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MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-7-3

REFERENCE MISSION 3B ASCENT TRAJECTORY

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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This Design Note is Submitted to NASA Under Task Order No. D0103, Task Assignment 1.4-7-F, Contract NAS 9-13970

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1.0 INTRODUCTION

This paper describes the ascent portion of mission 3B and the trajectory simulation which was developed as part of Task Assignment 1.4-7-F.

2.0 DISCUSSION OF GROUNDRULES AND CONSTRAINTS

Mission 3B is designed as a payload retrieval mission with both shuttle launch and orbiter landing to take place at the Western Test Range (WTR). The mission is designed for direct rendezvous with a passive satellite in a 100 NMI circular orbit with an inclination of 104 degrees. Rendezvous and return to the WTR occurs one revolution after liftoff.

The shuttle is in a tail south orientation while on the pad. Liftoff is an on-time launch; no launch window is considered. Following tower clearance, the vehicle simultaneously rolls to the launch azimuth and executes a pitchover maneuver. The launch azimuth is designed to insure planar flight to the target orbit (104 degree inclination). The pitch maneuver is designed to maximize weight at main engine cutoff (MECO) while limiting maximum dynamic pressure (max q) to less than 650 LB/FT^2. SRB separation occurs at SRB propellant depletion. The separation is an instataneous, nonpropulsive maneuver. The space shuttle main engines (SSME) are throttled to limit maximum sensed acceleration to 3.0 g's (96.522 FT/SEC^2). MECO state conditions are defined in Reference 1 and are designed for safe impact of the external tank (ET).

Following MECO, the orbiter attitude is held constant and orbiter/ET separation sequencing is initiated. The separation maneuver consists of the following sequence:

a. 5.0 second coast
b. 8.0 second RCS burn (a -Z body translation)
c. 30.0 second coast
d. 22.0 second, 2-engine OMS burn for ET clearance.

Following the separation sequence, the orbiter attitude is released and the OMS continues to burn to achieve the rendezvous orbit. The OMS cutoff conditions are such that 1) the orbiter is 9.4 NMI below and 6.7 NMI behind the target satellite at the OMS cutoff and 2) orbiter/satellite rendezvous occurs 18.0 minutes after insertion.

These groundrules and constraints for reference mission 3B are contained in Reference 2. A more detailed mission profile description (including rendezvous, de-orbit, re-entry and landing) is contained in Reference 3.

3.0 RESULTS OF TRAJECTORY SIMULATION

The reference mission 3B ascent trajectory was developed using the Space Vehicle Dynamics Simulation (SVDS) program. The simulation is a three-degree-of-freedom (translational degrees-of-freedom) program with vehicle attitude instantaneously defined by the guidance algorithms.

Platform orientation is defined at liftoff with 1) X-axis aligned with the geodetic vertical, 2) Z-axis in the local horizontal plane, pointing in the direction of launch, and 3) Y-axis completing the right-handed system. A tail south vehicle orientation on the pad is simulated by commanding a roll attitude of -161.242 degrees relative to the platform system.

Following liftoff, tower clearance is simulated by a 6.0 second vertical rise. Roll and pitchover maneuvers of 6.0 and 10.0 seconds duration, respectively, are initiated at tower clearance. The roll maneuver orients the vehicle in a tail down attitude, along a launch azimuth of 198.758 degrees east of north. The launch azimuth results in near planar flight from liftoff to MECO. Pitchover is optimized for maximum weight at MECO. Termination of the programmed pitchover maneuver occurs at 16.0 seconds and a zero angle of attack, gravity turn profile is initiated. The maximum dynamic pressure (588 LB/FT^2) occurs at 52.0 seconds. A sequence of events is given in Table I.

SRB separation occurs at 121.773 seconds. The separation is modeled as an instantaneous, non-propulsive maneuver and signals the end of simulated gravity turn.

Following SRB separation active guidance is initiated with guidance target conditions set for MECO. The MECO state conditions were selected from Reference 4 and are as follows:

Altitude (at MECO)	90. NMI
Velocity	25278. FT/SEC
Flight-path angle	.1 DEG

SSME throttling is initiated at 435.773 seconds when the 3g acceleration limit is reached. MECO occurs at 509.338 seconds, when the guidance time-to-go reaches 0.0 seconds.

The orbiter/ET separation sequence is initiated at MECO. Following a 5.0 second fixed attitude coast, physical separation is simulated by an 8.0 second (4. FT/SEC) -Z translation of the orbiter. The maneuver is an RCS maneuver with the orbiter attitude fixed. The RCS maneuver is followed by a 30.0 second fixed attitude coast. At this time (MECO + 43.0 seconds), the OMS is ignited (a 2-engine burn). The first 22.0 seconds of the OMS burn is simulated with orbiter attitude fixed. This portion of the OMS burn is required at a fixed attitude for ET clearance prior to guidance release. The remainder of the burn is for insertion into the rendezvous transfer orbit.

At 574.338 seconds, active guidance is re-initialized. OMS cutoff occurs at 720.547 seconds. The OMS cutoff conditions result in orbiter/satellite rendezvous 18.0 minutes later (1800.547 seconds). Insertion conditions for this simulation and the target satellite state which result in rendezvous are as follows:

	Orbiter at insertion	Target satellite
Radius - feet	21476507.	21533322.
Velocity - feet/second	25613.	25569.
Flight-path angle-degrees	0.124	0.000
Longitude - degrees	-129.99	-130.02
Geocentric latitude-degrees	8.58	8.48
Inertial azimuth-degrees	194.16	194.16

A sequence of major events for the mission 3B ascent profile is given in Table I. A weight summary and trajectory parameter summary are given in Tables II and III, respectively.

A weight history for the reference mission 3B ascent simulation is given in Figure 1. Weight drops are indicated at SRB separation and ET separation. Figures 2 through 7 illustrate thrust profiles as used in the trajectory simulation. Figure 2 is SRB atmospheric thrust. SSME throttle setting history is given in Figure 3. Figures 4 and 5 are SSME vacuum and atmospheric thrust, respectively. Shuttle total thrust histories from liftoff to MECO are given in Figures 6 and 7. The weight and thrust data indicated by Figures 1 through 7 correspond to the mission 3B data indicated in Reference 2. Sensed acceleration and Mach number resulting from the indicated thrust and weight sequences are illustrated by Figures 8 and 9. Acceleration data is presented from liftoff to OMS cutoff. OMS propulsion characteristics for this simulation (Reference 2) are

Vacuum Thrust - 6000 LB   Vacuum ISP - 313.2 SEC

Time histories of altitude, inertial range, relative velocity, inertial velocity, relative flight-path angle, inertial flight-path angle and inertial azimuth from liftoff to OMS cutoff are presented in Figures 10 through 16. Altitude as a function of inertial range is presented in Figure 17. The range data is based on a spherical earth model and the inertial radius vector of the launch site. Altitude is geodetic altitude.

Angle of attack and sideslip angle histories for the mission 3B trajectory simulation are given in Figures 18 and 19. The resulting $q \cdot \alpha$ and $q \cdot \beta$ (product of dynamic pressure and angle) values are illustrated in Figures 20 and 21. Data is presented for both angle of attack and sideslip angle. Dynamic pressure and axial force histories are presented in Figures 22 and 23.

Two closed loop guidance segments are utilized during the mission 3B reference trajectory simulation. The first segment is from SRB separation to MECO; the second is for the OMS insertion burn. The guidance commanded pitch and yaw histories are illustrated in Figures 24 and 25. The values are inertially referenced values. The estimated time remaining before achieving the required target conditions (time-to-go) for the two guidance maneuvers is presented in Figures 26 and 27. Gimbal angles are given in Figures 28, 29 and 30. Vehicle attitude relative to a local horizontal system is illustrated by the pitch and yaw attitude data of Figures 31 and 32. The local system is defined using the geocentric radius and relative velocity vectors. Table IV contains definitions of some of the parameters illustrated in Figures 1 through 32.

4.0 CONCLUSIONS

The reference mission 3B ascent trajectory described in this design note is a three-degree-of-freedom, point mass simulation which adheres to the groundrules defined for this mission.

A data tape of some of the key parameters for the mission 3B reference trajectory is on file at the JSC computer center. The tape format is described in Reference 5. JSC tape library number for the trajectory tape is V15457. The mission 3B ascent trajectory simulation is to comprise a portion of the Space Shuttle System Baseline Reference Mission document to be released by the NASA at a future date. Future reference mission ascent trajectories will consider six degrees of freedom and moment balancing as the simulation tools are upgraded.

TABLE I SEQUENCE OF MAJOR EVENTS

EVENT	TIME
Liftoff	0.000
End vertical rise-initiate tilt and roll maneuvers	6.000
End tilt and roll maneuvers-begin gravity turn	16.000
Maximum dynamic pressure	52.000
SRB separation	121.773
Begin closed loop guidance	121.773
Begin throttling SSME for 3g acceleration limit	435.773
Freeze steering commands	503.773
MECO - begin attitude hold for ET separation	509.338
Orbiter/ET separation - RCS maneuver	514.338
End -Z maneuver - maintain attitude hold	522.338
OMS ignition - fixed attitude maneuver	552.338
Begin closed loop guidance	574.338
Freeze steering commands	714.338
Orbit insertion-OMS cutoff	720.547
Shuttle/target rendezvous	1800.547

TABLE II WEIGHT SUMMARY

Event	Time			Weight
Liftoff	0.0			4366620
		SRB propellant	-2202400	
		ET propellant	-377194	
SRB cutoff	121.773			1787206
		SRB	-350380	
SRB/Orbiter Separation	121.773			1436646
		ET propellant	-1151508	
MECO	509.338			285138
		ET (Dry)	-75000	
		Unused ME propellant (from ET)	-17648	
		ME FPR propellant in ET	-2616	
		ME fuel bias propellant in ET	-1091	
		ME propellant trapped in orbiter (unusable)	-2697	
		ME FPR propellant in orbiter	-2584	
Orbiter/ET Separation	514.338			183502

TABLE II WEIGHT SUMMARY
(continued)

Event	TIME			WEIGHT
OMS ignition	552.338			183502
		Orbiter OMS propellant	-843	
Initiate closed loop guidance	574.338			182659
		Orbiter OMS propellant	-5602	
OMS cutoff-orbit insertion	720.547			177057

Orbiter (Dry)	150000
Personnel group	2411
Non-prop. unuseable consumables	1757
Non-prop. useable consumables	2778
Unuseable OMS propellant	557
Useable OMS propellant	9663
Unuseable RCS propellant	394
Useable FWD RCS	2344
Useable AFT RCS	4653
Payload	2500

TABLE III TRAJECTORY PARAMETERS AT KEY EVENTS DURING ASCENT FOR MISSION 3B

Event	Time-seconds	Geodetic Altitude-feet	Geodetic latitude-degrees	Longitude-degrees	Inertial velocity-ft/sec	Inertial flight-path angle degrees	Inertial azimuth-degrees	Weight-pounds
Liftoff	0.0	338.	34.57	-120.62	1251.	0.000	90.00	4366620.
Begin pitchover	6.0	637.	34.57	-120.62	1256.	4.731	89.98	4211417.
Begin gravity turn	16.0	2711.	34.57	-120.62	1285.	14.414	90.77	3943870.
SRB propellant depletion	121.773	150027.	34.23	-120.77	4280.	34.388	179.95	1787026.
Begin closed loop guidance	121.773							1436646.
Begin throttling for 3g acceleration	435.773	546221.	26.72	-123.83	18214.	1.150	-165.29	464054.
MECO	509.338	557112.	22.58	-125.35	25278.	.095	-164.83	285138.
ET separation	514.338	557032.	22.25	-125.47	25278.	.086	-164.86	183502.
Terminate Z-body translation	522.338	556853.	21.73	-125.65	25278.	.063	-164.92	183502.
OMS ignition	552.338	555740.	19.76	-126.34	25278.	.008	-165.12	183502.
Begin closed loop guidance	574.338	554564.	18.32	-126.83	25325.	-.026	-165.24	182659.
Orbit insertion	720.547	552338.	8.63	-129.99	25613.	0.124	-165.84	177057.
Shuttle/target rendezvous	1800.547	643952.	-61.51	-163.84	25537.	0.031	-149.65	177057.

