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EFFECT OF TRANSITION AERODYNAMICS ON AEROASSIST FLIGHT EXPERIMENT TRAJECTORIES

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ABSTRACT

Various transition methods are used here to study the viscous effects encountered in low density, hypersonic flight, through the transition from free molecular to continuum flow. Methods utilizing Viking Data, Shuttle orbiter data, a Potter number parameter and a Shock Reynolds number were implemented in the Program to Optimize Simulated Trajectories (POST). Simulations of the Aeroassist Flight Experiment (AFE) using open loop guidance were used to assess the aerodynamic performance of the vehicle. A bank angle was found for each transition method that would result in a 200 nautical-mile apogee.

Once this was done, the open loop guidance was replaced by the proposed guidance algorithm for the AFE. Simulations were again conducted using that guidance and the different transitions for comparison. For the gains used, the guidance system showed some sensitivity in apogee altitude to the transition method assumed, but the guidance was able to successfully complete the mission.

ABBREVIATIONS

AFE	Aeroassist Flight Experiment
AOTV	Aeroassisted Orbital Transfer Vehicle
SRM	Solid-Propellant Rocket Motor
LEO	Low Earth Orbit
POST	Program to Optimize Simulated Trajectories
C_D	Coefficient of Drag
C_L	Coefficient of Lift
Btu	British thermal units
NM	Nautical Miles
ft	Feet
ft/s	Feet per second
Alpha	Angle of attack
Inc	Inclination angle
Gamma	Flight path angle
Alta	Apogee altitude
Veli	Inertial Velocity
Altito	Oblate Altitude

Heatrt   Heat rate

Bnkang   Bank angle

INTRODUCTION

The development of an orbiting Space Station has generated a need for a space-based, reusable vehicle, capable of transferring large payloads from a high energy orbit to a Low Earth Orbit (LEO). Although this type of maneuver can be done propulsively through a Hohmann transfer, the amount of propellant required limits the payload capacity. Another method is an aeroassisted maneuver which utilizes the aerodynamics of the vehicle by dipping into the Earth's upper atmosphere and expending energy through drag and heat.[1] Once the vehicle exits, a comparatively smaller change in velocity is needed to circularize the orbit at apogee, thus providing significant propellant savings. Remaining in the atmosphere too long, however, will result in extreme heat rates, and excessive energy loss which will prevent the vehicle from escaping.

Because the success of the mission depends heavily on the energy loss induced by the atmospheric pass, the aerodynamic performance of the vehicle is important. From previous missions it can be seen that in low density, hypersonic flight, vehicles experience a large decrease in performance due to viscous effects encountered in the transition from free molecular to continuum flow.[2] Rarefied, hypersonic flow causes: (1) a large increase of friction effects; (2) a moderate increase of some pressures; (3) wall and shock slip; and (4) a thickening and merging of the shock and boundary layers. Current research facilities are unable to simulate the conditions encountered in this type of situation, and the existing data are insufficient for further AOTV design studies. The Aeroassist Flight Experiment (AFE) is an effort to obtain further data that will aid in the verification of the computational codes needed to design the AOTV's.

The AFE will be deployed by the Shuttle orbiter in LEO and will fire its Solid-propellant Rocket Motors (SRM) in order to give it the velocity necessary to simulate an AOTV return from geosynchronous orbit. After passing through the atmosphere and expending enough energy to achieve the required target apogee, the vehicle will continue to apogee where it will circularize to rendezvous with the Shuttle (Figures 1 and 2). In order to predict realistically the trajectory of the mission for instrument calibration purposes and guidance development, the viscous effects encountered in the transition regime must be taken into account. Because no agreement exists on a fundamental parameter to correlate accurately the effects on aerodynamic performance, only the continuum values have been used previously. Four existing methods are studied and discussed in this paper: (1) Viking data correlation;[3] (2) Lockheed bridging formula;[4] (3) a Potter number;[5] and (4) the Shock Reynolds number transition.[6] Because none of the methods have been verified in a direct flight application, the guidance algorithm used in the guidance system of the AFE must be universal enough to be able to handle a reasonable amount of error.

Modifications were made in the three degree-of-freedom version of the Program to Optimize Simulated Trajectories (POST) to include two subroutines: (1) one with four viscous calculation options (Appendix A); and (2) one with the current proposed guidance algorithm for the AFE. In order to rate the aerodynamic performance of the AFE, open loop guidance versions of the program were run with the four different aerodynamic transition models, and with the standard continuum values to be used for comparison. Closed loop guidance versions using the proposed algorithm were also run in order to test its ability to handle the different bridging models and still reasonably meet the targeted conditions.[7] The same initial conditions and event criteria were used for all the runs and are shown on Figures 1 and 2.

TRANSITION FROM FREE MOLECULAR TO CONTINUUM FLOW

The first opportunity to study the effects of low density hypersonic flight on a vehicle entering the atmosphere arose with the entry of the Mars probe, the Viking lander, into the Martian atmosphere. Using flight measurements from pressure instruments, accelerometers, and a mass spectrometer, the previously unknown values of the drag coefficient between the free molecular and continuum values were defined.[3] Using these data, Jim Jones of the Langley Research Center established an equation which calculates values for the drag coefficient in the transition regime as a function of a parameter called VBAR. VBAR is the Mach number divided by the square root of the free stream Reynolds number.

Another method was derived using the Shuttle Aerodynamic Design Data Book. The Lockheed Bridging Formula that comes from these data requires only two endpoints, which are the free molecular and continuum values for the drag coefficient. This formula is modeled after the relatively high pressure drag component of hot cylinders. The rarefaction effects of the transition hypersonic flow are accounted for using a fundamental parameter called the Knudsen number. This parameter is equal to the free stream mean free path divided by the characteristic length of the vehicle, which is the diameter in this case. This bridging formula is unique to the design of the vehicle, and is based solely on empirical data. In the studies done in this paper the coefficient of lift is also varied using the Lockheed Bridging Formula.[4]

The third method to be discussed in this paper was formulated by Leith Potter of Vanderbilt University, who is an expert in low density fluid dynamics. The parameter used here, Potter number, is a Reynolds number corrected for the enthalpy of the flow. An argument proposed by Potter is that lifting flight through different types of flow involves changes in angles of attack and even changes in the shape of the vehicle. To account for these effects, he includes an SSTAR in his Potter number calculation which is the cross sectional area divided by the wetted area of the vehicle raised to the one half power. Sometimes there is a problem with calculating the wetted area when the lines of separation are hard to determine. A variety of drag coefficient data obtained from spheres, blunt nosed cones, lifting bodies and the Shuttle orbiter closely correlate with the Potter number.[5]

The fourth transition method involves a correlating parameter called the Shock Reynolds number (R_{e_2}). The Shock Reynolds number is defined as

$$R_{e_2} = \frac{\rho_\infty V_\infty D}{\mu_2}$$

where ρ_∞ is the free stream density, V_∞ is the free stream velocity, D is a reference length, and μ_2 is the viscosity behind the shock.[6] For $Re_2 < 10^4$ and

Mach number > 14, lift, drag, and moment coefficients tend to correlate with R_{e_2} for blunt bodies. A representation of C_D and C_L variations with R_{e_2} between free molecular flow and continuum flow has been developed and these transition equations have been included in this investigation.

All four transition methods resemble an exponential curve fit between the free molecular and continuum hypersonic flight drag coefficients. Figure 3 shows the difference between the two drag coefficient values versus angle of attack, and Figure 4 compares the transition methods used to bridge the gap. Figure 5 shows the gap between the two lift coefficient values versus angle of attack, and Figure 6 compares the coefficient of lift variation used in the Lockheed Bridging and R_{e_2} methods with the constant value used in the Viking and Potter versions. It should be noted that the aerodynamics of the vehicle were cut off once the vehicle reached 400,000 feet, which is considered to be the edge of the atmosphere.

OPEN LOOP AERODYNAMIC SIMULATIONS

Before a guidance algorithm could be implemented into the program it was necessary to determine the vehicle's performance capabilities. Comparative trajectories using the four available transition lift and drag coefficients, along with the continuum lift and drag coefficient were examined using POST. A target apogee of 200 nautical miles, and a heat rate not exceeding 180 Btu/ft^2-sec was required for the mission to be considered successful. It should be noted that the heating rates shown here do not include corrections for viscous effects like those included for the aerodynamic coefficients. Therefore, this is not a valid evaluation of the actual heating rates. The vehicle was kept at a constant angle of attack of 17 degrees, and the program continued to alter the bank angles until the mission objectives were met. The bank angle which worked for the standard version was then used in the other three versions in order to determine the sensitivity of the maneuver. The results of these runs can be studied in Table I. It can be seen that a change of less than 0.1 degrees in the bank angle can result in an error of almost 8 nautical miles in the projected apogee. This can also be interpreted as a very small change required to put the AFE back on course in case something unforeseen arises. Overall the AFE has the aerodynamic capability necessary to make this mission a success. What is needed is a guidance algorithm which can use these performance capabilities to their best advantage.

CLOSED LOOP GUIDANCE SIMULATIONS

The guidance algorithm implemented in POST was developed to meet the demands for an aerobraking trajectory guidance technique that was uncomplicated, easily integrated and adaptable to a range of vehicle aerodynamic configurations. Included in the requirements was the ability to handle dispersions in entry conditions, atmospheric conditions, and aerodynamic characteristics. This algorithm uses the bank angle to control the lift vector so the vehicle will retain only the magnitude of energy needed at the exit point in order to achieve the target apogee.

Roll reversals are used to control the inclination at the exit point. No orbital plane change is wanted in this case, so the vehicle must bank left and right. The roll rate is limited to a maximum of 15 degrees per second in all the cases presented here, and the reaction control system is not activated so the angle of attack stays constant. Other than the the differences described above the same conditions were used here as in the open loop runs.

During the initial use of the guidance routine, some unsteady behavior in the bank angle was observed. Discussion with the authors of reference 5 indicated that this unsteady behavior had been reduced by changing the method of maintaining the desired inclination angle. This new guidance algorithm was used in this study.[7]

The guidance version was run for all four transition cases, and again it must be noted that no viscous corrections were included for the heat rate calculation. The results are shown in tabular form in Table II and on plots in Figures 7-16. In all four cases the mission objectives were achieved with an error of less than .01 degrees in the inclination, but the apogee attained varied by as much as 8 nautical miles. Errors of up to 20 nautical miles in apogee can be compensated for so these errors were not excessive. The change in velocity required at apogee to circularize the orbit does not exceed the budget allocation. The heat rate, minimum altitude, and maximum acceleration all fell within the acceptable design limits of the vehicle. The bank angles commanded by the guidance are shown as Figures 17 through 21 for the five transition methods. As can be seen the character of the command is affected by the transition assumed.

CONCLUSIONS

Plots of the transition values for the drag coefficient were similar and seem to bridge the gap reasonably.

The C_D using the Potter number transition never reaches the continuum value, emphasizing the effects included in the SSTAR parameter.

The trajectory parameters did not vary greatly regardless of which transition method was used in the simulation and the guidance algorithm essentially handled the mission in each case. However, the transition method assumed changed the character of the commanded bank angle and the apogee altitude showed some sensitivity to the transition method.

