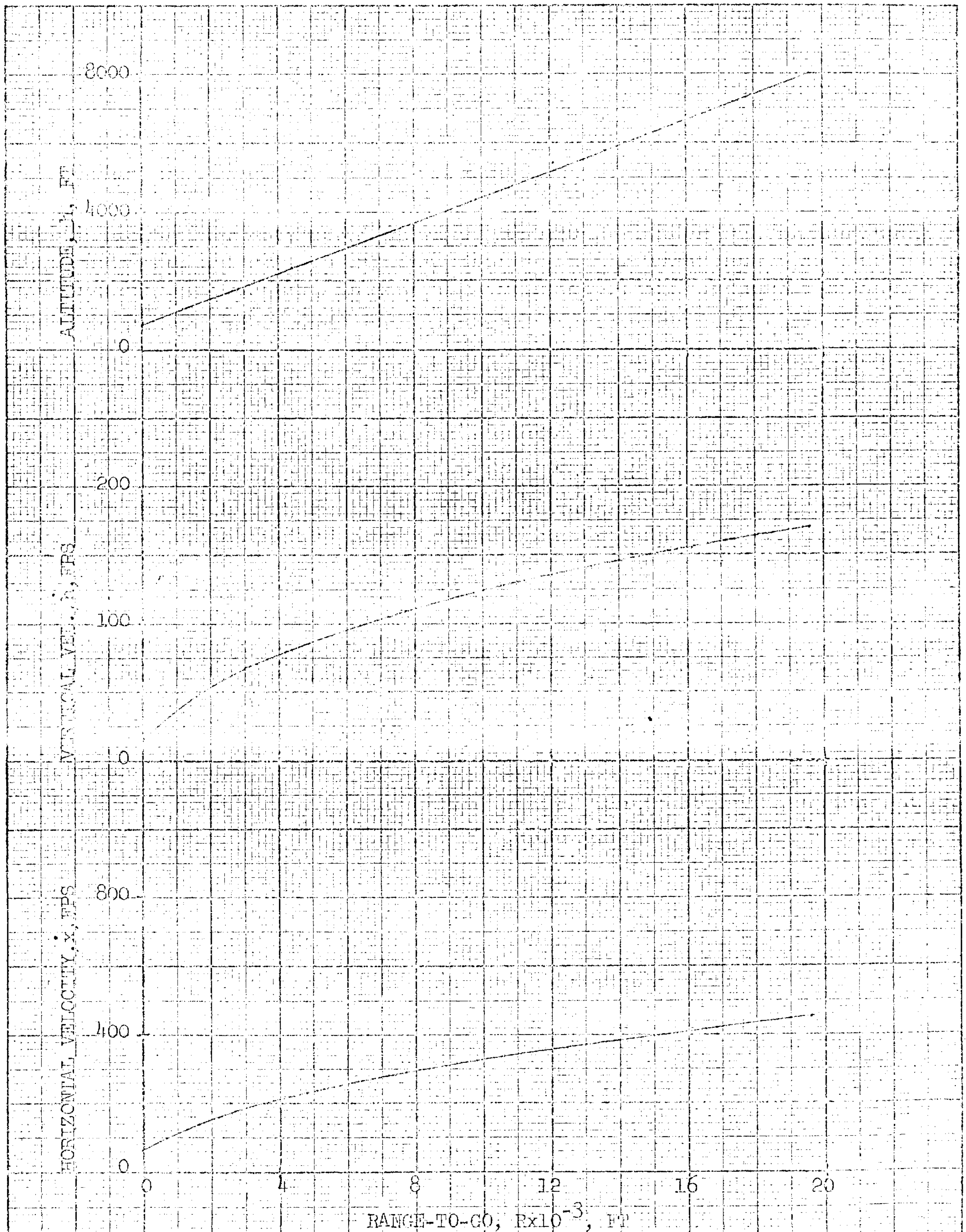

FIGURE 13.- TRAJECTORY CHARACTERISTICS FOR PHASE II LOOK ANGLE = 35 DEG, AND FLIGHT PATH ANGLE = 20 DEG, PITCH ANGLE = 125 DEG, THRUST = 5040 LB