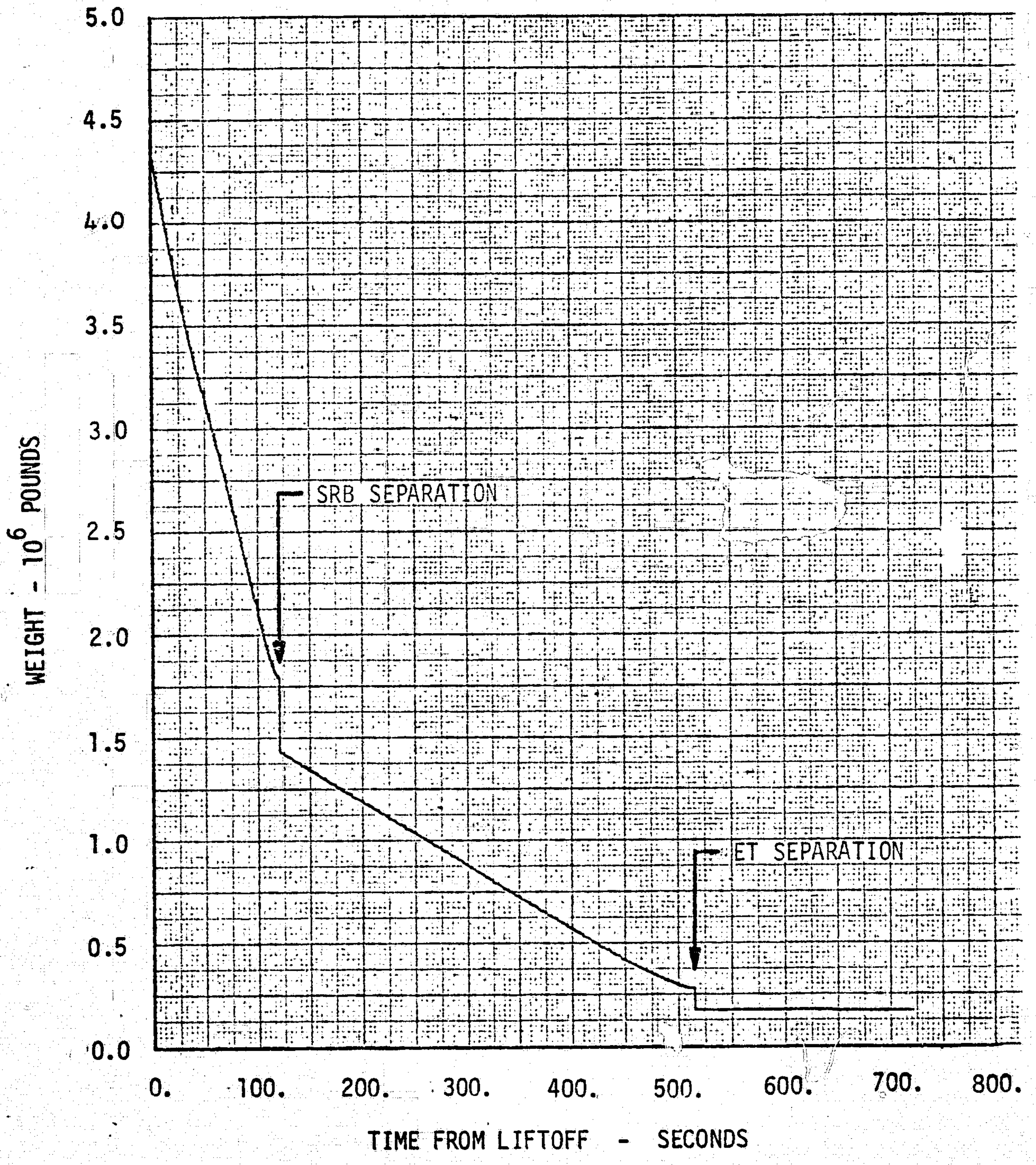


FIGURE 1 WEIGHT HISTORY

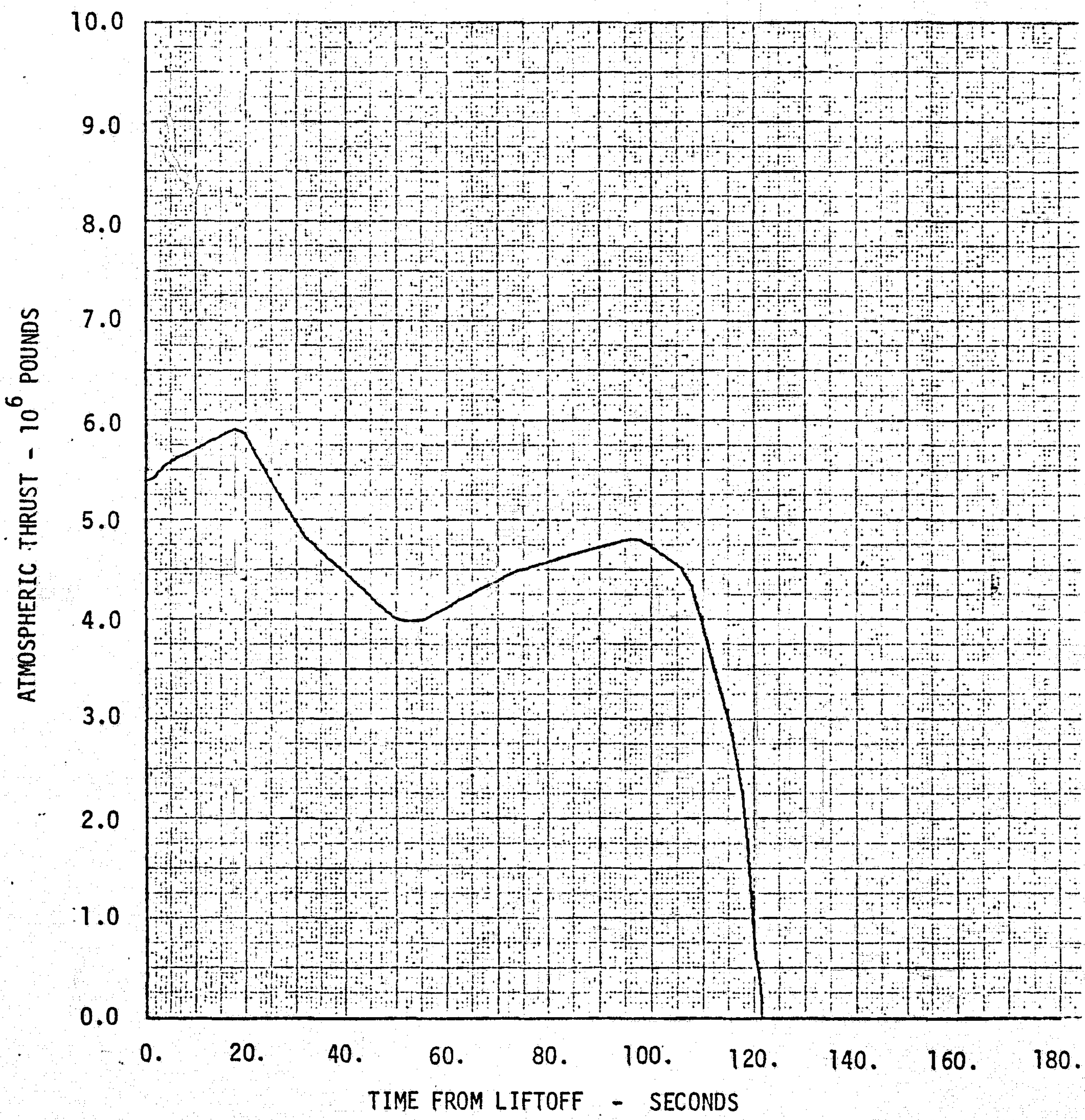


FIGURE 2 SRB ATMOSPHERIC THRUST HISTORY

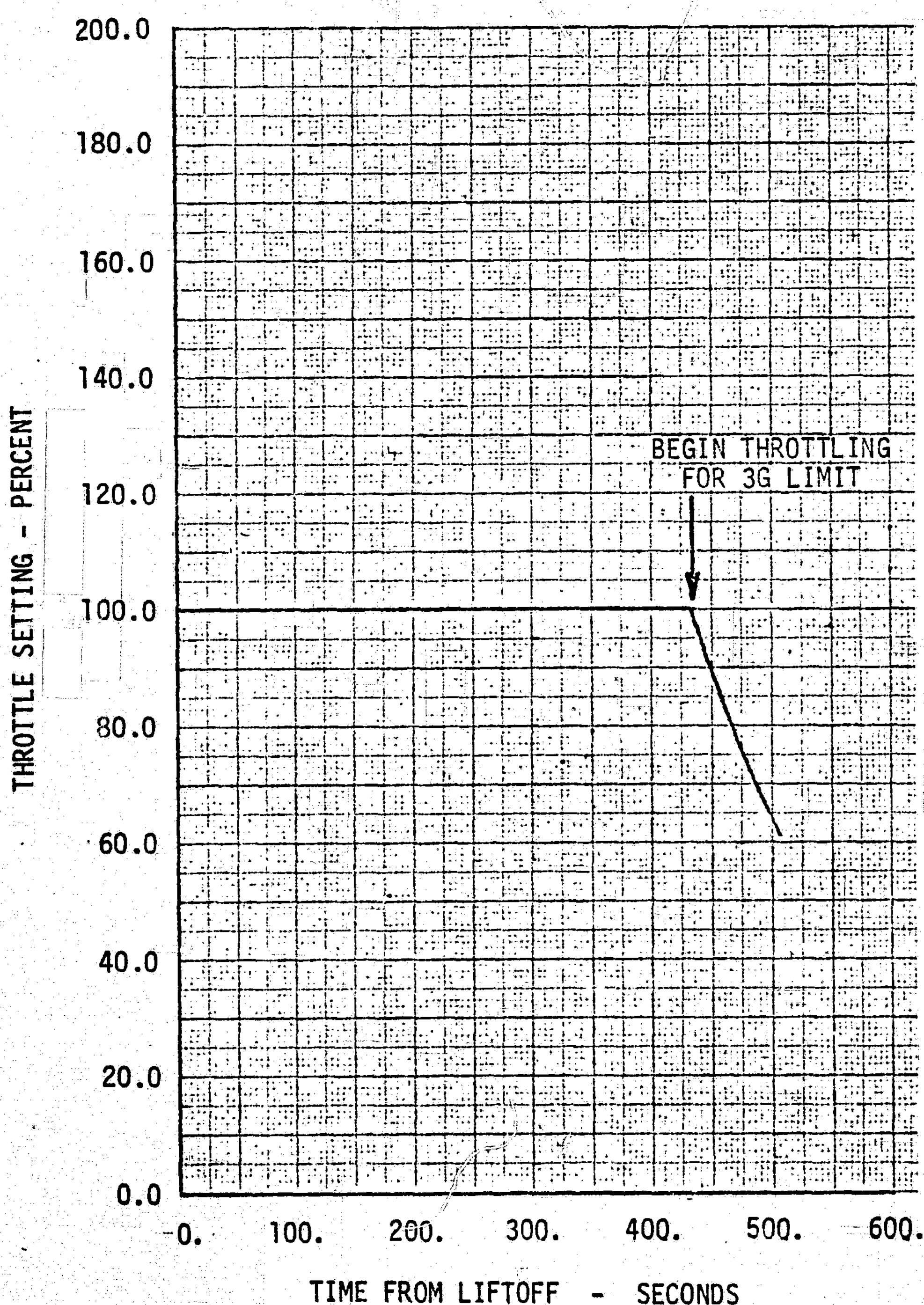


FIGURE 3 SSME THROTTLE SETTING HISTORY

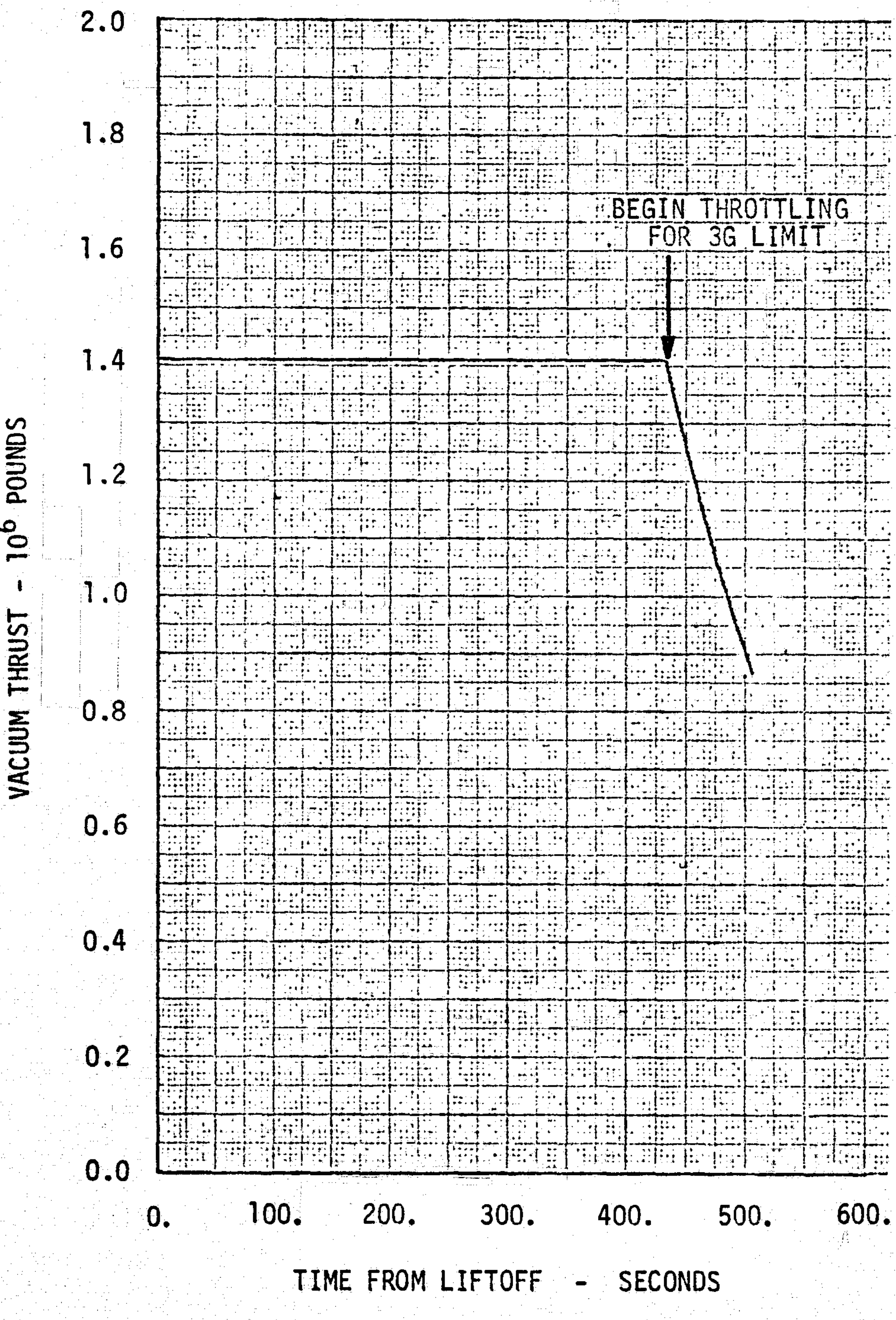


FIGURE 4 SSME VACUUM THRUST HISTORY