APPENDIX A

"SUBROUTINE VISAERO"

```
      SUBROUTINE AERO
      IMPLICIT REAL*8(A-H,O-Z)
C*** VISAERO
C              COMPUTE AERODYNAMIC COEFFICIENTS
C
        INCLUDE '[SUIT.INCLUDE]LOCAL  .CMN/LIST'
        INCLUDE '[SUIT.INCLUDE]MOTBL  .CMN/LIST'
        INCLUDE '[SUIT.INCLUDE]MNMMLT.CMN/LIST'
        INCLUDE '[SUIT.INCLUDE]MOTIC  .CMN/LIST'
        INCLUDE '[SUIT.INCLUDE]MOTVC  .CMN/LIST'
        INCLUDE '[SUIT.INCLUDE]SERVC  .CMN/LIST'
      COMMON /AAIV/ VI(1)
C
      IF (NPC(5).EQ.0) RETURN
      IF (IOFLAG-2) 11,12,12
 11   CONTINUE
      TEMP(10)=2.2696811E-08
      TEMP(11)=198.72
      GO TO 13
 12   CONTINUE
      TEMP(10)=1.458E-06
      TEMP(11)=110.4
 13   CONTINUE
      VMU   = TEMP(10)*SQRT(ATEM**3)/(ATEM + TEMP(11))
      REYNO  =   (DENS*VELA*LREF)/VMU
      IF   (REYNO.LT.1.) REYNO=1.
      IF    (NPC(8).EQ.1) GO TO 450
C
C***COMPUTE AERODYNAMIC COEFFICIENTS***
C
      IF (NPC(8).NE.2) GO TO 100
      CD = GENTAB(CDT) * VI(IDNM)
      CDDPS = GENTAB(CDDPT)
      CDDP = CDDPS * VI(IDDPNM)
      CDDYS = GENTAB(CDDYT)
      CDDY = CDDYS * VI(IDDYNM)
      CD = CD + CDDP + CDDY
      GO TO 300
 100  CONTINUE
      DIAMTR = 14
      VMUREF = 0.3586E-06
      CDI = GENTAB(CDT)
      CDFM = GENTAB(CDOT)
      IF (NPC(8).NE.4) GO TO 150
C
C***COMPUTE VISCOUS EFFECTS USING JONES' EQUATIONS***
C
      VBAR = MACH/DSQRT(REYNO)
      VBARL = LOG10(VBAR)
      F1 = 1.09395
      F2 = 0.32608
      F3 = 0.20167
      F4 =-0.051746
      F5 =-0.042578
      IF (VBARL.LT.-0.4) GO TO 110
      IF (VBARL.GT.1.5) GO TO 120
      FO = F1+(F2*VBARL)+(F3*VBARL**2)+(F4*VBARL**3)+
     +      (F5*VBARL**4)
      GO TO 130
 110  CONTINUE
      FO = 1
      GO TO 130
 120  CONTINUE
      FO = 1.646
 130  CONTINUE
      CD = CDI * FO
      GO TO 300
 150  CONTINUE
      IF (NPC(8).NE.5) GO TO 200
C
C***COMPUTE VISCOUS EFFECTS USING LOCKHEED FORMULA***
C
      CLI = GENTAB(CLT)
      CLFM = GENTAB(CLOT)
      RKNUD = 3.6947E-11/DENS
      IF (RKNUD.LT.10.AND.RKNUD.GT.0.01) THEN
          PI = 3.141593
          CDBAR = (SIN(PI*(0.333333+0.166667*LOG10(RKNUD))))**2
          CLBAR = CDBAR
      ENDIF
      CL = CLI + CLBAR*(CLFM - CLI)
      CD = CDI + CDBAR*(CDFM - CDI)
      GO TO 400
 200  IF (NPC(8).NE.6) GO TO 250
C
C***COMPUTE VISCOUS EFFECTS USING POTTER METHOD***
C
      TSTAG = ATEM * (1.0 + ( (0.4 / 2.0) * (MACH**2) )  )
      TWALL = 0.95 * TSTAG
      HWALL = 6000 * TWALL
      HSTAG = VELA**2/2.
      HFRSM = 6000 * ATEM
      PTRNO = ((VELA * DENS/VMU) * 9.38 *(HFRSM/(0.2*HSTAG + 0.5*HWALL))
     +           **0.63)**0.5
      CDBAR = 1.0 / (0.663 + 0.381 * PTRNO)
      CD = CDI + CDBAR * (CDFM - CDI)
      GO TO 300
 250  CONTINUE
      IF (NPC(8).LT.7.AND.NPC(8).GT.8) GO TO 625

C
C***COMPUTE VISCOUS EFFECTS USING SHOCK REYNOLDS NUMBER***
C
      VMU2 = VMUREF *(5.675 + 0.01125 * (ALTITO / 1000))
      REYNO2 = (DENS * VELA * DIAMTR)/ VMU2
      IF (REYNO2.LT.0.1) THEN
          CLBAR = 1.
          CDBAR = 1.
      ELSEIF (REYNO2.GT.10000.) THEN
          CLBAR = 0.
          CDBAR = 0.
      ELSE
          X = 1/DSQRT(REYNO2)
          CLBAR = 0.01114 + 1.993 * X - 1.7662 * X**2 + 0.6855 * X**3
     +              - 0.0933 * X**4
          CDBAR = 0.882 + 1.4/DSQRT(REYNO2) + 0.8/REYNO2
      ENDIF
      CLI = GENTAB(CLT)
      CLFM = GENTAB(CLOT)
      CL = CLI + CLBAR * (CLFM - CLI)
      CD = CDI * CDBAR/.882
      IF (NPC(8).EQ.8) GO TO 300
      GO TO 400
 300  CONTINUE
      CL = GENTAB(CLT) * VI(ILNM)
      CLDPS = GENTAB(CLDPT)
      CLDP = CLDPS * VI(ILDPNM)
```

```
      CL = CL + CLDP
 400  CONTINUE
      CA = CD * CALPHA - CL * SALPHA
      CN = CL * CALPHA + CD * SALPHA
      IF (NPC(10)) 410,475,410
 410  CONTINUE
      CADP   = CDDP*CALPHA-CLDP*SALPHA
      CADY   = CDDY*CALPHA
      CNDP   = CLDP*CALPHA+CDDP*SALPHA
      CADPS  = CDDPS*CALPHA-CLDPS*SALPHA
      CADYS  = CDDYS*CALPHA
      CNDPS  = CLDPS*CALPHA+CDDPS*SALPHA
      GO TO 475
 450  CONTINUE
      CA     = GENTAB (CAT)   * VI(IANM)   + GENTAB (CAOT)
      CADPS  = GENTAB (CADPT)
      CADP   = CADPS * VI(IADPNM)
      CADYS  = GENTAB (CADYT)
      CADY   = CADYS * VI(IADYNM)
      CA     = CA + CADP + CADY
      CN     = GENTAB (CNAT) * VI(INANM) + GENTAB (CNOT)
      CNDPS  = GENTAB (CNDPT)
      CNDP   = CNDPS * VI(INDPNM)
      CN     = CN + CNDP
 475  CONTINUE
      CY     = GENTAB (CYBT) * VI(IYBNM) + GENTAB (CYOT)
      CYDYS  = GENTAB (CYDYT)
      CYDY   = CYDYS * VI(IYDYNM)
      CY     = CY + CYDY
C
C*** COMPUTE AERO FORCES IN THE BODY SYSTEM***
C
      FAXB(1)=-QSREF*CA
      FAXB(2)=+QSREF*CY
      FAXB(3)=-QSREF*CN
C
C     PARACHUTE DRAG CALCULATION
      IF (NPC(32) .EQ. 0) GO TO 575
      IF (NPC(32) .NE. 1) VELAP = VELA
      TEMP(1) = DYNP*(PI/FP4)
      DRAGPT  = 0.0
      DO 560 I=1,3
      IF (PARIF(I)) 525,500,525
 500  CONTINUE
      DIARP(I) = 0.0
      GO TO 550
 525  CONTINUE
      DIARP(I) = VELAP/PARIF(I)
 550  CONTINUE
      J = 2*I-1
      CDP(I)   = GENTAB(CDPIT(J))
      DRAGP(I) = TEMP(1)*CDP(I)*DIAMP(I)**2
      DRGPP(I) = DRGPK(I)*DRAGP(I)
      DRAGPT   = DRAGPT + DRAGP(I)
 560  CONTINUE
      FAXBP(1) = DRAGPT * CALPHA
      FAXBP(3) = DRAGPT * SALPHA
      FAXB(1)  = FAXB(1) - FAXBP(1)
      FAXB(3)  = FAXB(3) - FAXBP(3)
 575  CONTINUE
C
C***COMPUTE MOMENT COEFFICIENTS FOR STATIC TRIM***
C
      IF (NPC(10)) 600,625,600
 600  CONTINUE
      CM     = GENTAB (CMAT) * VI(IMANM) + GENTAB (CMOT)
      CMDPS  = GENTAB (CMDPT)
      CMDP   = CMDPS * VI(IMDPNM)
      CM     = CM + CMDP
      CW     = GENTAB (CWBT) * VI(IWBNM) * GENTAB (CWOT)
      CWDYS  = GENTAB (CWDYT)
      CWDY   = CWDYS * VI(IWDYNM)
      CW     = CW + CWDY
 625  CONTINUE
      RETURN
      END
```

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[2] Talay, T.A.; White, N.H.; and Naftel, J.C.: Impact of Atmospheric Uncertainties and Viscous Interaction Effects on the Performance of Aero-Assisted Orbital Transfer Vehicles, AIAA paper 84-0408, January 1984.

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[4] Aerodynamic Design Data Book - Volume I: Orbiter Vehicle. NASA CR-160386, 1978.

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[6] Bailey, A.B.: Sphere Drag Measurements in an Aeroballistics Range at High Velocities and Low Reynolds Numbers, AEDC-TR-66-59, 1966.

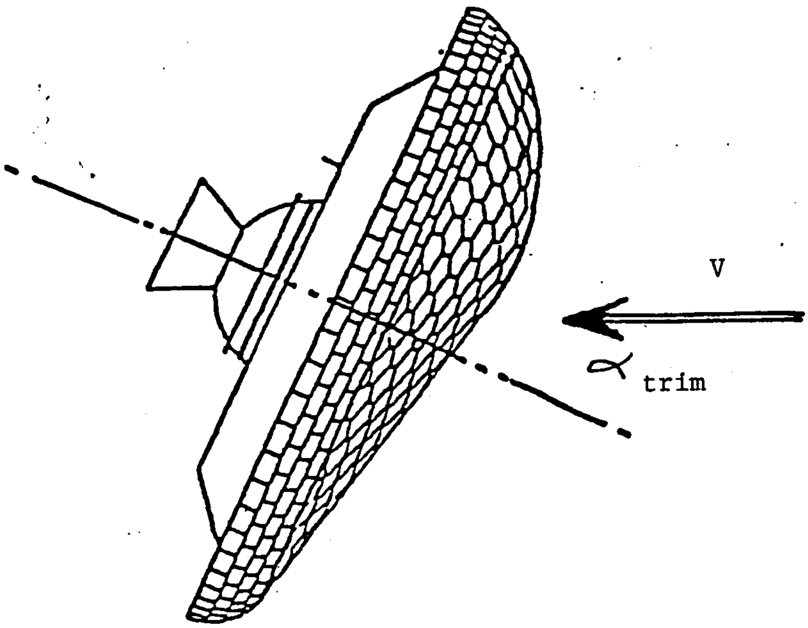
[7] Cerimele, C.J.; and Gamble J.D.: A Simplified Guidance Algorithm for Lifting Aeroassist Orbital Transfer Vehicles, AIAA paper 85-0348, January 1985.

Table I. Transition Method Comparison with Aerodynamic Model

Transition Method Used for C_L and C_D	ϕ for a 200 NM Alta	ΔV to Circularize at Apogee	Max Heat Rate Btu/ft^2-sec	Max Accel (g's)	Minimum Altitude	Inclination Angle 400,000 ft.	Projected Alta Using ϕ=97.367 (NM)
Continuum C_L and C_D	97.367	334.079	155.794	2.598	249 065	32.246	200.000
Viking Data C_D	97.420	334.733	155.758	2.598	245 423	32.242	191.527
Lockheed Bridging C_D and C_L	97.416	334.536	155.785	2.568	245 419	32.238	192.090
Potter Number C_D	98.427	337.418	154.347	2.609	245 749	32.125	85.753
Shock Reynolds Number C_L and C_D	98.107	338.300	154.734	2.573	245 628	32.161	86.430

Table II. Transition Method Comparison with Guidance Model

Transition Method Used for C_L and C_D	ΔV to Circularize at Apogee	Max Heat Rate Btu/ft^2-sec	Max Accel (g's)	Minimum Altitude	Inclination Angle 400,000 ft.	Apogee Achieved
Continuum C_L and C_D	322.80	148.448	2.274	251 812	28.50	198.0
Viking Data C_D	318.20	148.378	2.272	251 829	28.50	195.0
Lockheed Bridging C_D and C_L	320.10	148.407	2.273	248 010	28.50	195.9
Potter Number C_D	320.4	146.433	2.264	248 670	28.49	192.1
Shock Reynolds Number C_L and C_D	315.4	154.8	2.58	245 583	28.50	189.2

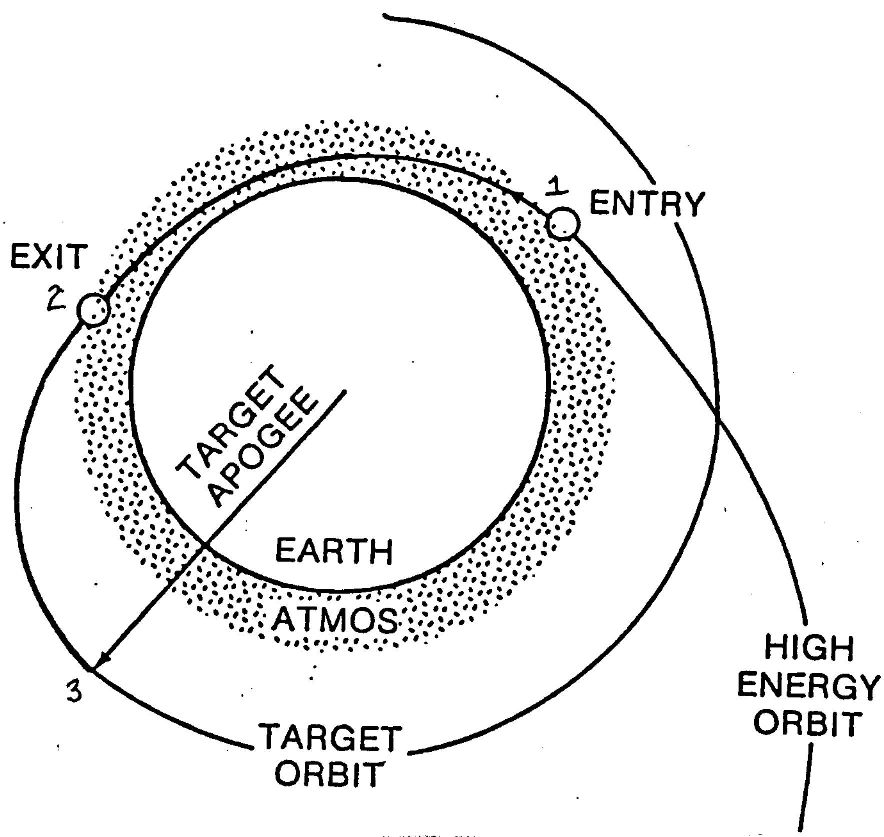


Initial Flight
Characteristics of Proposed
AFE

Weight	2741 lbs.
Velocity	3382.6 ft/sec.
Sref	154 sq. ft.
Gamma	-4.5 deg.
Alpha	17 deg. (trim)
L_{ref}	14 ft.