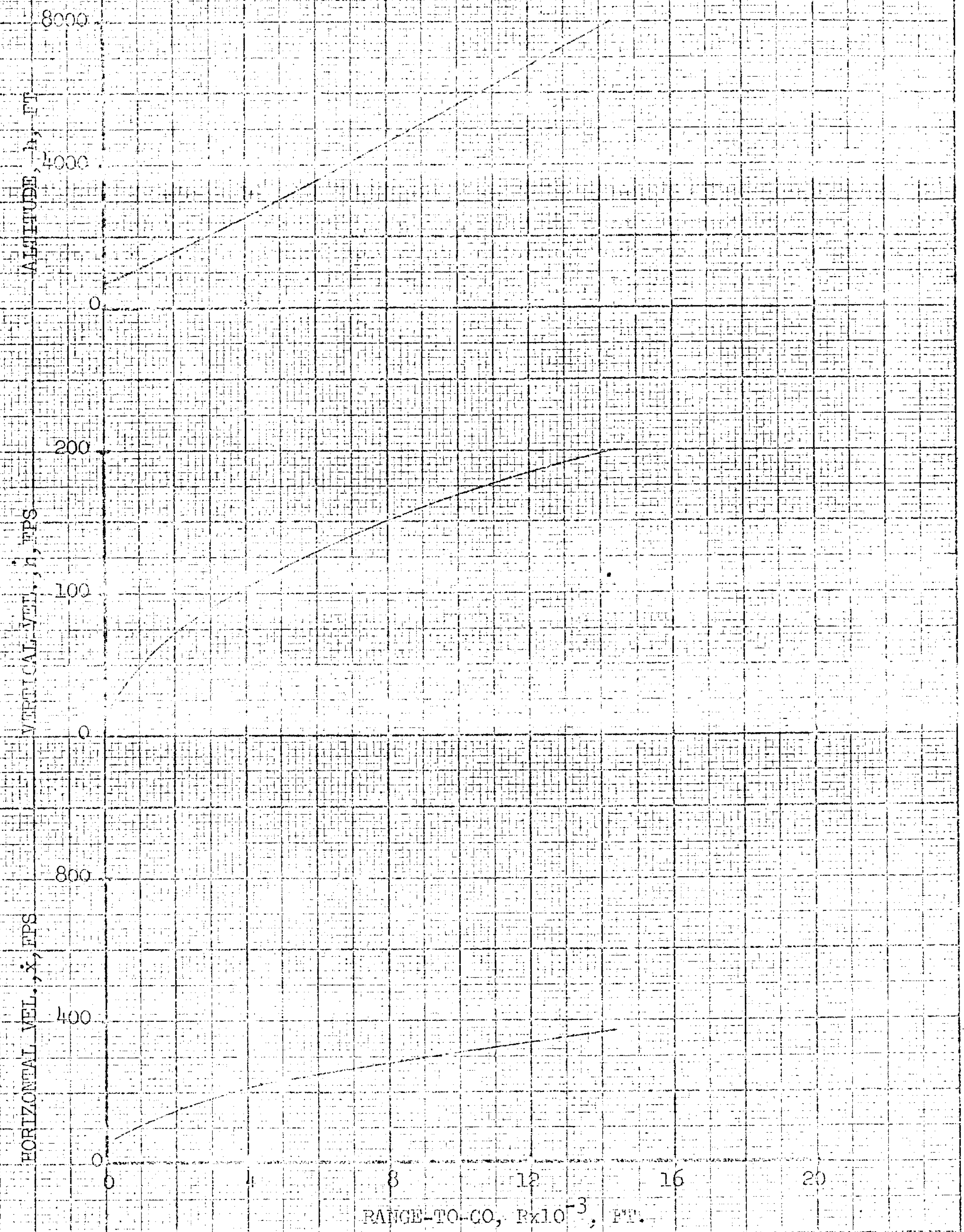

FIGURE 14.- TRAJECTORY CHARACTERISTICS FOR PHASE II LOOK ANGLE = 40 DEG AND FLIGHT PATH ANGLE = 25 DEG, PITCH ANGLE = 120 DEG, THRUST = 5250 LBS