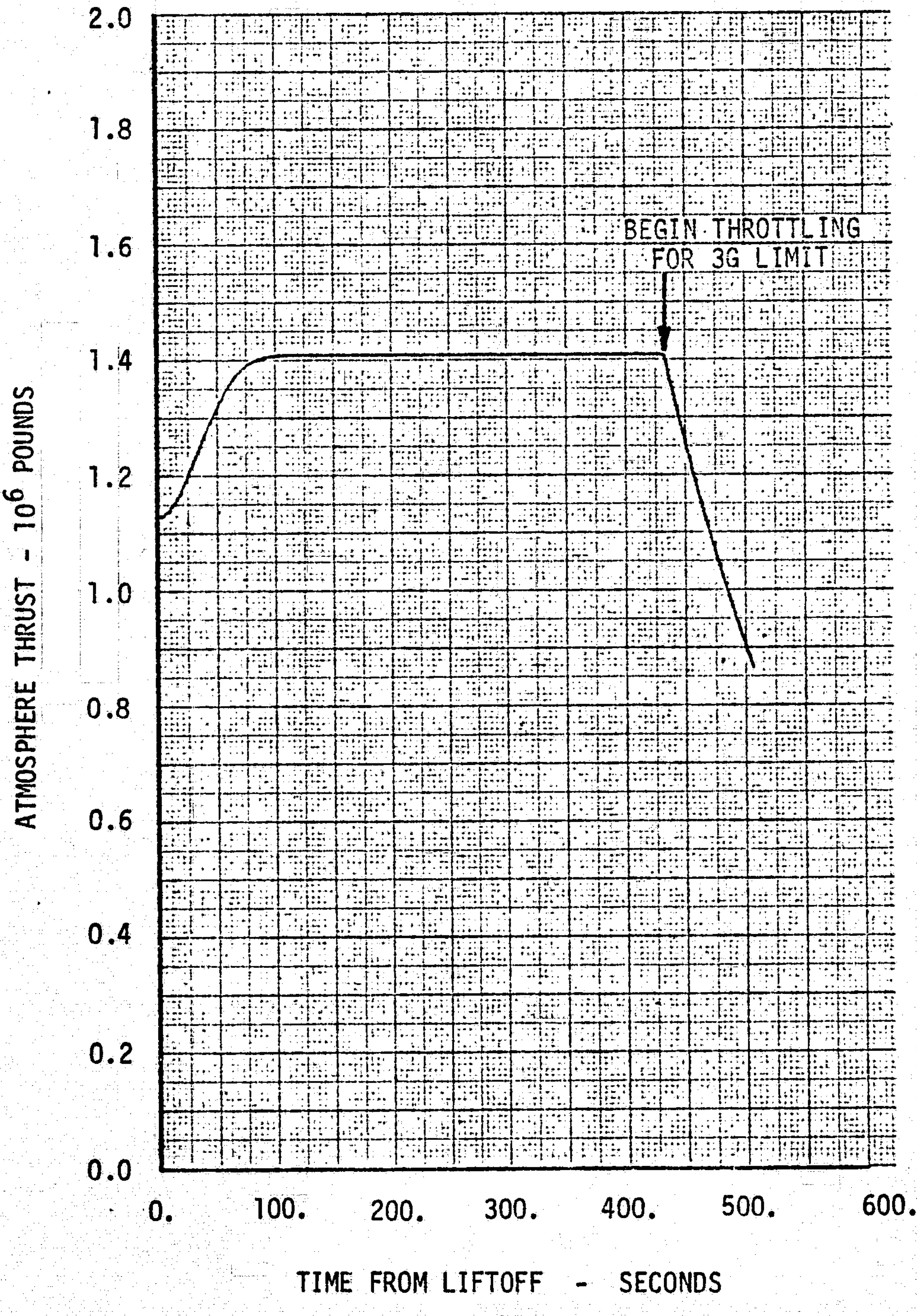


FIGURE 5 SSME ATMOSPHERIC THRUST HISTORY

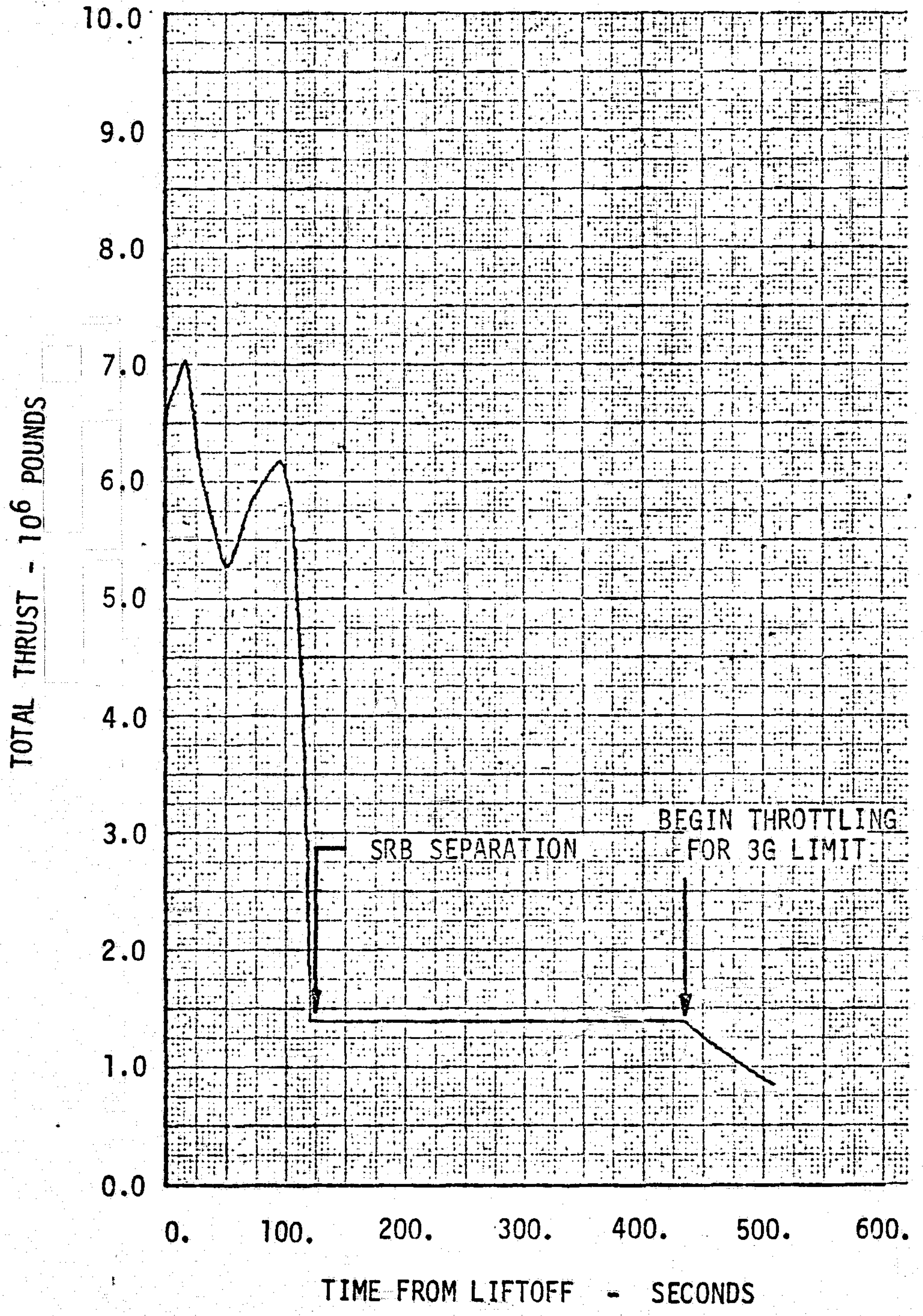


FIGURE 6 TOTAL ATMOSPHERIC THRUST HISTORY

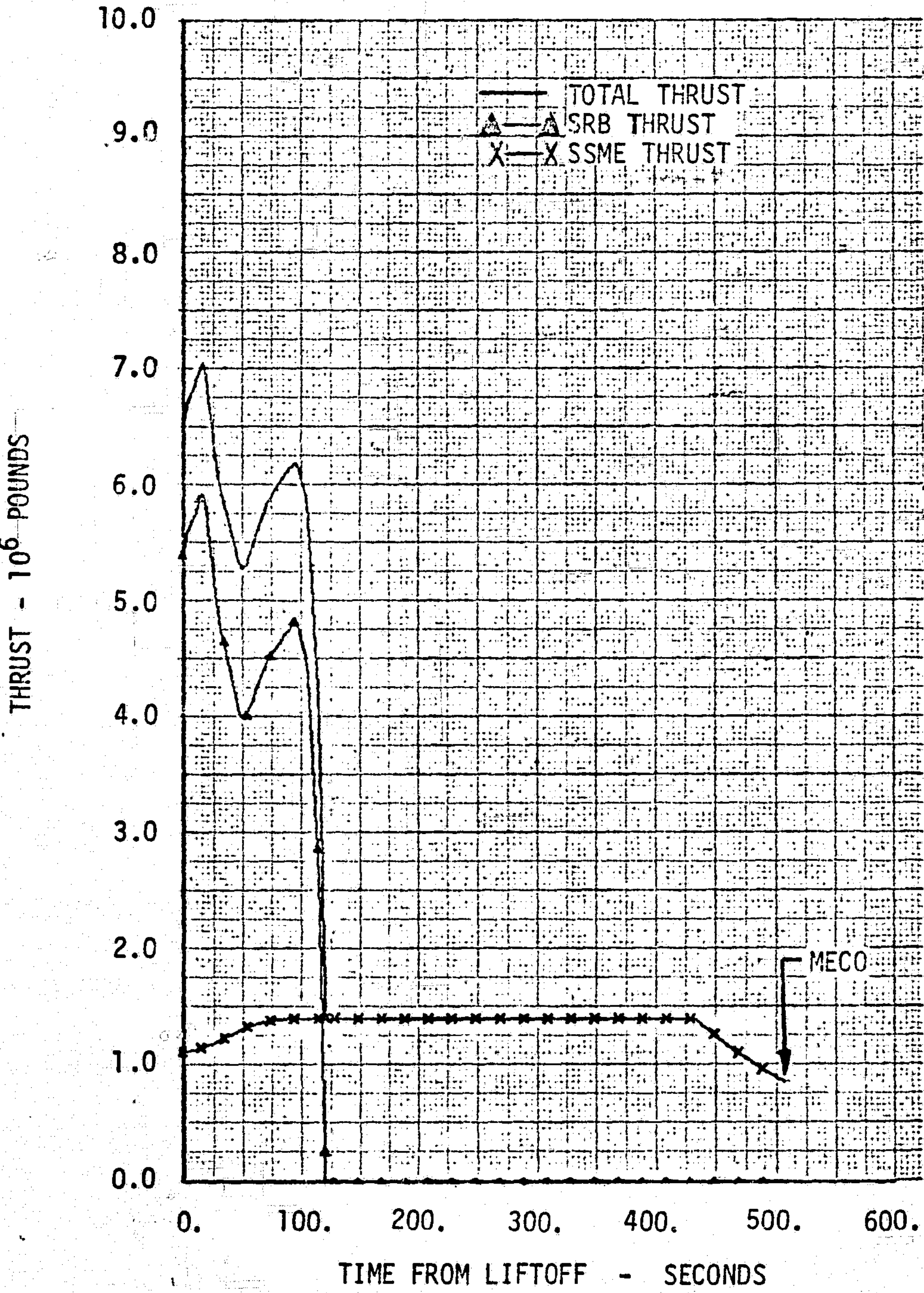


FIGURE 7 ACCUMULATIVE ATMOSPHERIC THRUST HISTORY

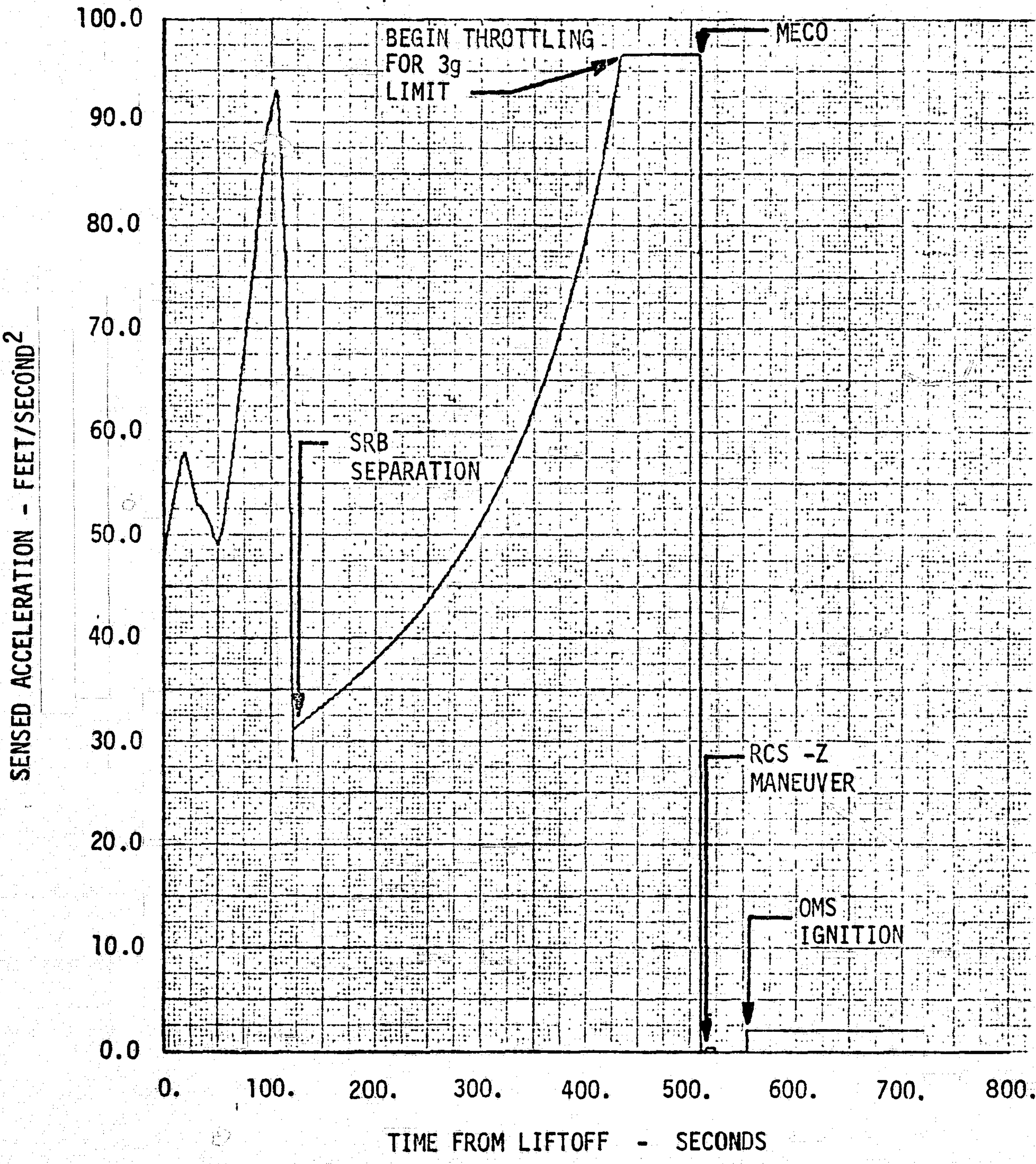


FIGURE 8 SENSED ACCELERATION HISTORY FROM LIFTOFF TO OMS CUTOFF