1976 Standard Atmosphere assumed

Figure 1. AFE basic structure - propulsion module, and heat shield with a thermal protection system.



AFE Mission Events

1. Enter Atmosphere at 400000 ft.
2. Exit Atmosphere at 400000 ft.
3. Circularize at 200 Nm Apogee.

Figure 2. AFE trajectory profile.

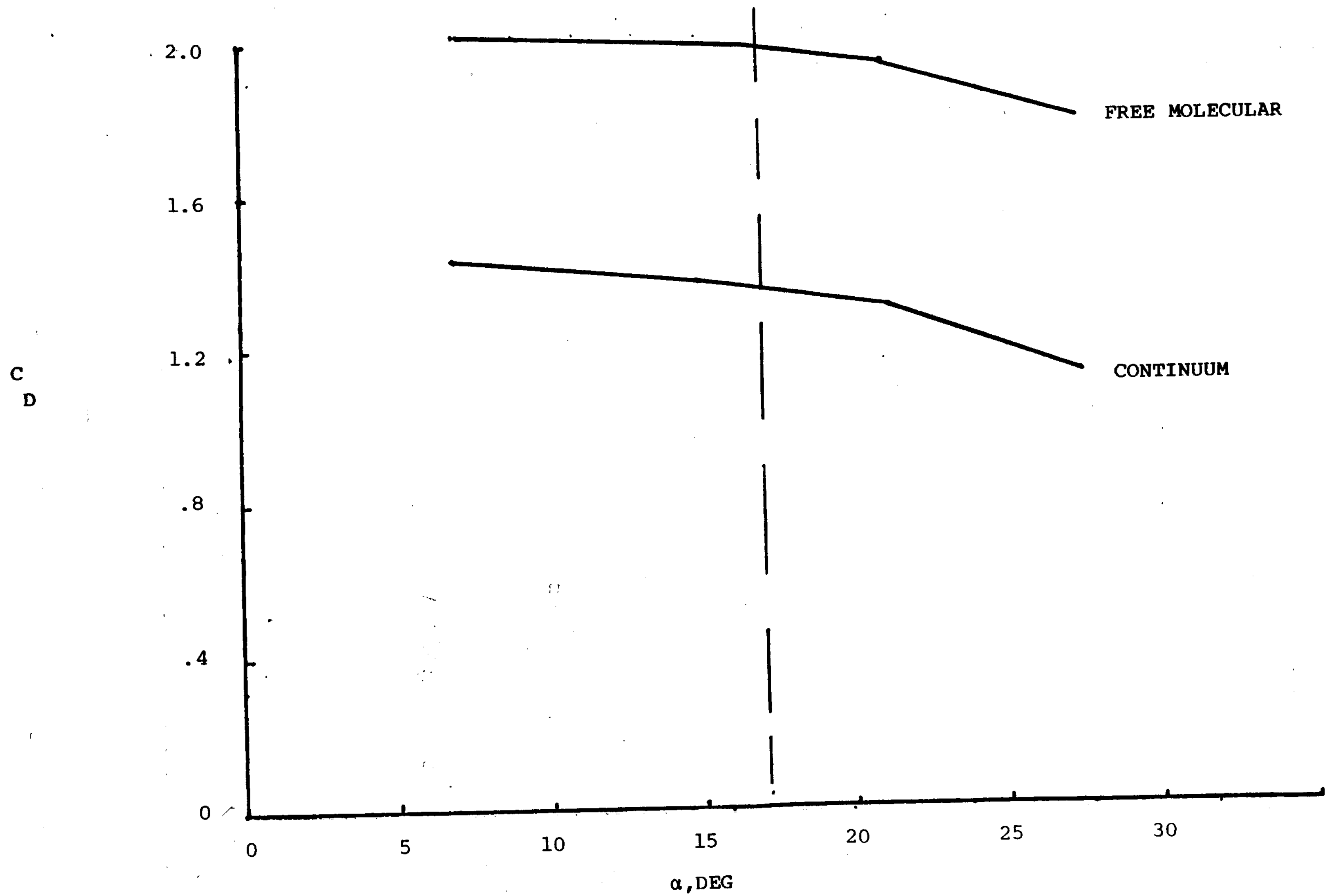


Figure 3. Free molecular and continuum drag coefficient versus angle of attack.

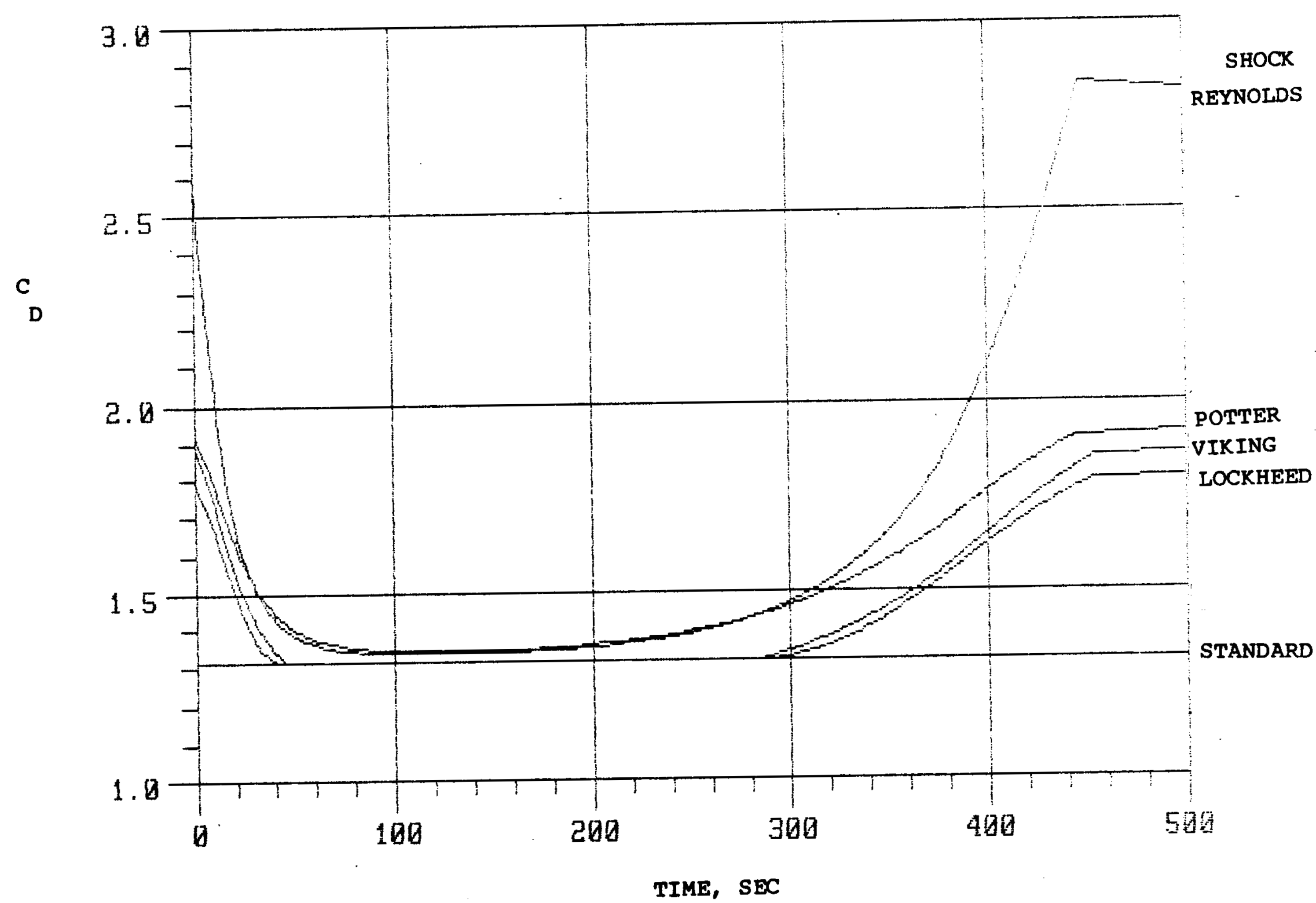


Figure 4. Comparison of drag coefficient from several transition methods versus time and at 17° angle of attack.

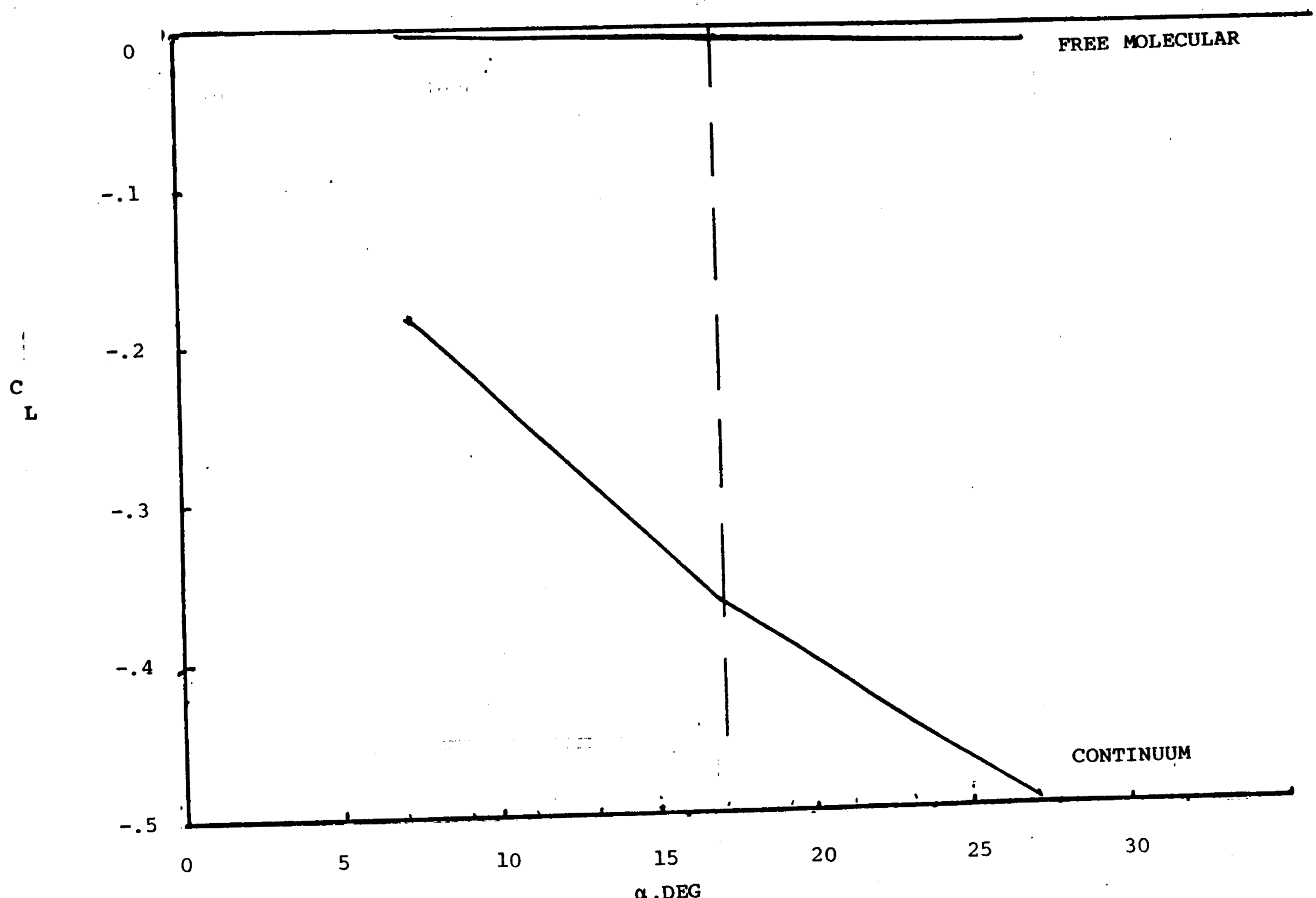


Figure 5. Free molecular and continuum lift coefficient versus angle of attack.

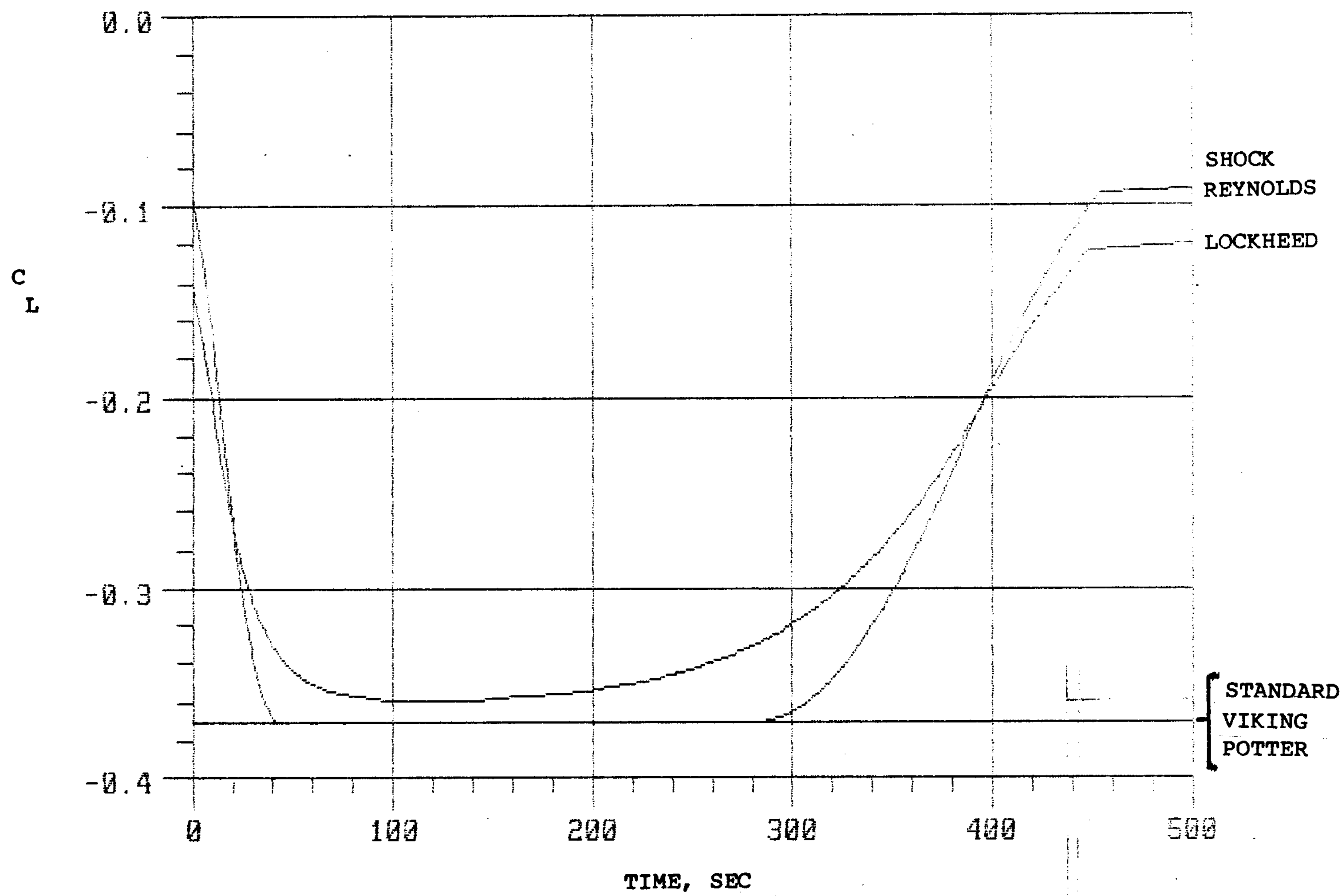


Figure 6. Lockheed, Shock Reynolds, and continuum lift coefficient versus time.

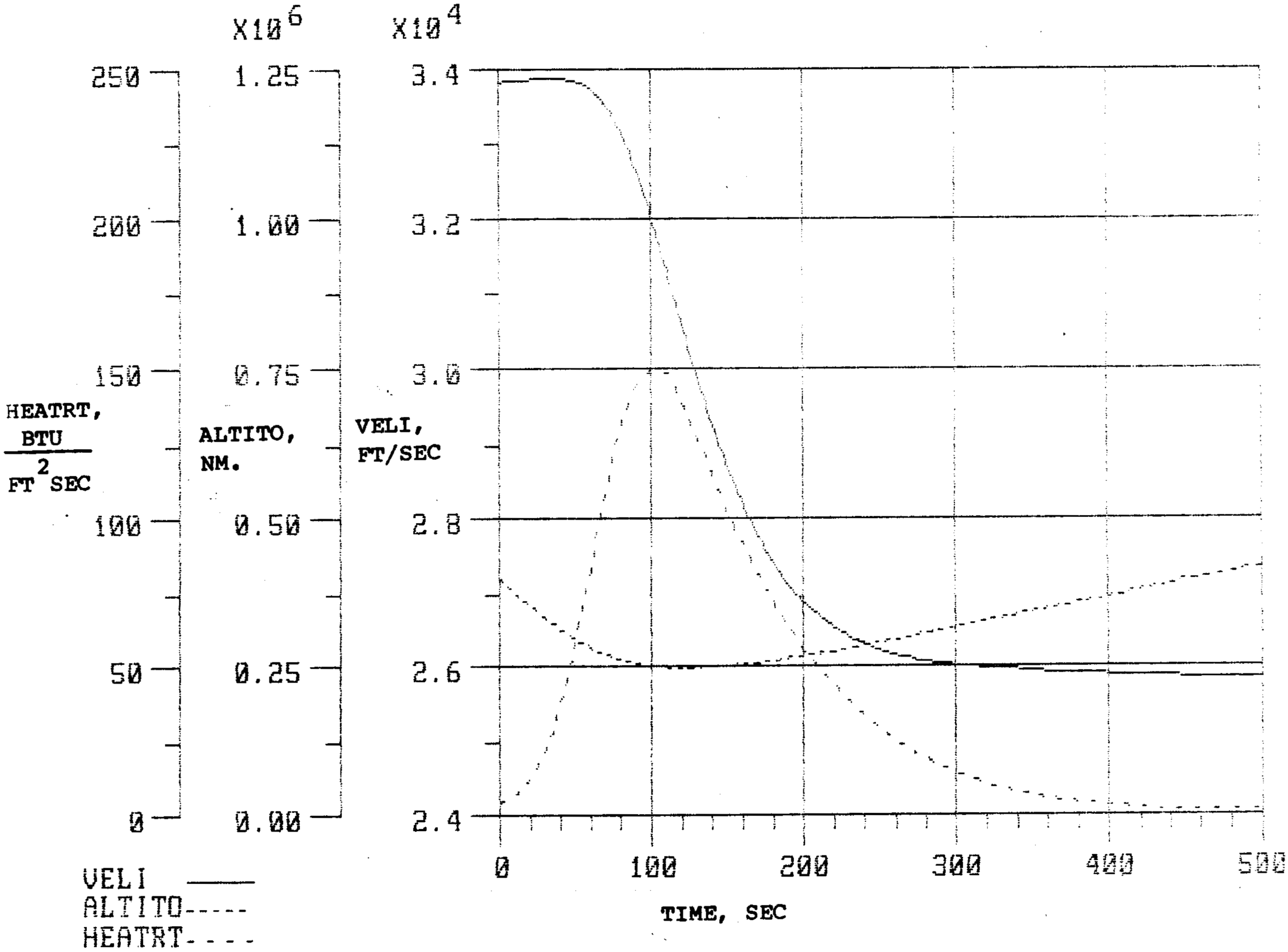


Figure 7. Time histories of inertial velocity, altitude, and heat rate for runs with standard C_L and C_D and guidance active.

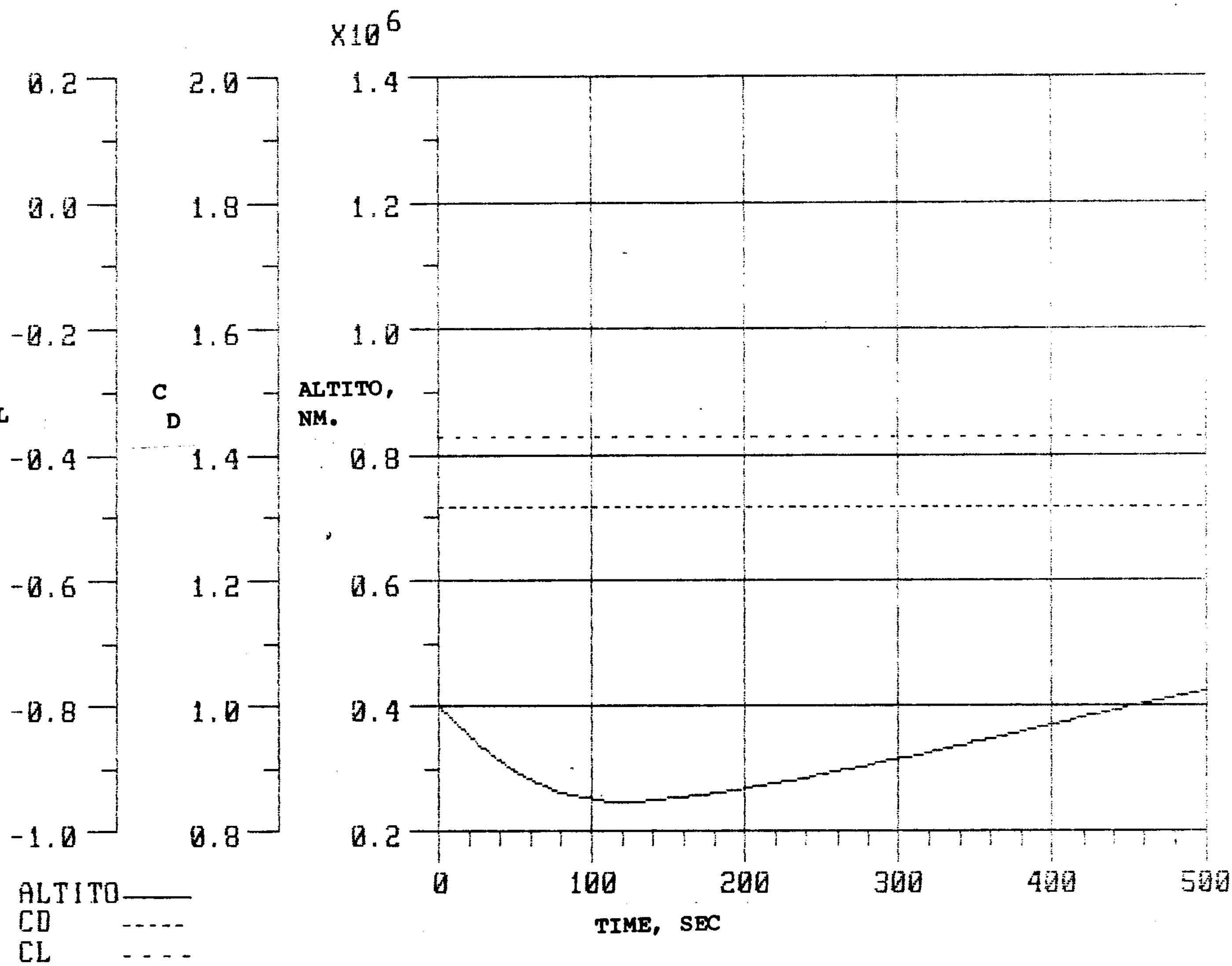


Figure 8. Time histories of drag coefficient, lift coefficient, and altitude for runs with standard lift coefficient and drag coefficient and guidance active.