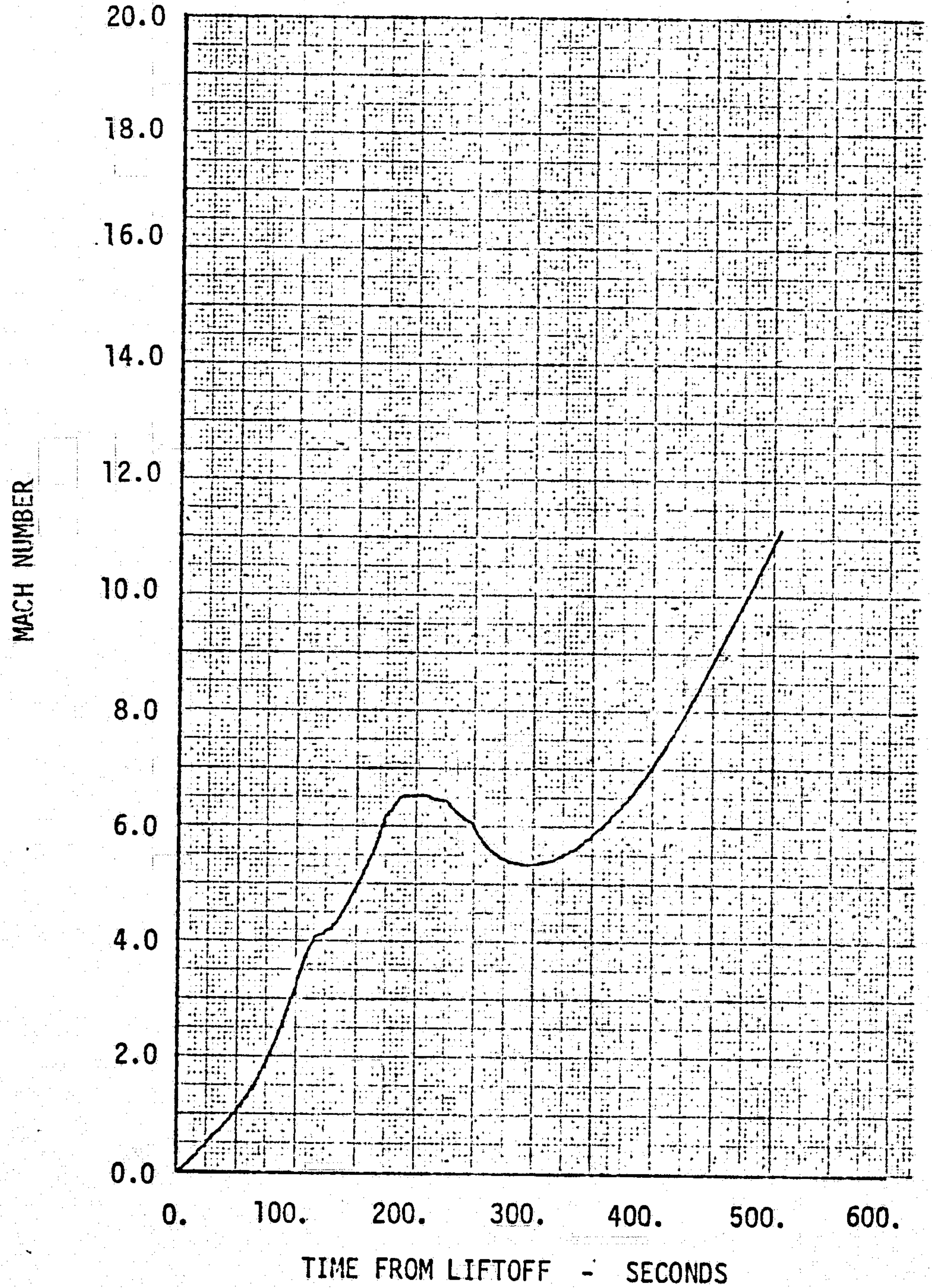


FIGURE 9 MACH NUMBER HISTORY

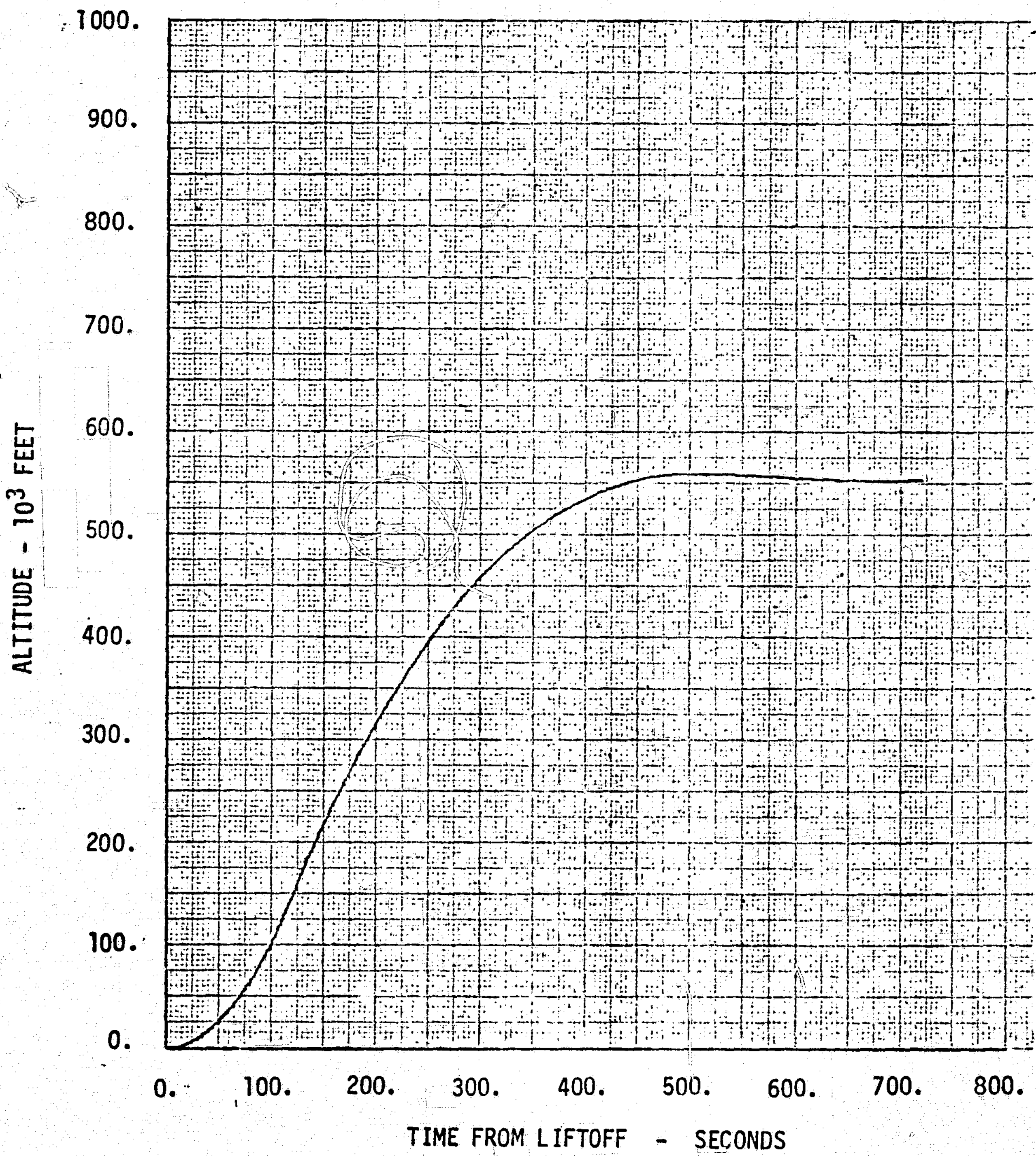


FIGURE 10 ALTITUDE HISTORY

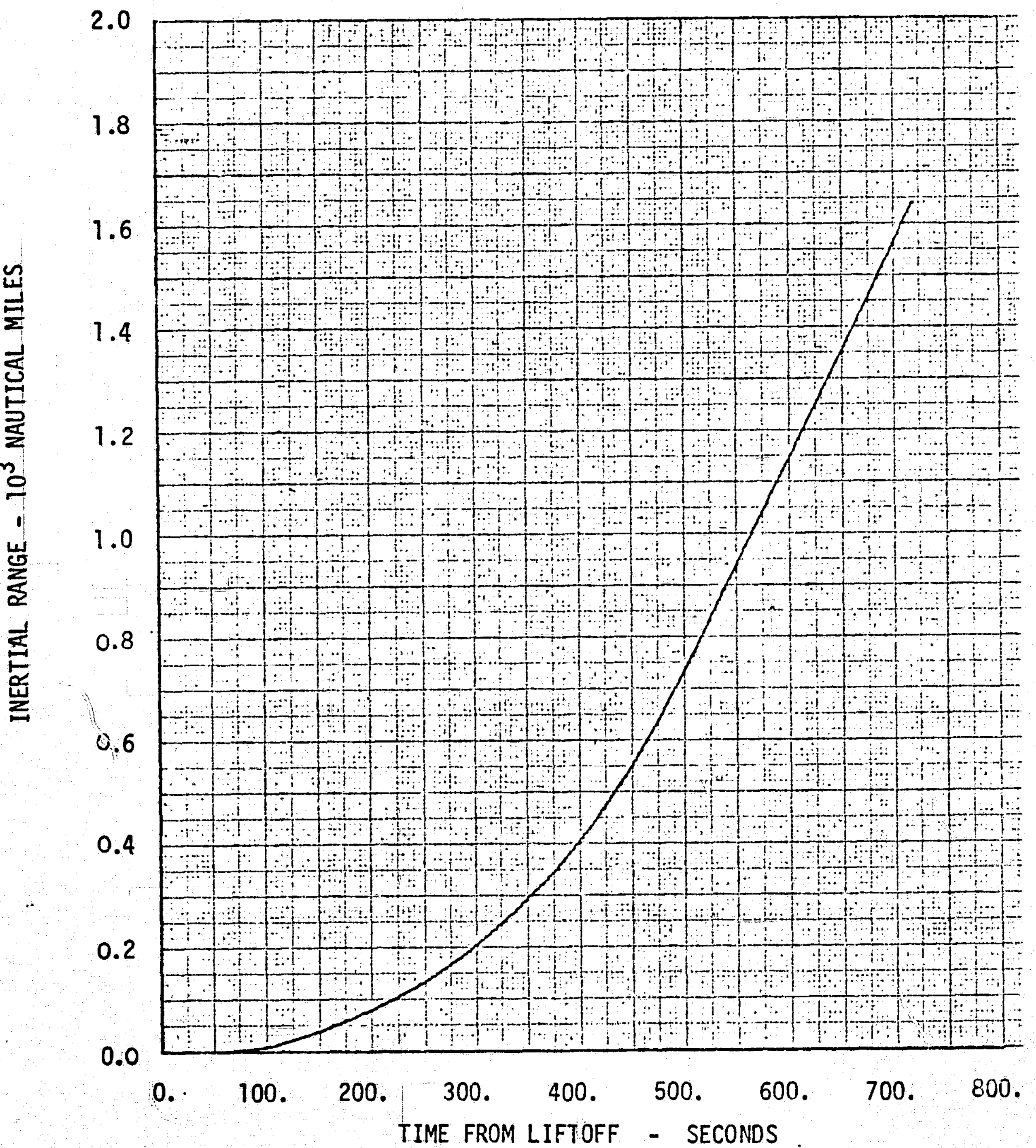


FIGURE 11 INERTIAL RANGE HISTORY

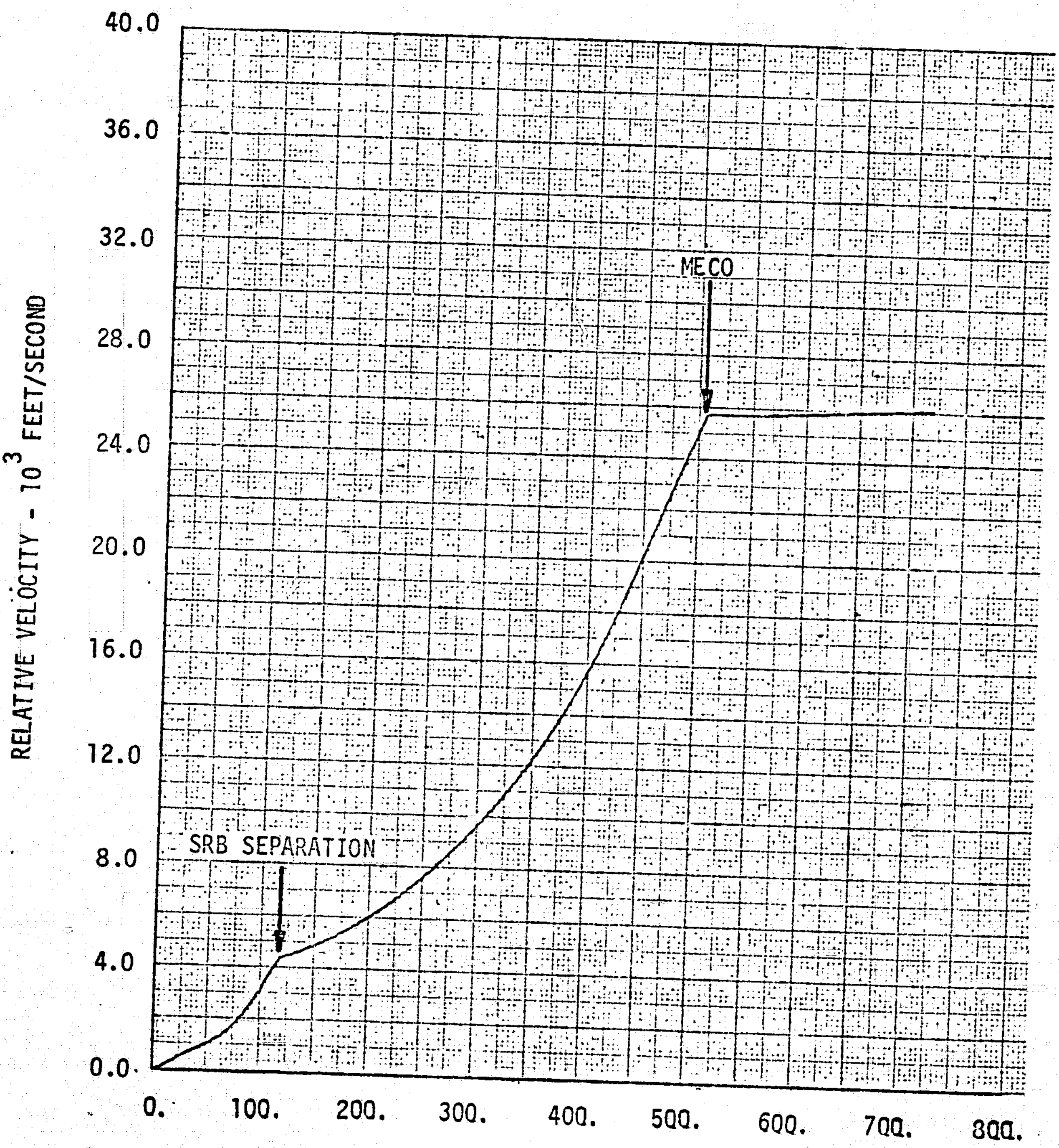


FIGURE 12 RELATIVE VELOCITY HISTORY