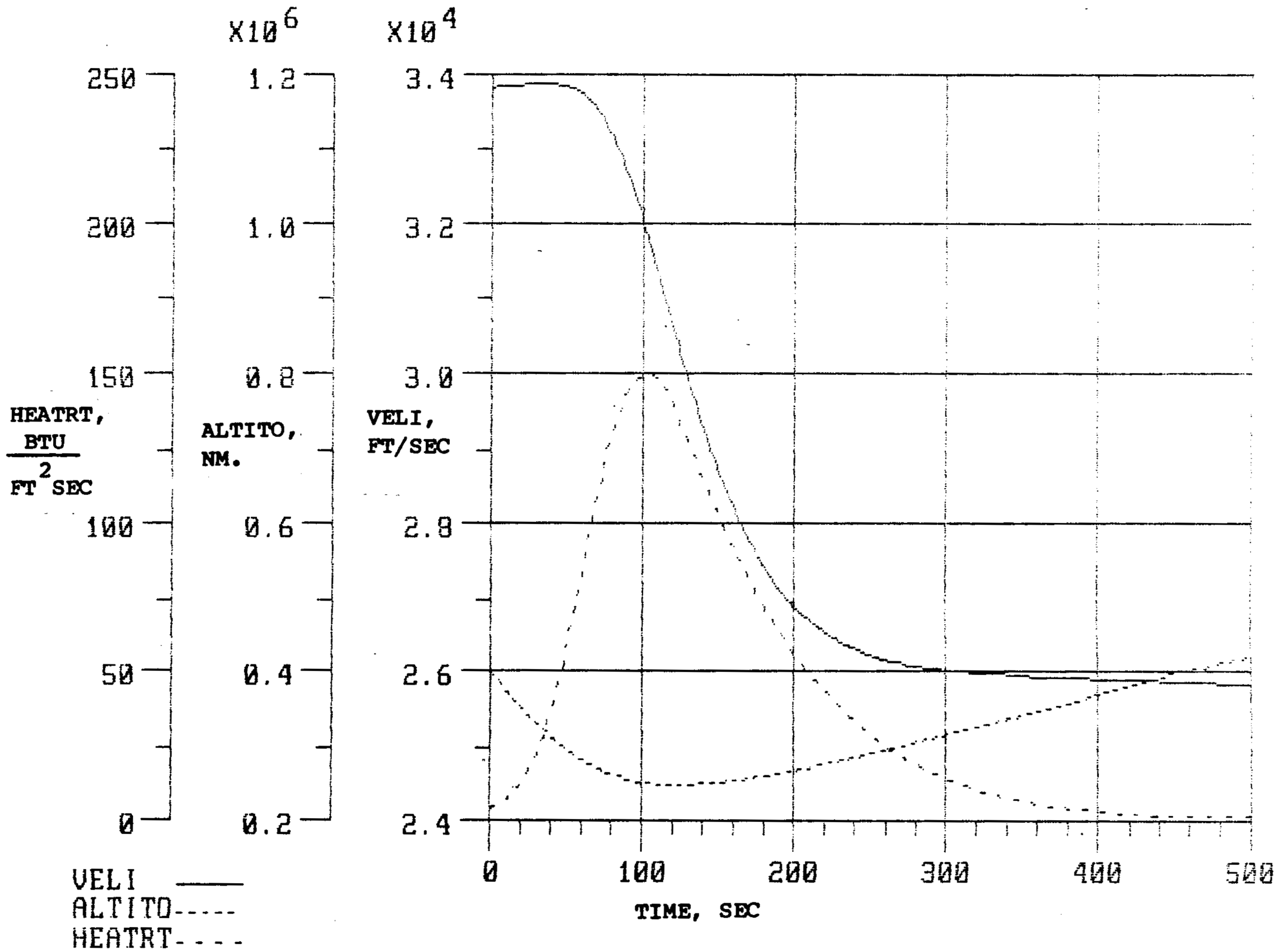


Figure 9. Time histories of velocity, altitude, and heat rate for runs with Viking lift coefficient and drag coefficient and guidance active.

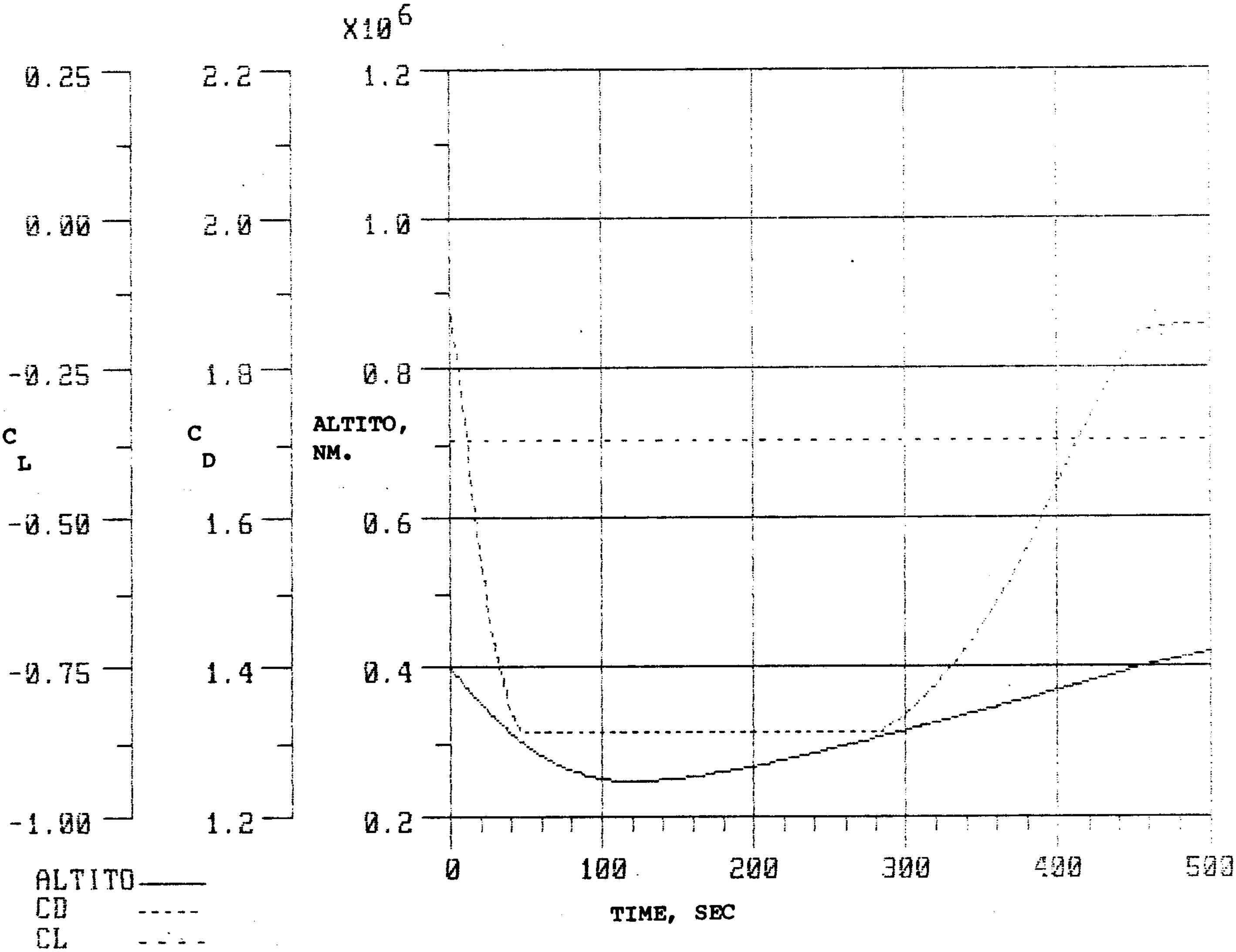


Figure 10. Time histories of drag coefficient, lift coefficient, and altitude for runs with Viking drag coefficient and guidance active.

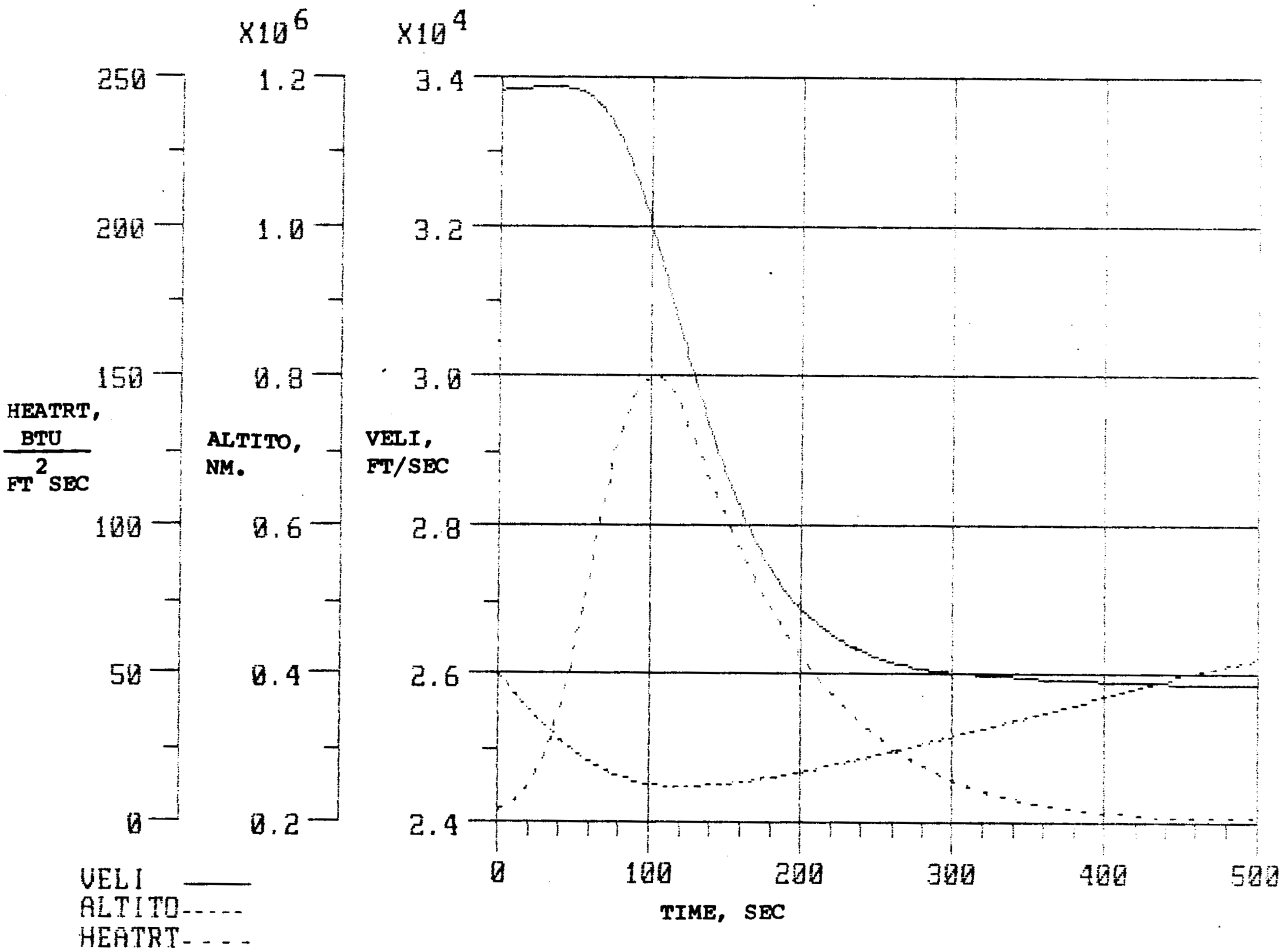


Figure 11. Time histories of velocity, altitude, and heat rate for runs with Lockheed lift coefficient and drag coefficient and guidance active.

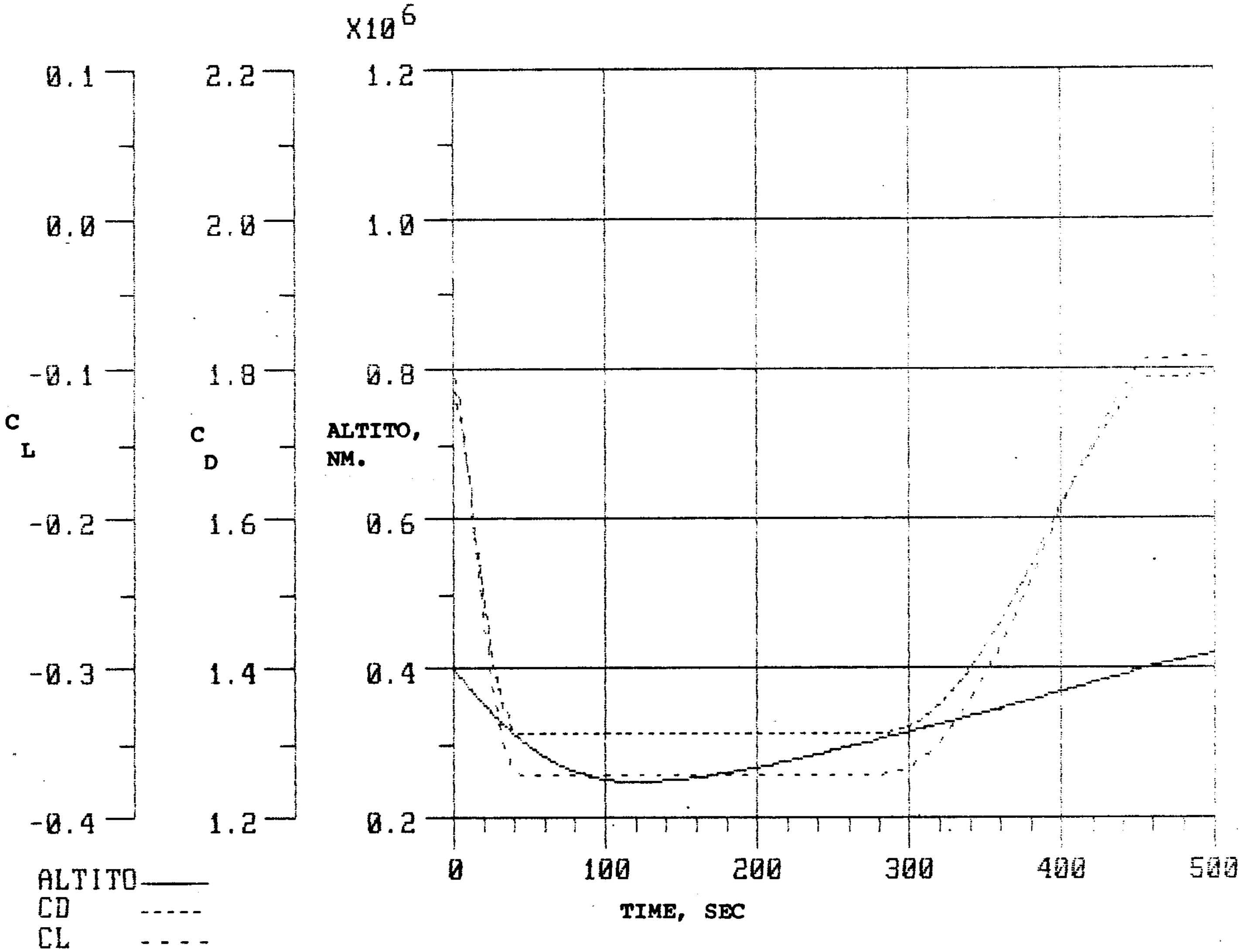


Figure 12. Time histories of drag coefficient, lift coefficient, and altitude for runs with Lockheed drag coefficient and lift coefficient and guidance active.

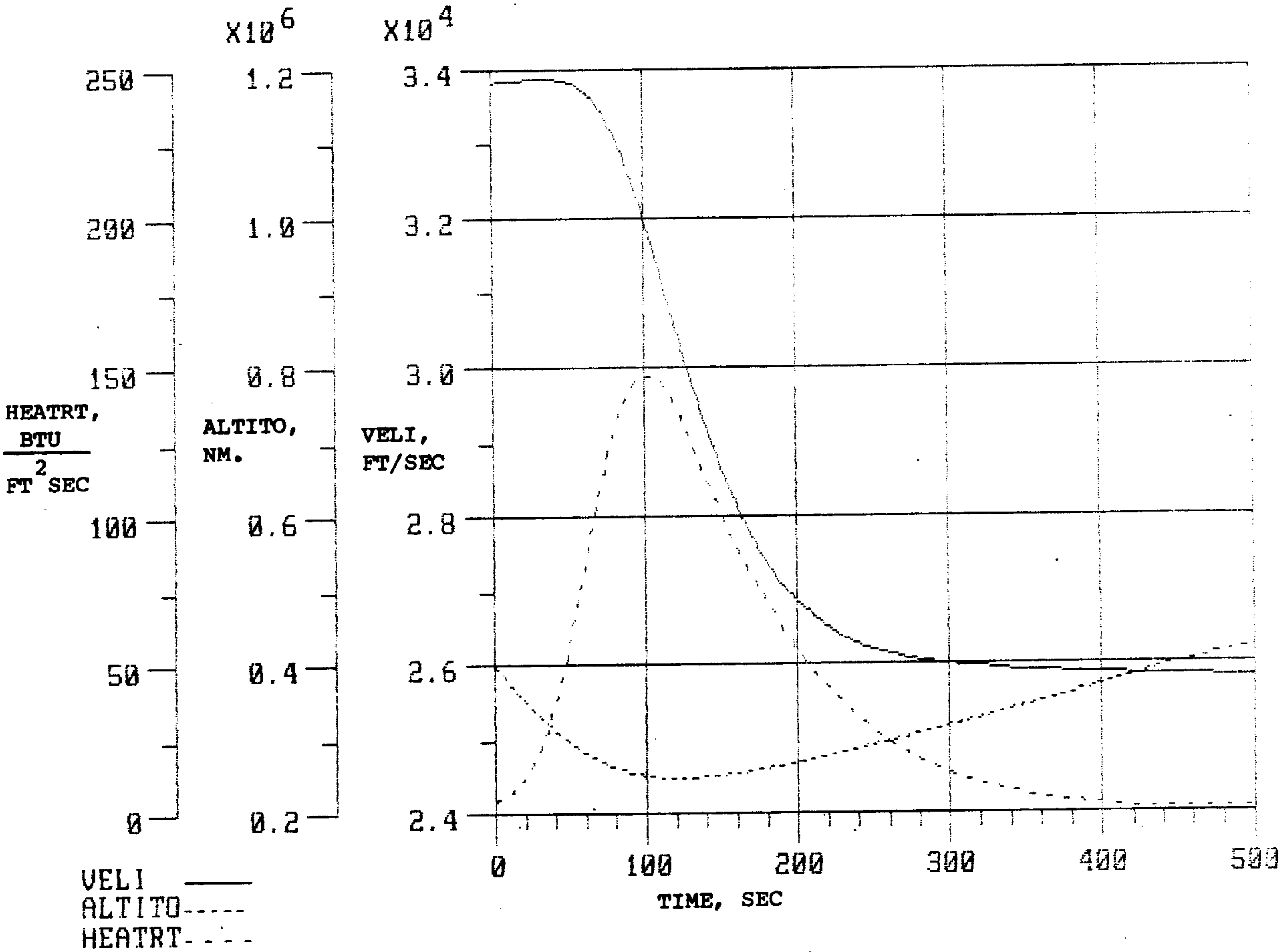


Figure 13. Time histories of velocity, altitude, and heat rate for runs with Potter lift coefficient and drag coefficient and guidance active.

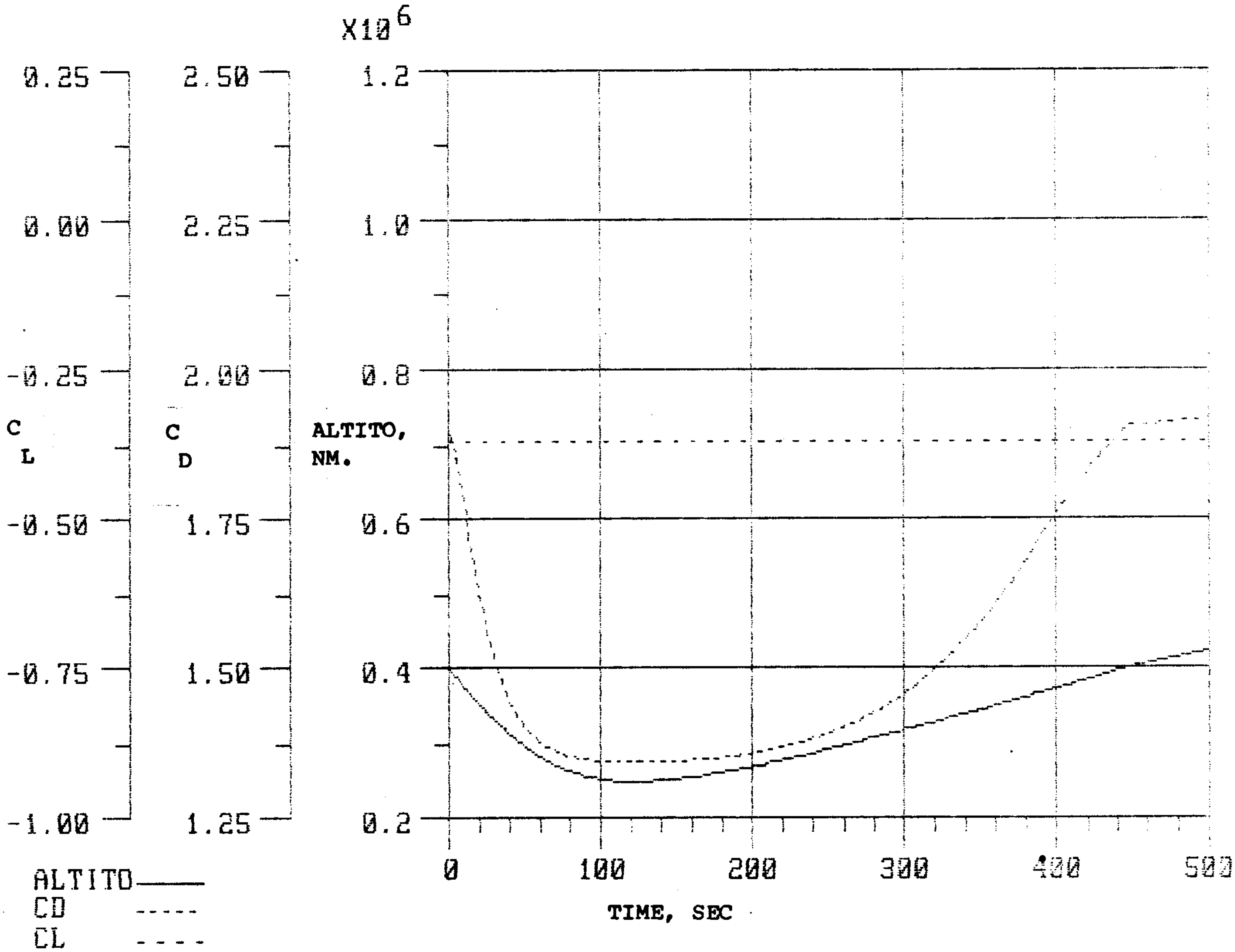


Figure 14. Time histories of drag coefficient, lift coefficient, and altitude for runs with Potter drag coefficient and guidance active.

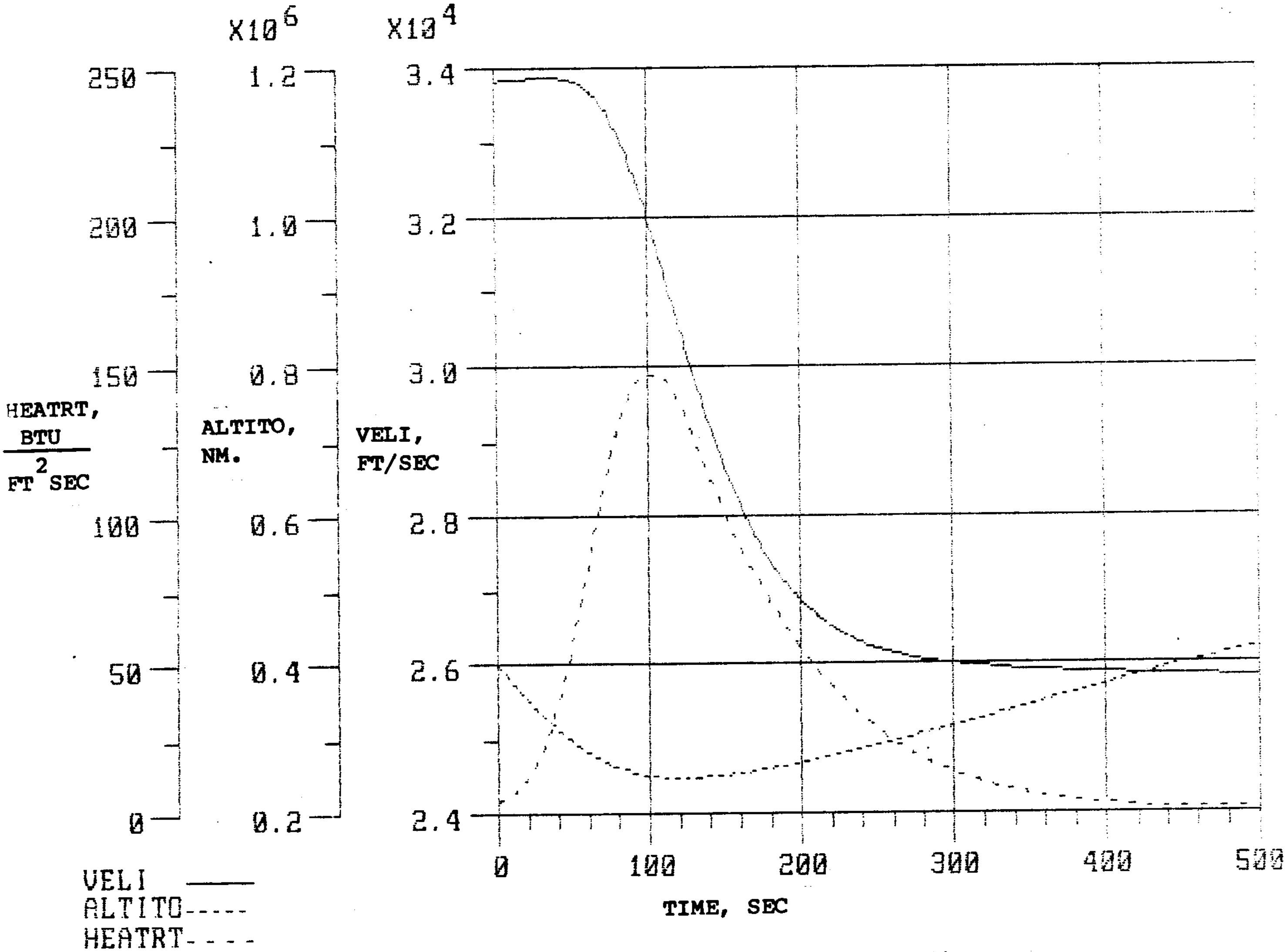


Figure 15. Time histories of velocity, altitude, and heat rate for runs with Shock Reynolds lift coefficient and drag coefficient and guidance active.