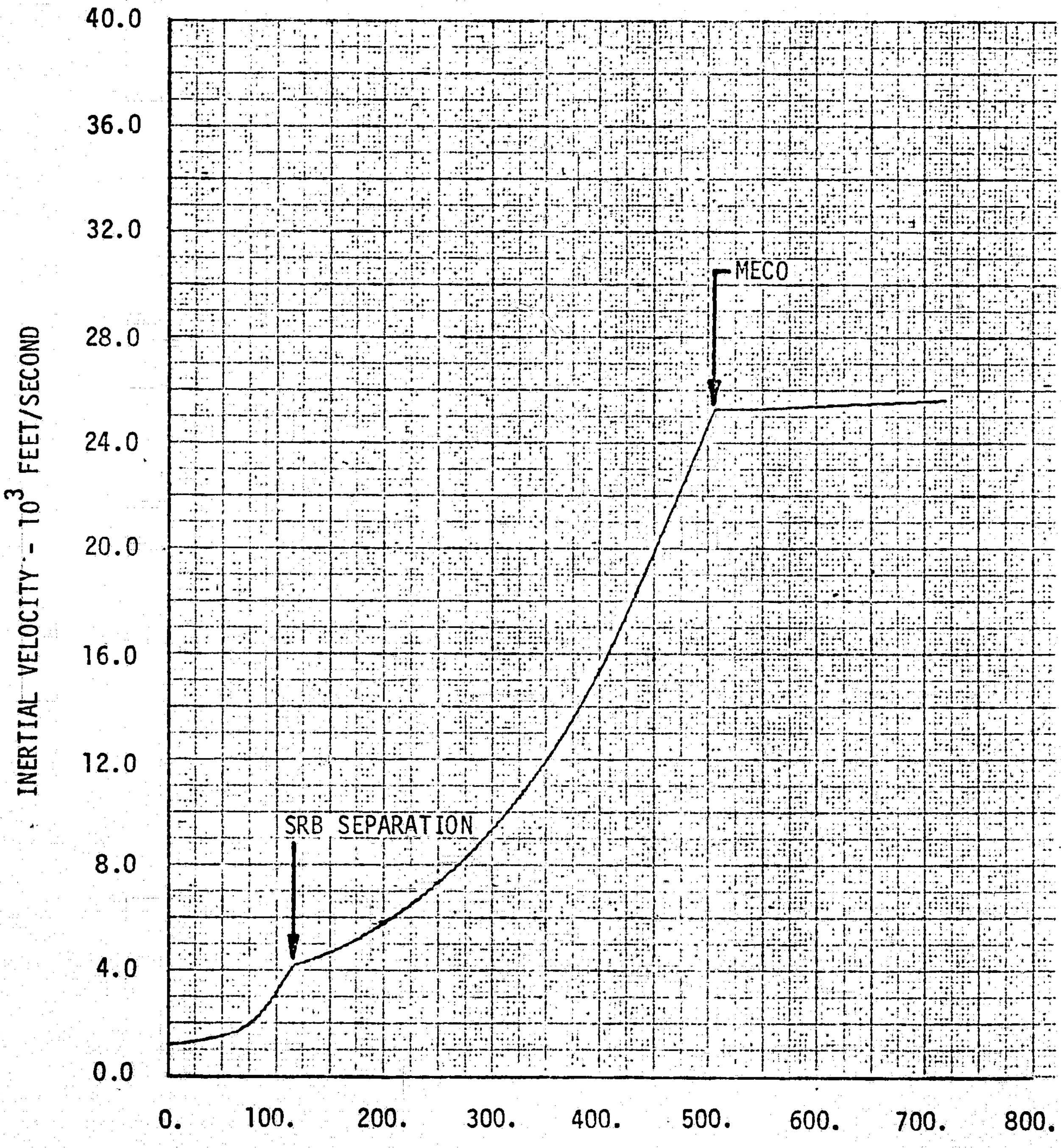


FIGURE 13 INERTIAL VELOCITY HISTORY

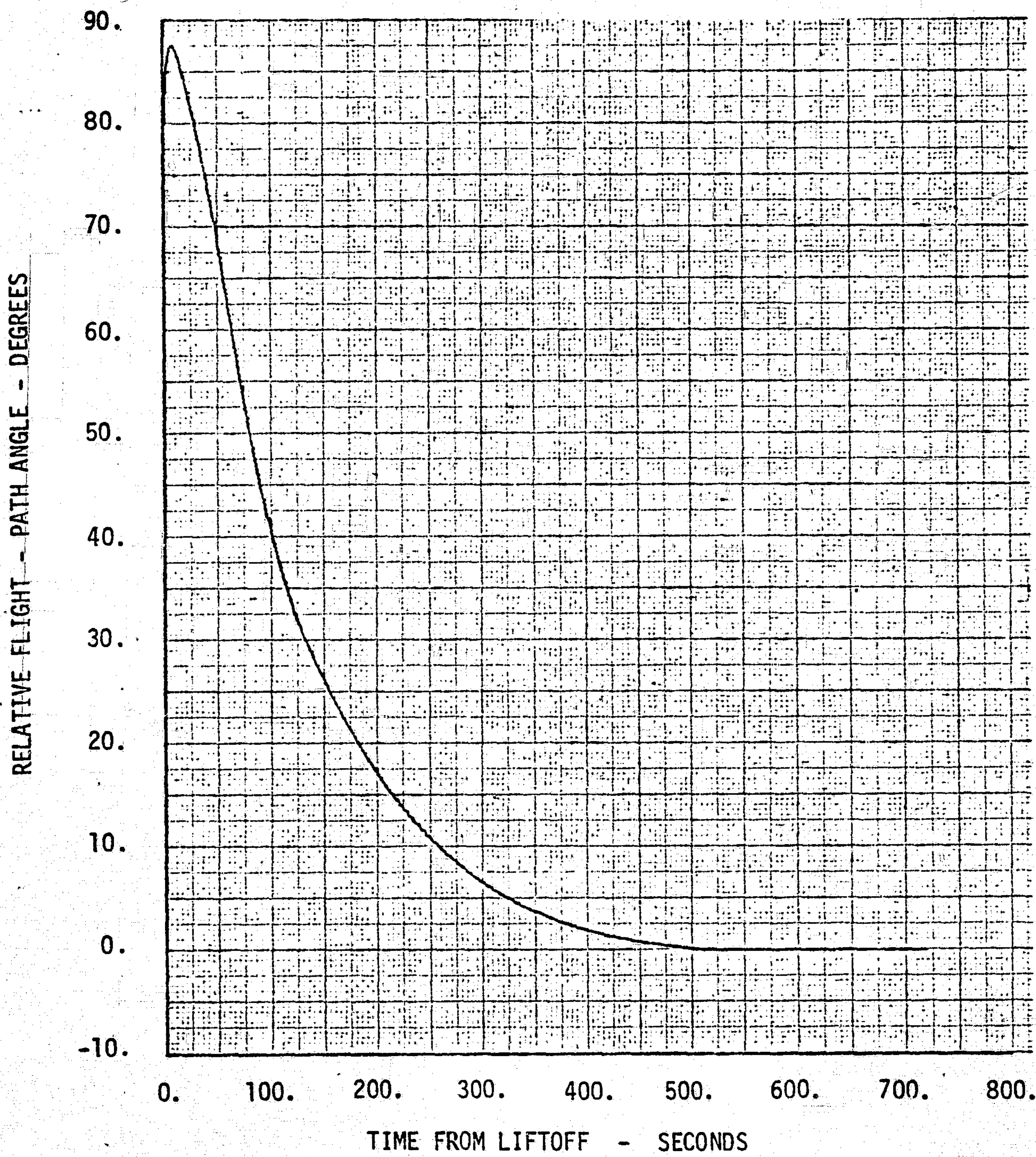


FIGURE 14 RELATIVE FLIGHT - PATH ANGLE HISTORY

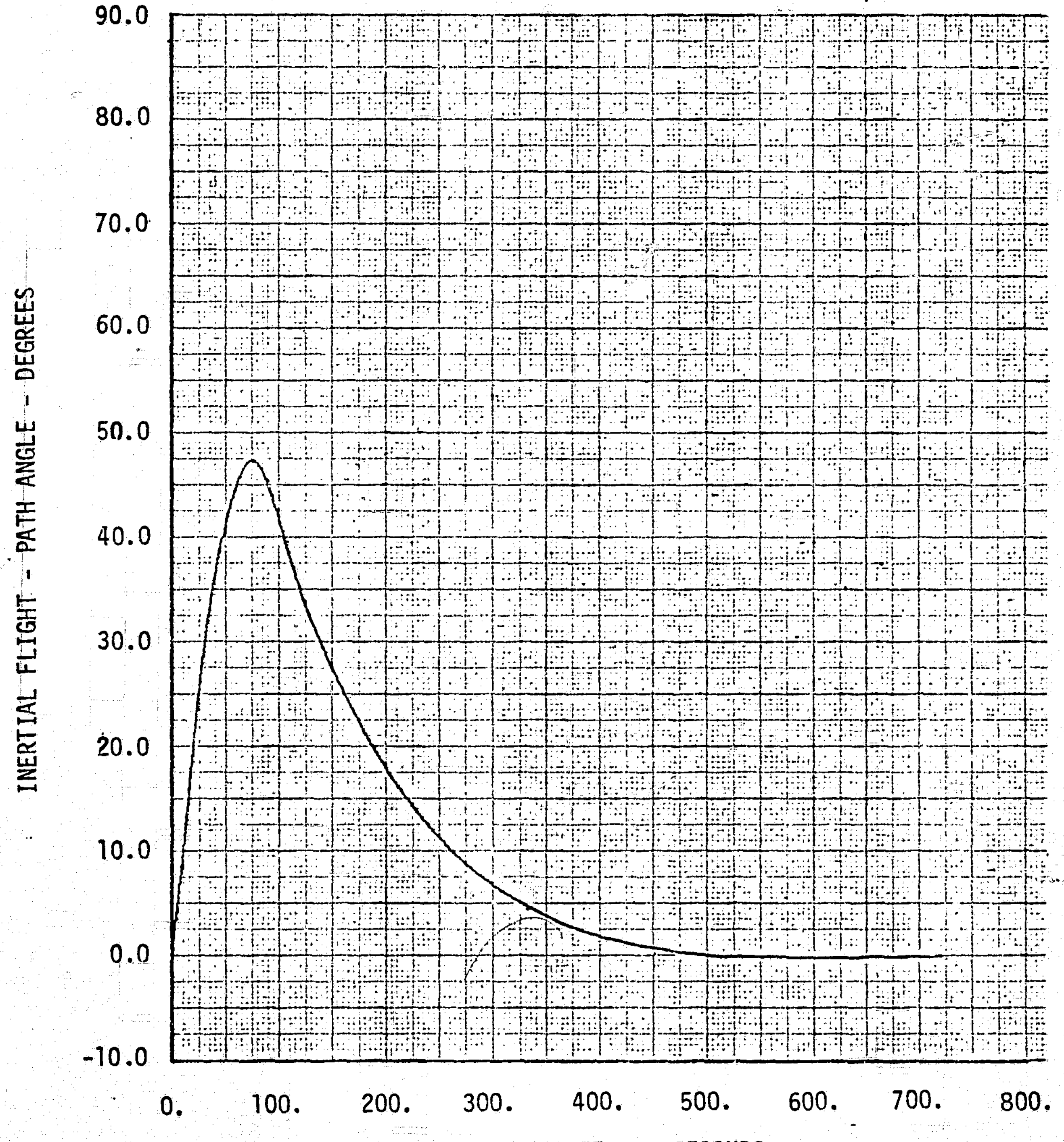


FIGURE 15 INERTIAL FLIGHT - PATH ANGLE HISTORY

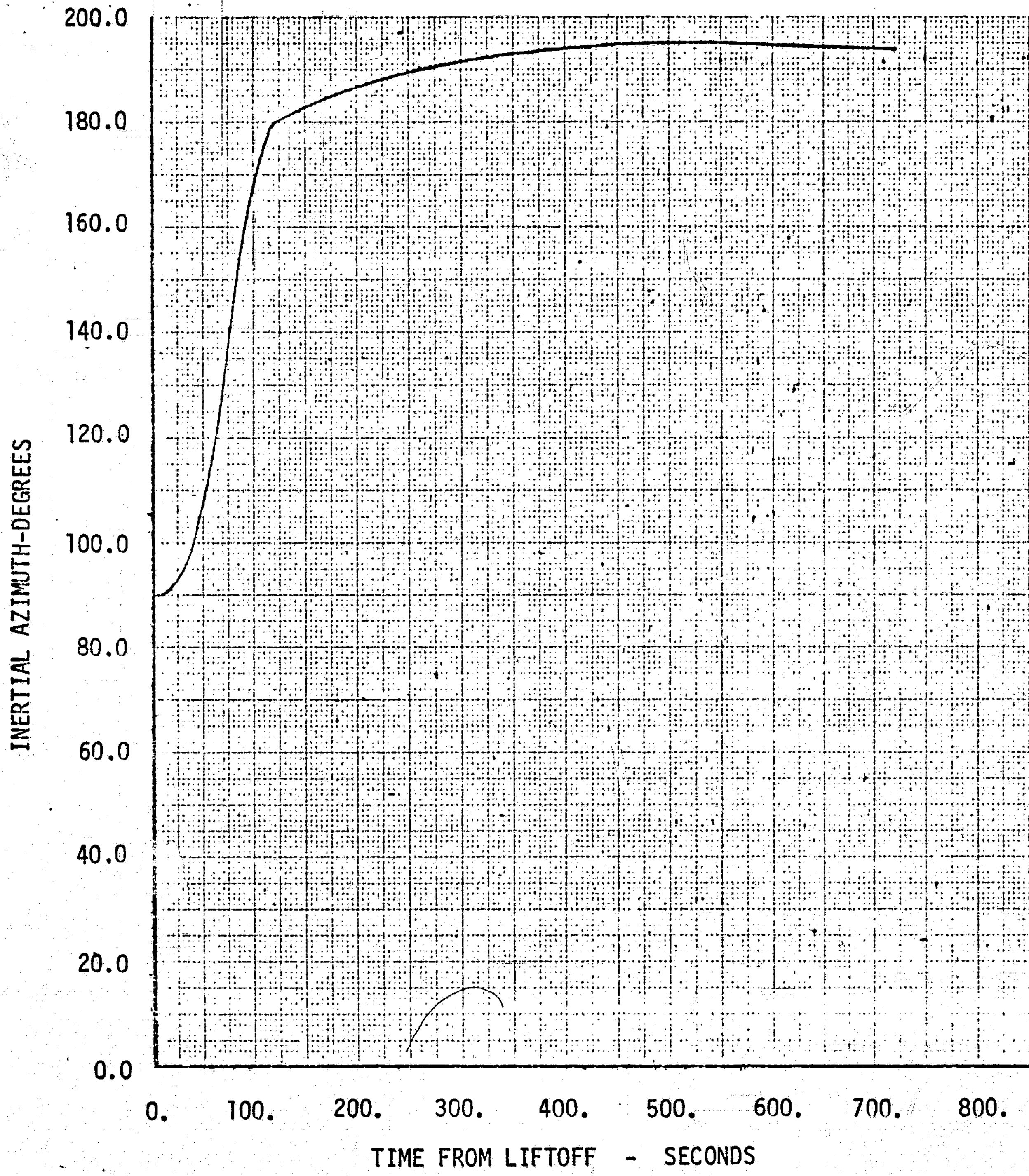


FIGURE 16 INERTIAL AZIMUTH HISTORY