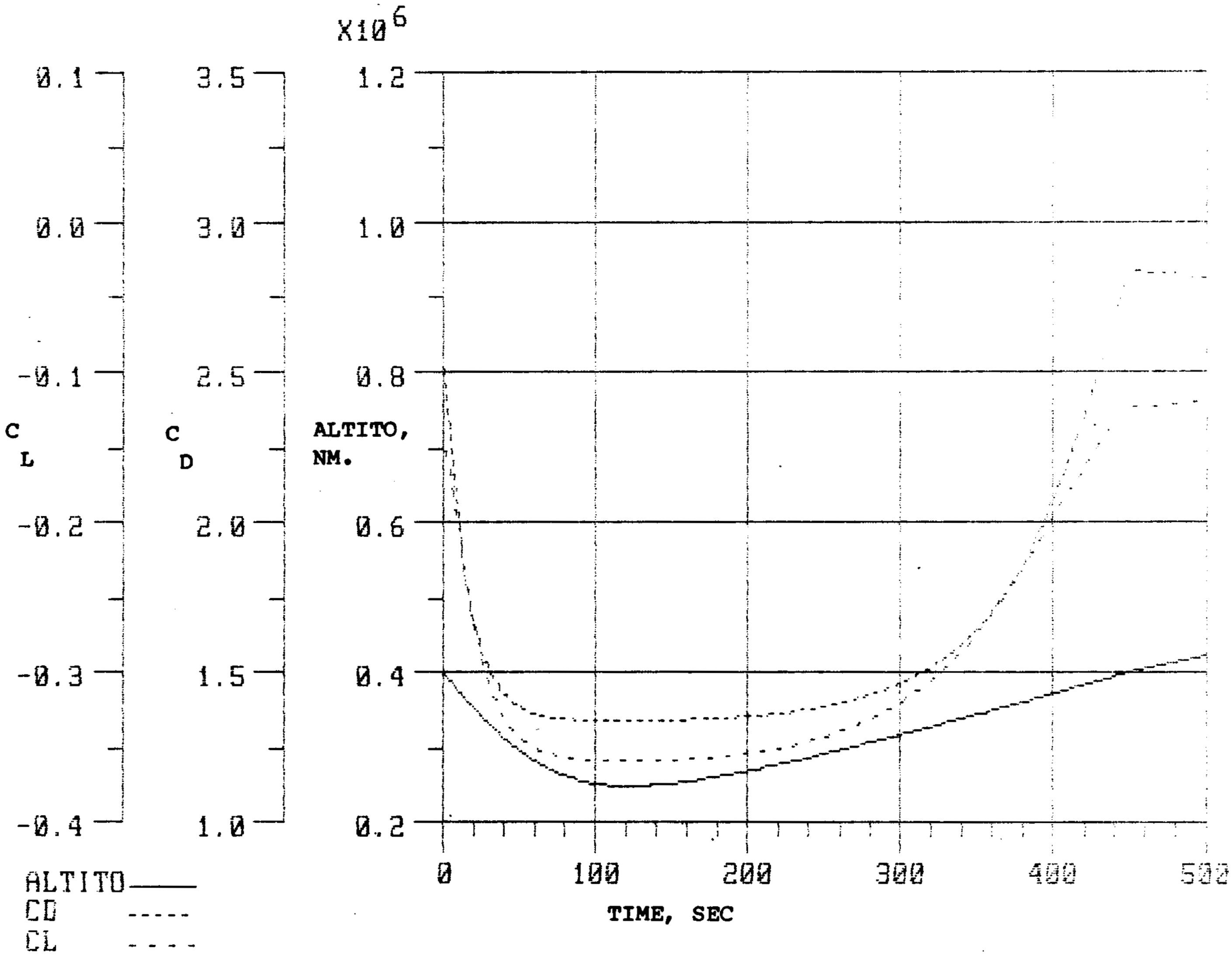


Figure 16. Time histories of drag coefficient, lift coefficient, and altitude for runs with Shock Reynolds lift coefficient and drag coefficient guidance active.

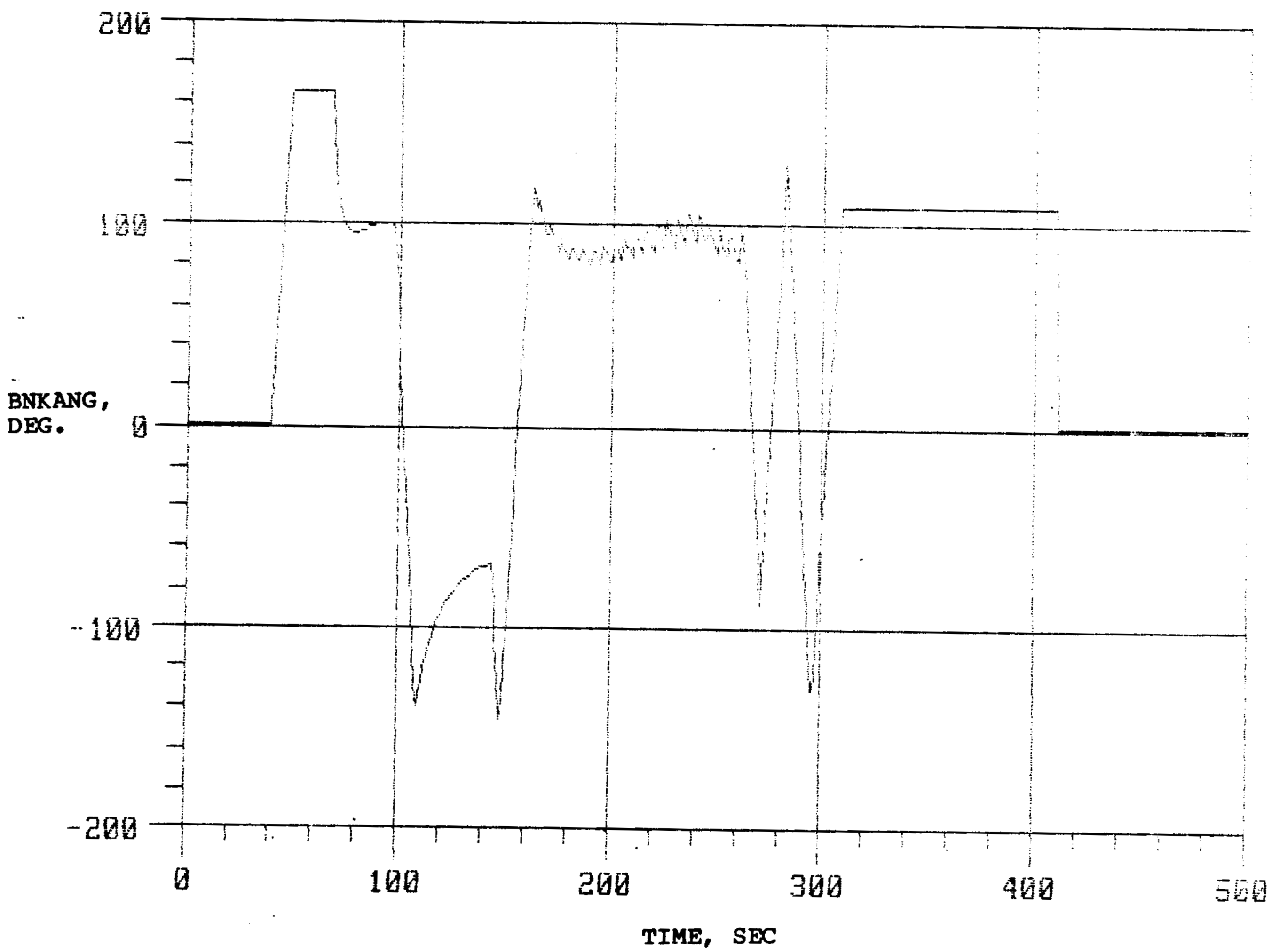


Figure 17. Bank angle time history for no transition.

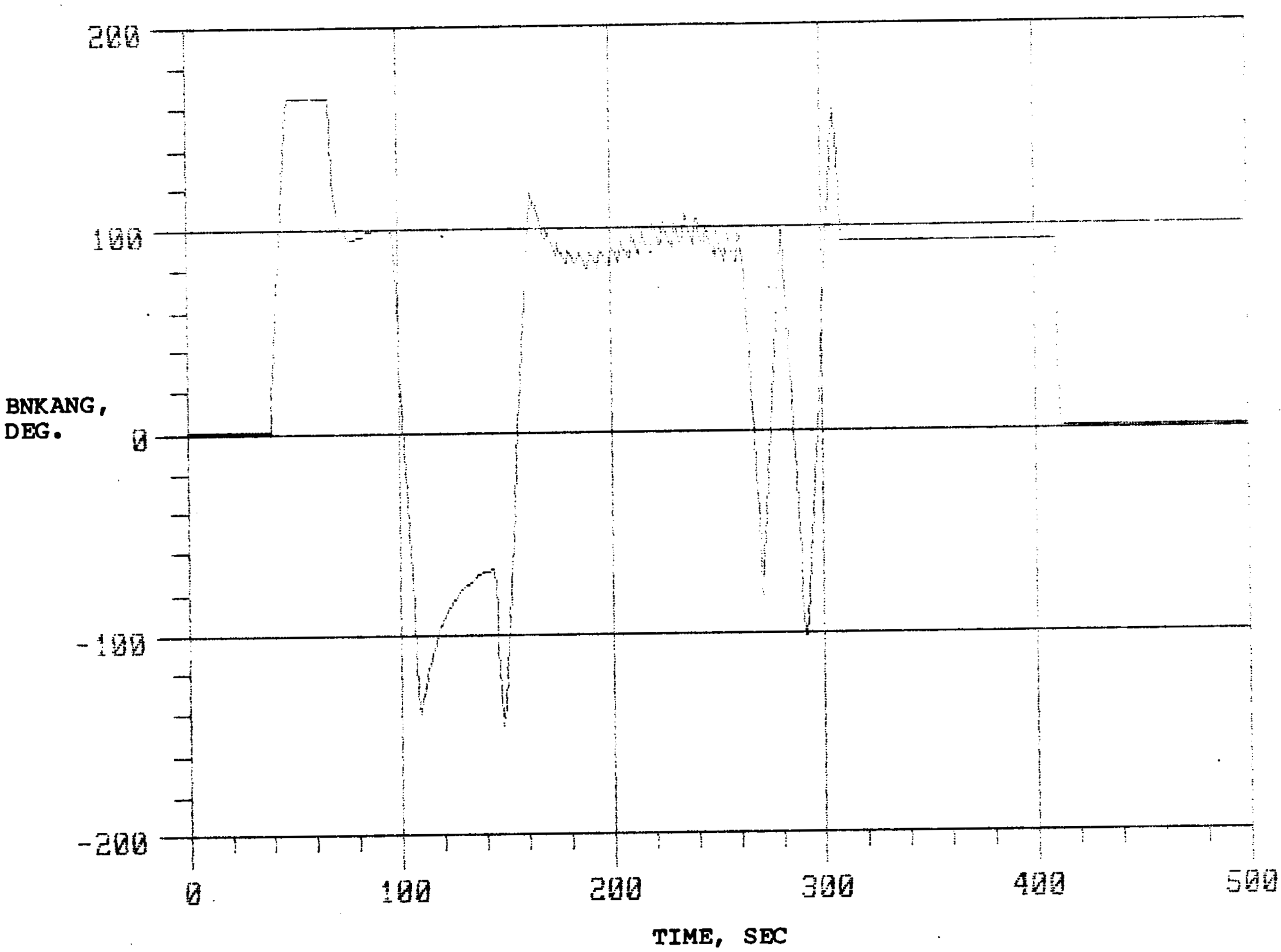


Figure 18. Bank angle time history for Viking transition.