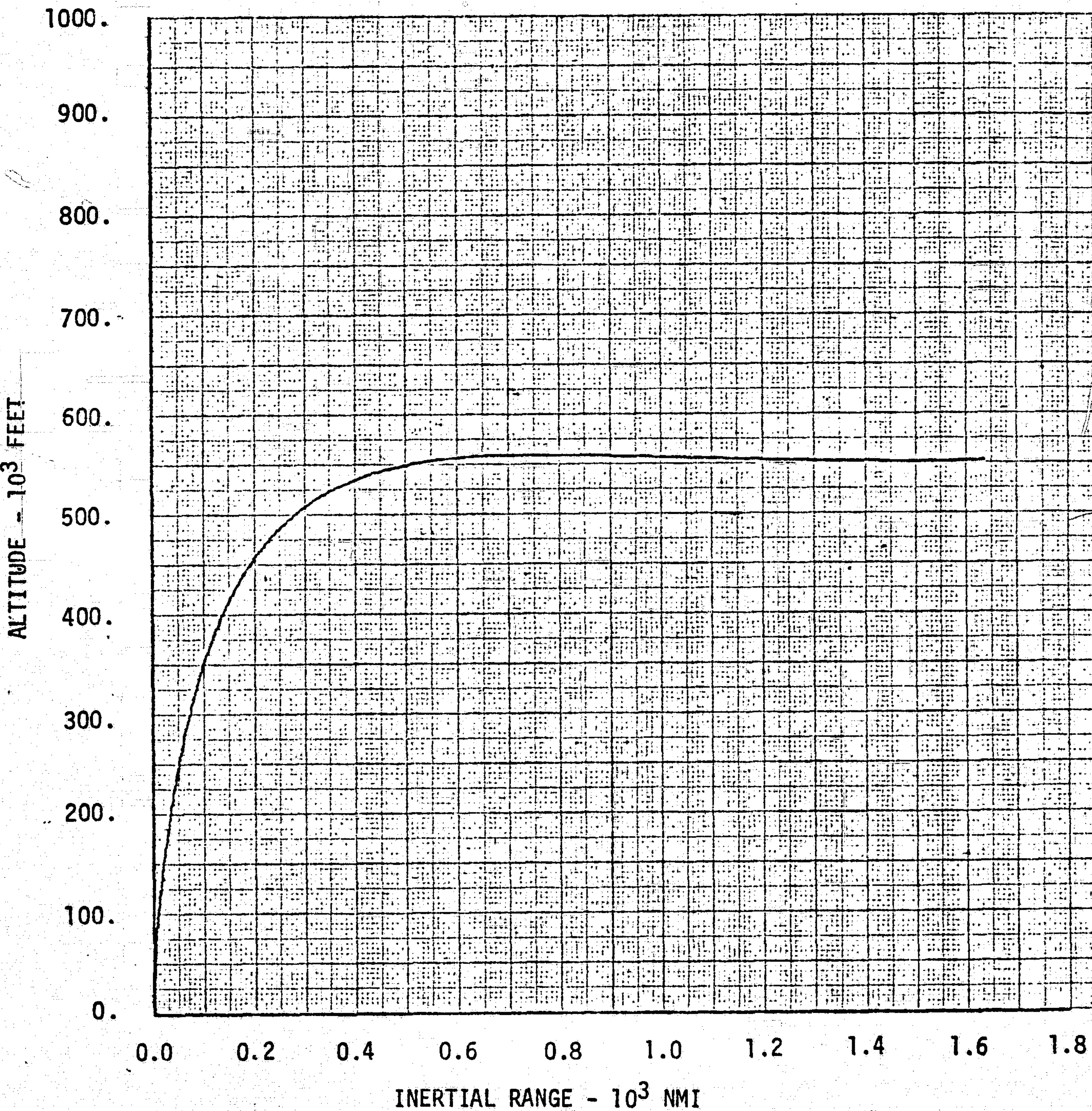


FIGURE 17 ALTITUDE AS A FUNCTION OF RANGE

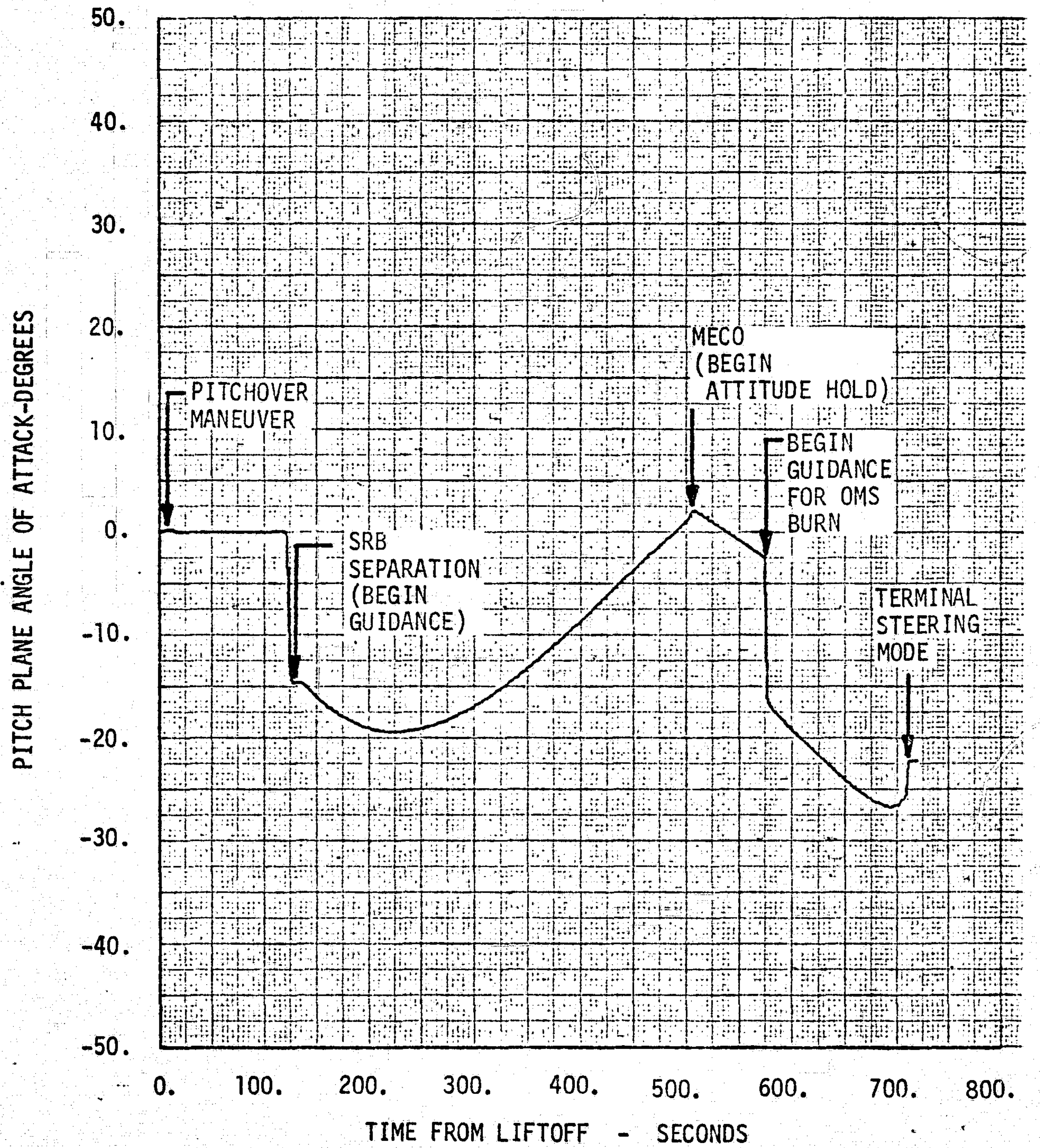


FIGURE 18 PITCH PLANE ANGLE OF ATTACK HISTORY

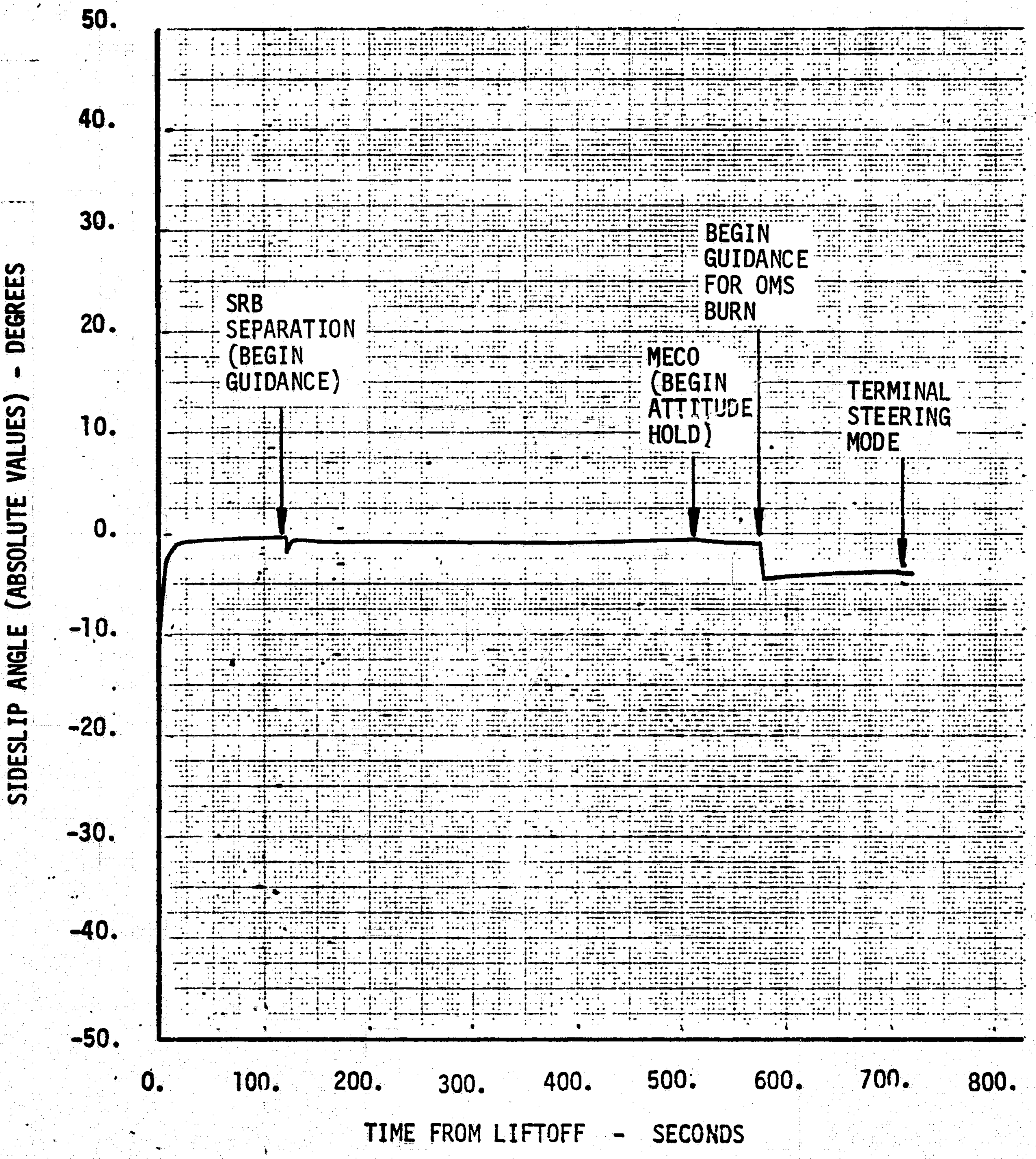


FIGURE 19 SIDESLIP ANGLE HISTORY

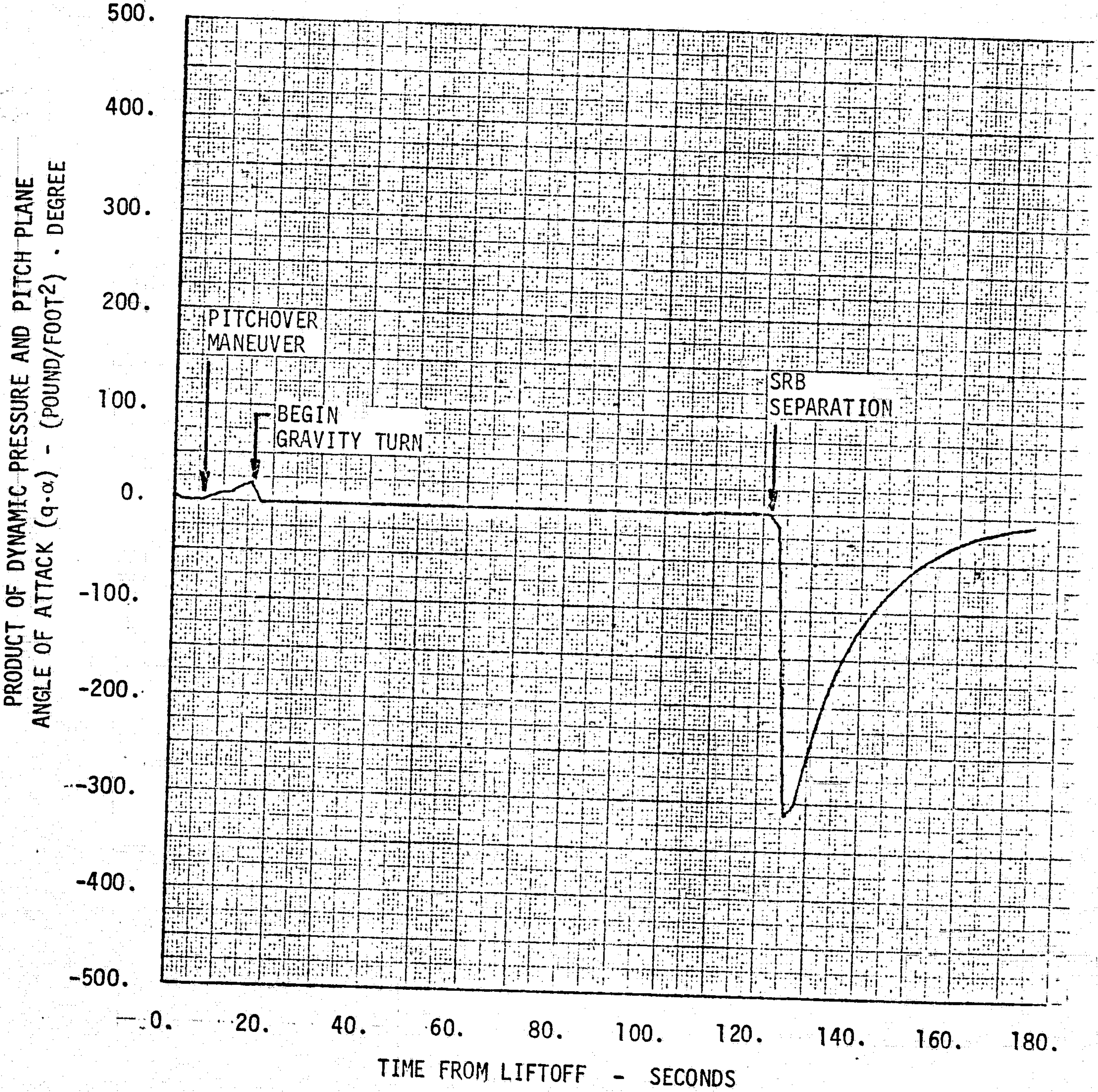
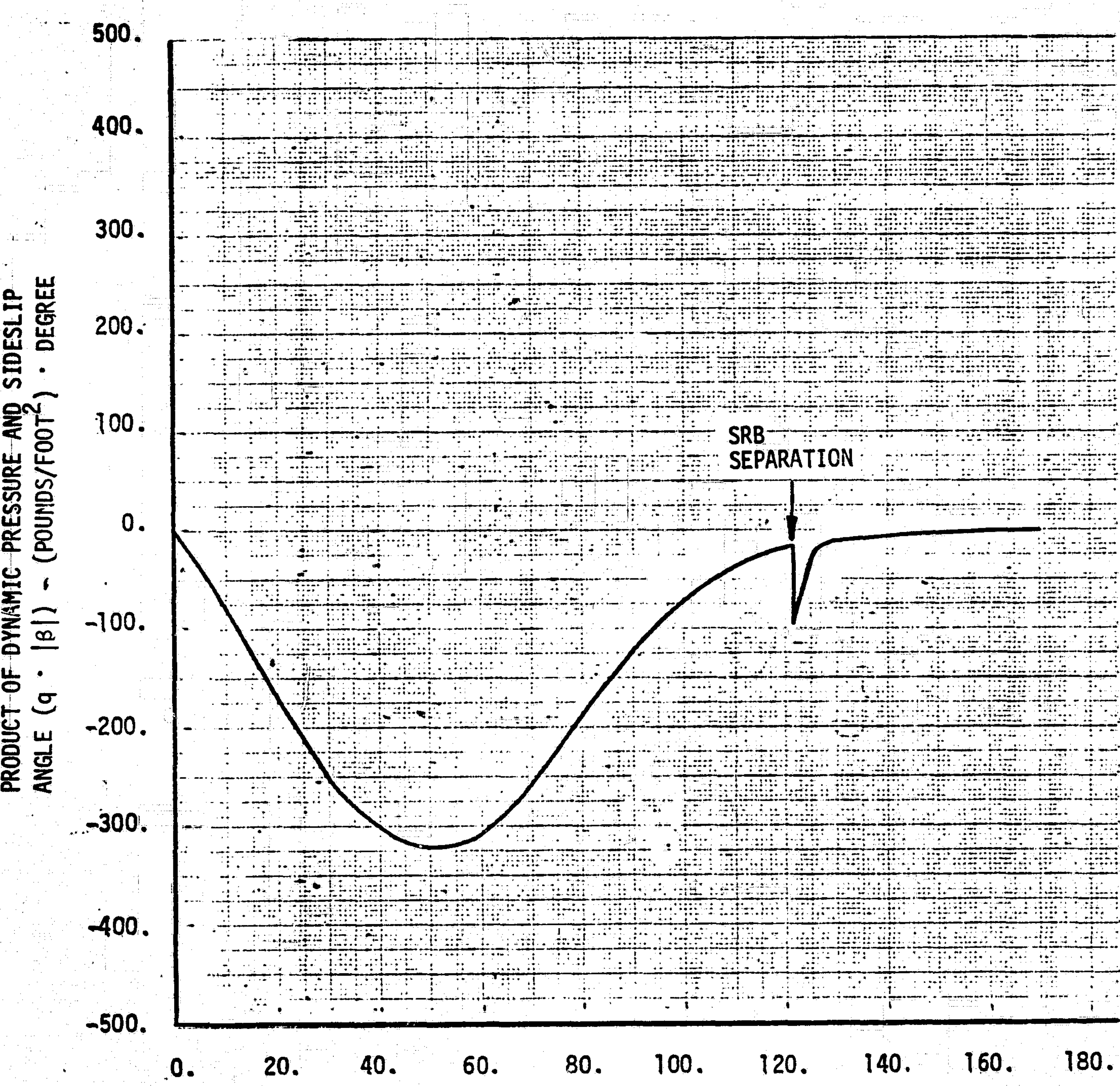


FIGURE 20 PRODUCT OF DYNAMIC PRESSURE AND PITCH PLANE ANGLE OF ATTACK



TIME FROM LIFTOFF - SECONDS

FIGURE 21 PRODUCT OF DYNAMIC PRESSURE AND SIDESLIP ANGLE

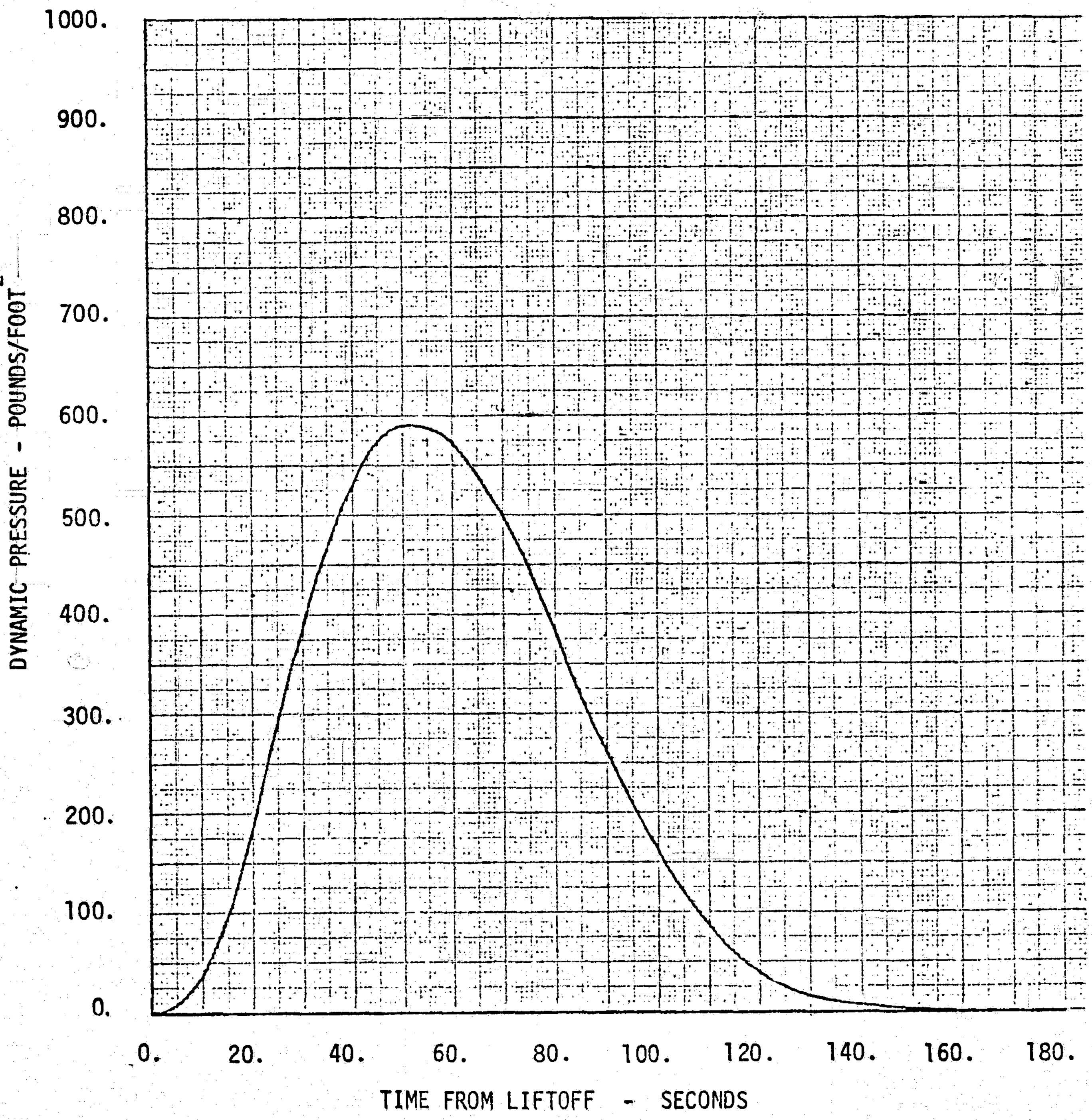


FIGURE 22 DYNAMIC PRESSURE HISTORY

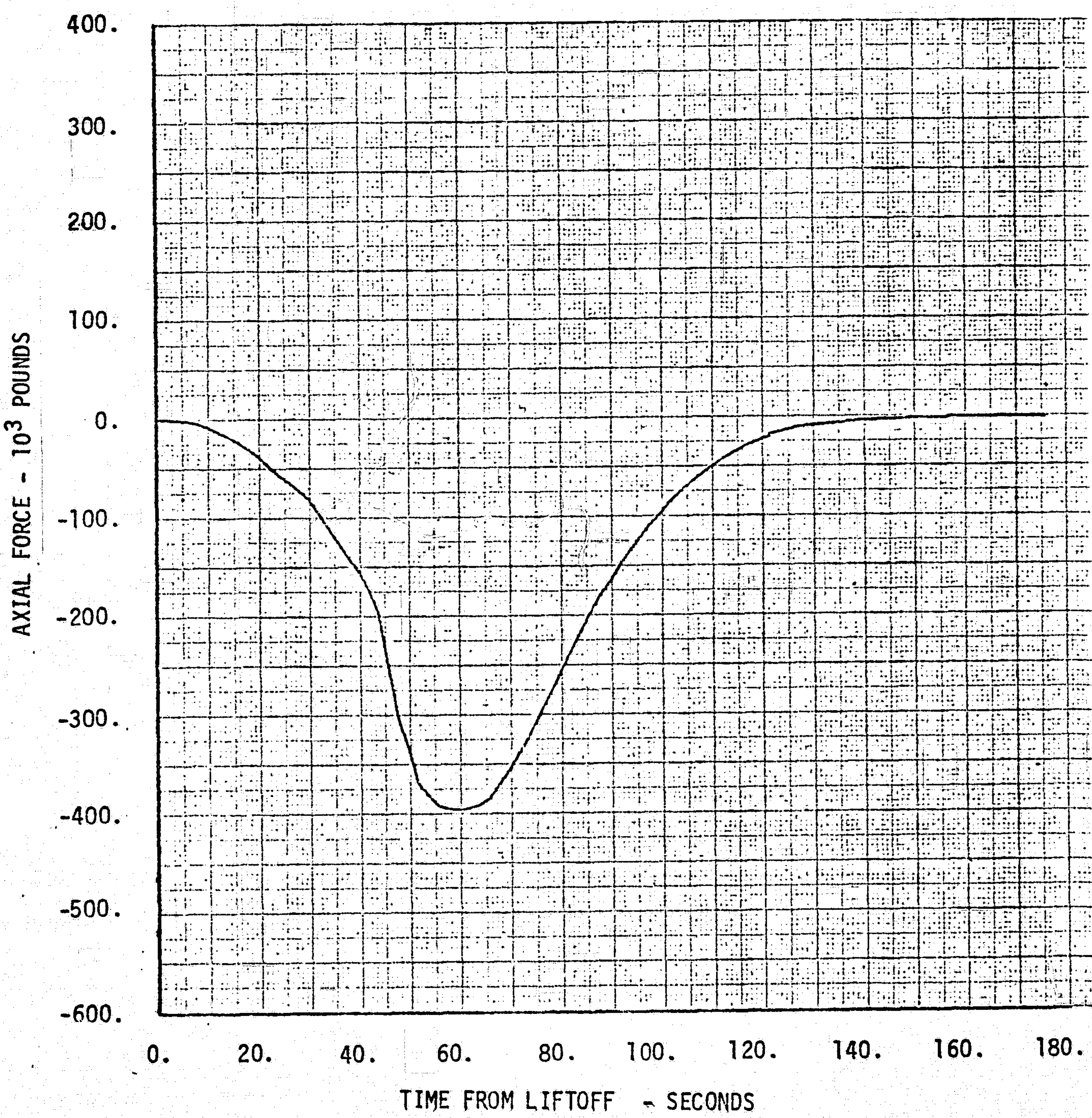


FIGURE 23 AXIAL FORCE HISTORY

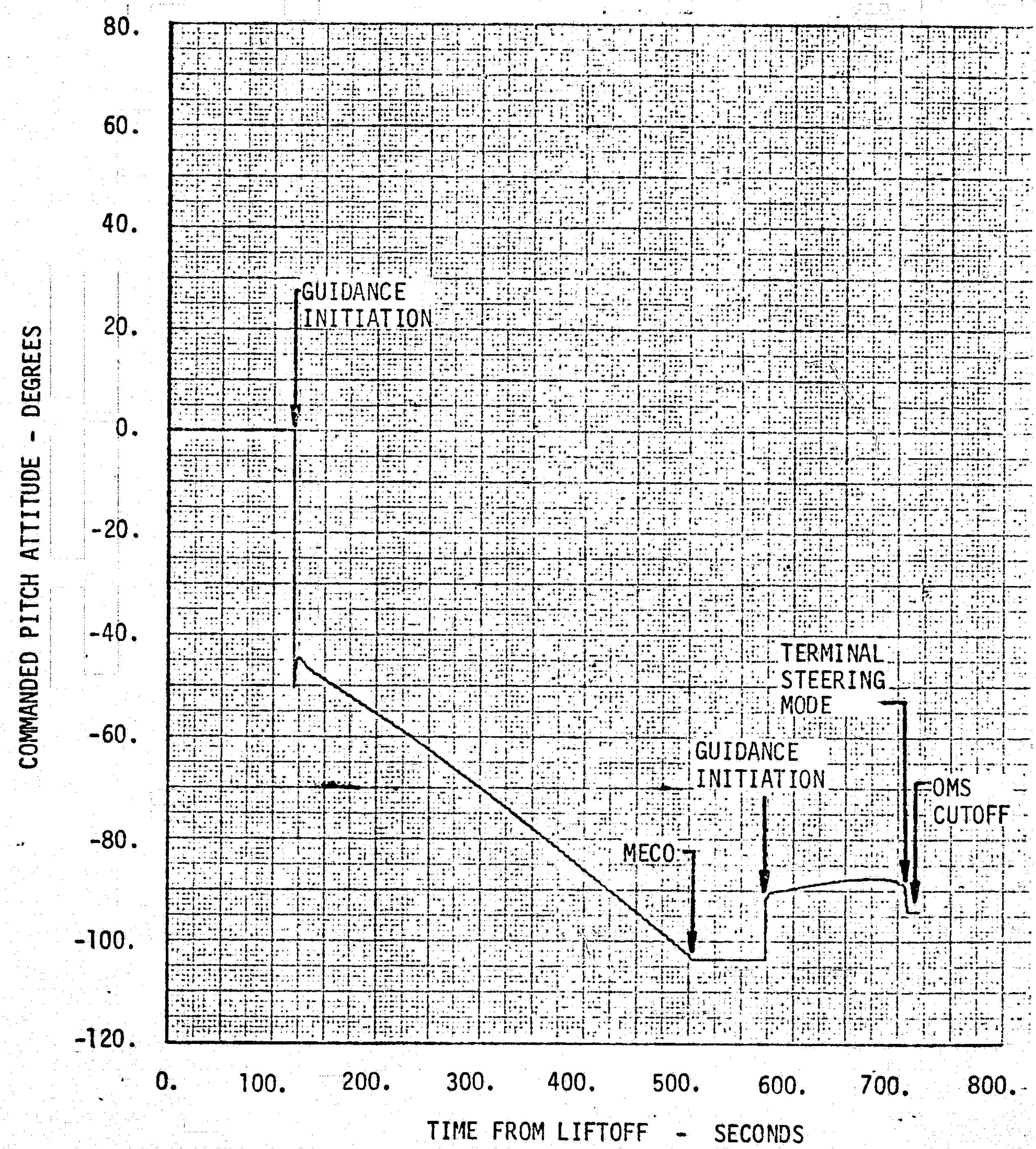