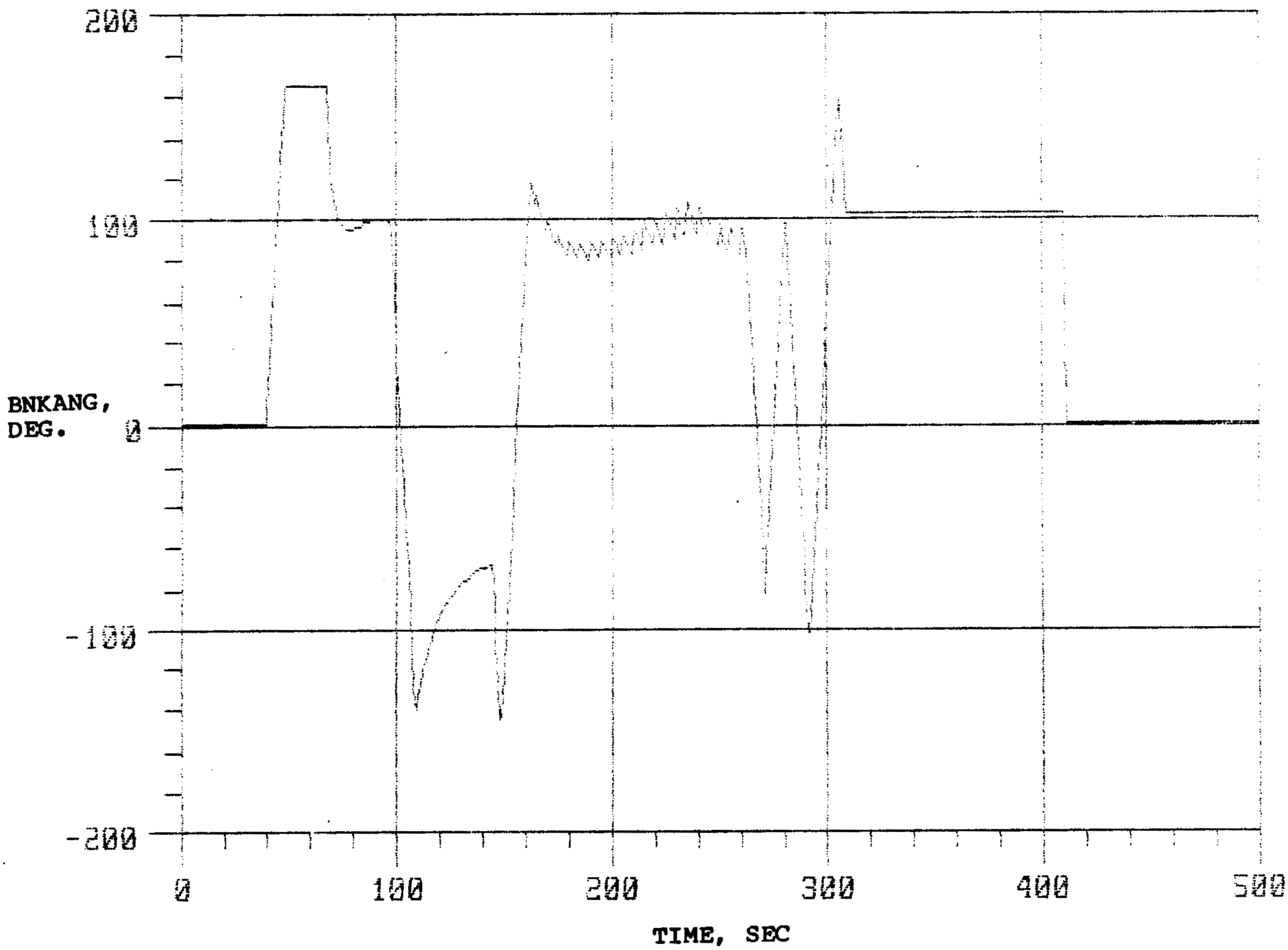


Figure 19. Bank angle time history for Lockheed transition.

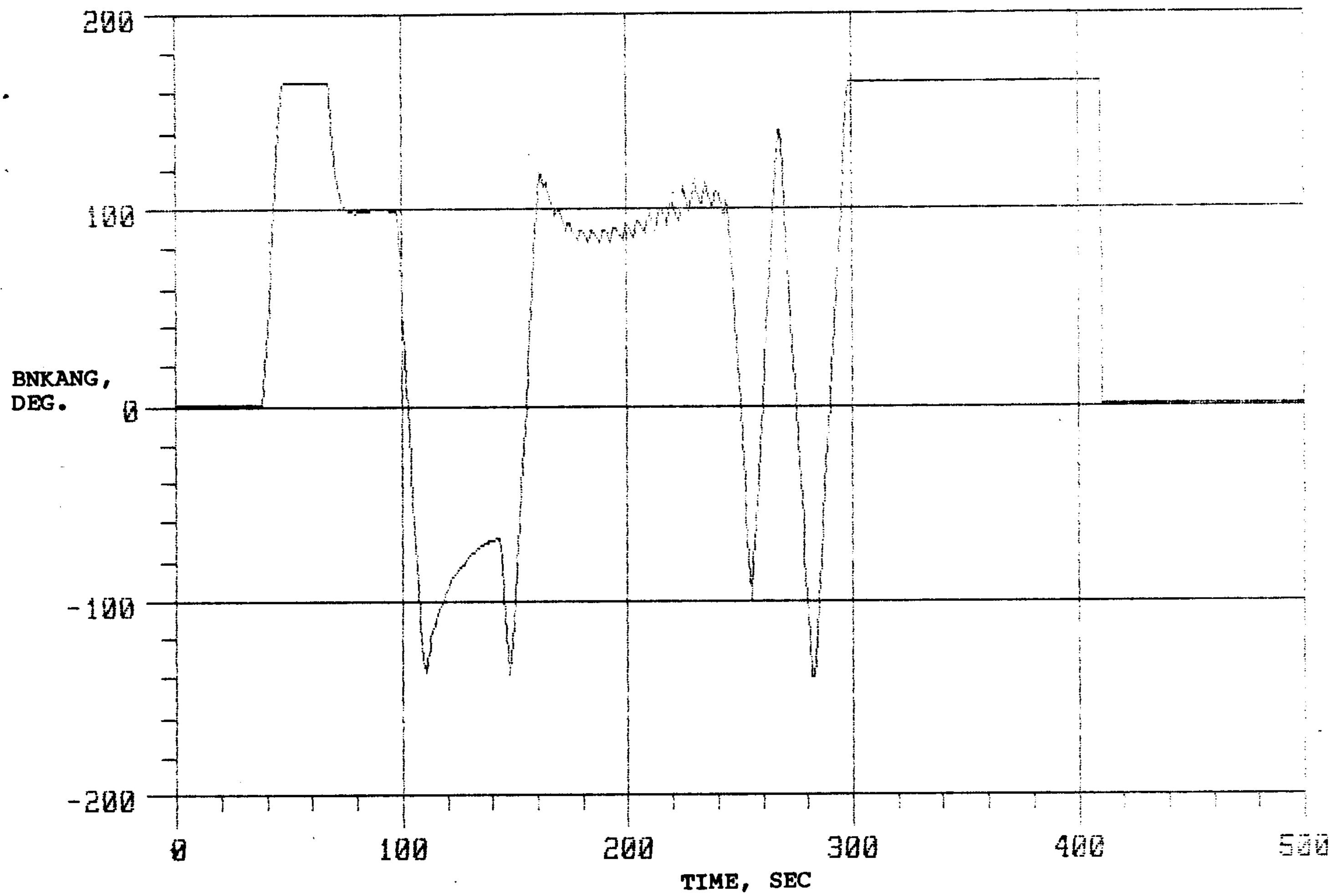


Figure 20. Bank angle time history for Potter transition.

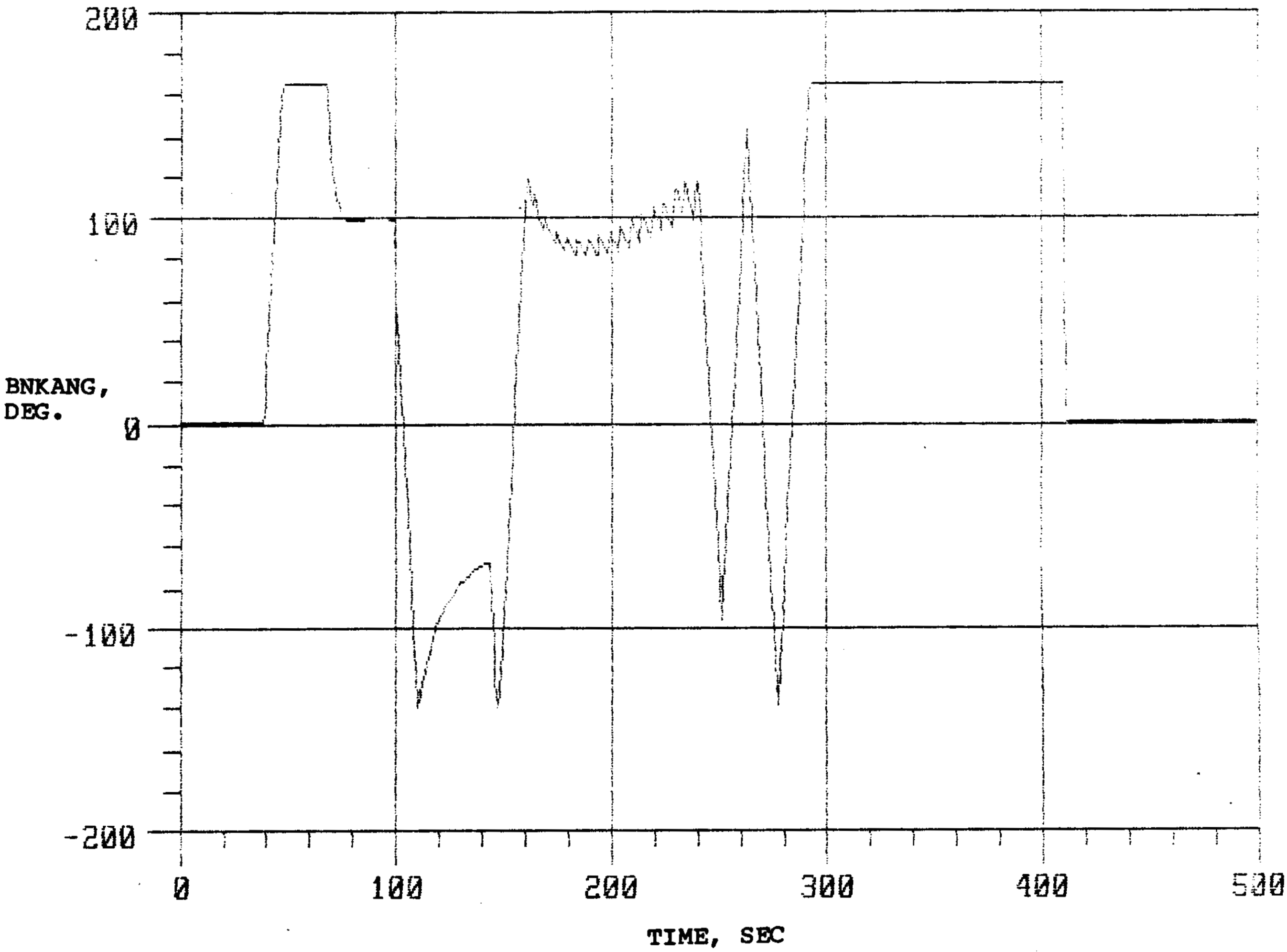


Figure 21. Bank angle time history for Shock Reynolds transition.

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15. Supplementary Notes

16. Abstract

Various transition methods are used here to study the viscous effects encountered in low density, hypersonic flight, through the transition from free molecular to continuum flow. Methods utilizing Viking Data, Shuttle orbitor data, a Potter number parameter, and a Shock Reynolds number were implemented in the Program to Optimize Simulated Trajectories (POST). Simulations of the Aeroassist Flight Experiment (AFE) using open loop guidance were used to assess the aerodynamic performance of the vehicle. A bank angle was found for each transition method that would result in a 200 nautical-mile apogee.

Once this was done, the open loop guidance was replaced by the proposed guidance algorithm for the AFE. Simulations were again conducted using that guidance and the different transitions for comparison. For the gains used, the guidance system showed some sensitivity in apogee altitude to the transition method assumed, but the guidance was able to successfully complete the mission.

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