FIGURE 24 GUIDANCE COMMANDED PITCH ATTITUDE HISTORY

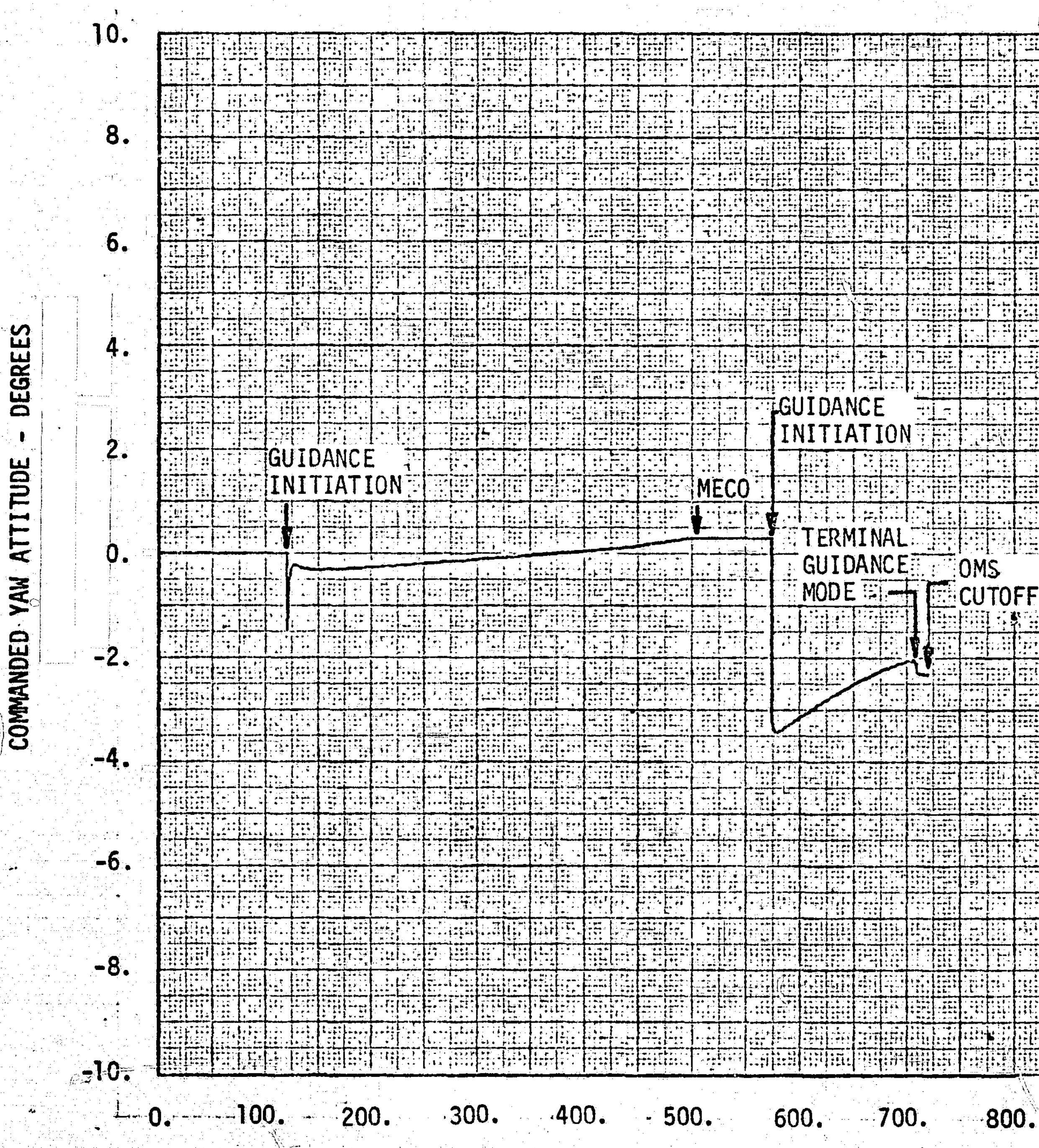


FIGURE 25 GUIDANCE COMMANDED YAW ATTITUDE HISTORY

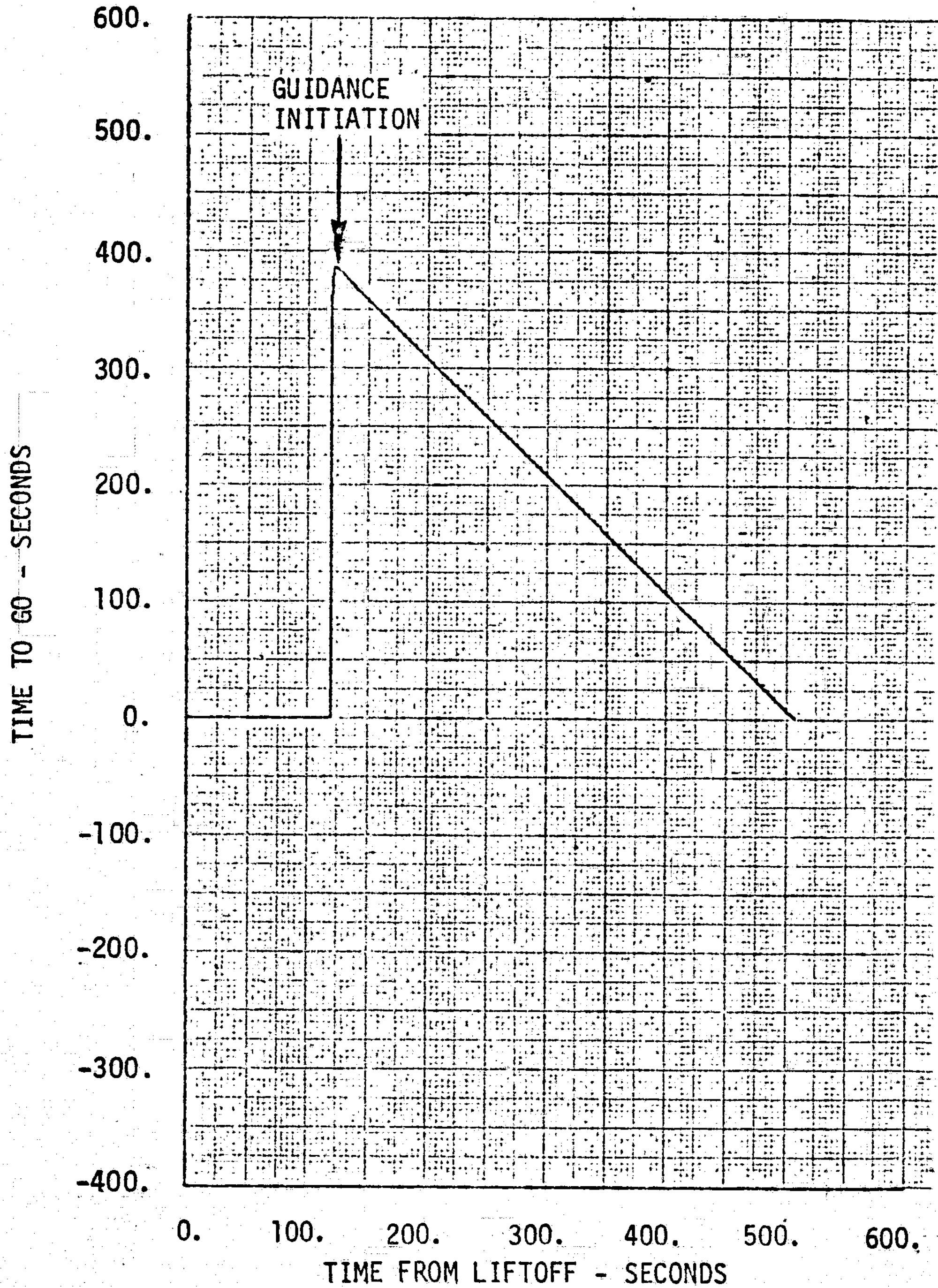


FIGURE 26 TIME TO GO HISTORY DURING BURN TO MECO

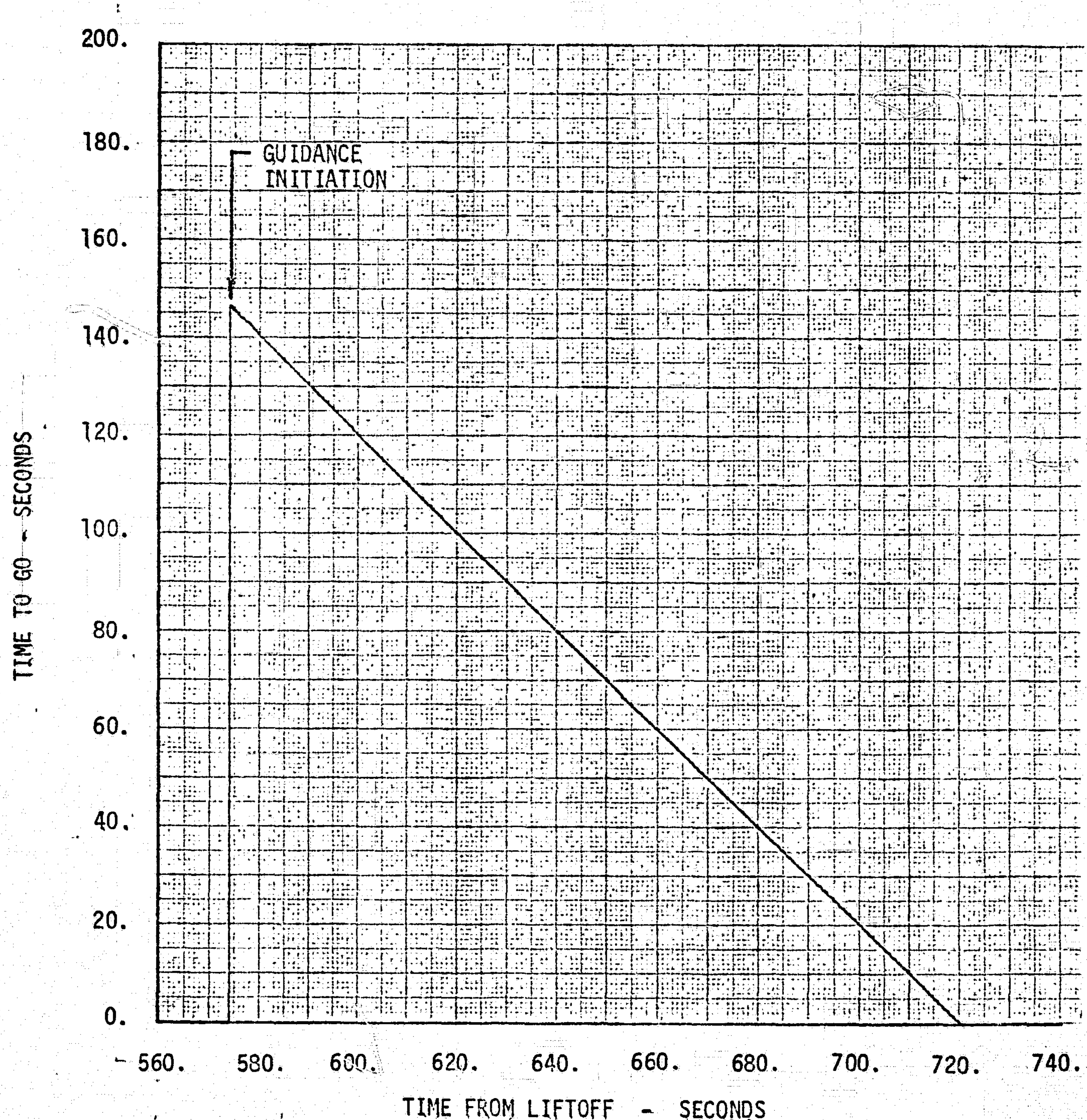


FIGURE 27 TIME TO GO HISTORY DURING OMS INSERTION BURN

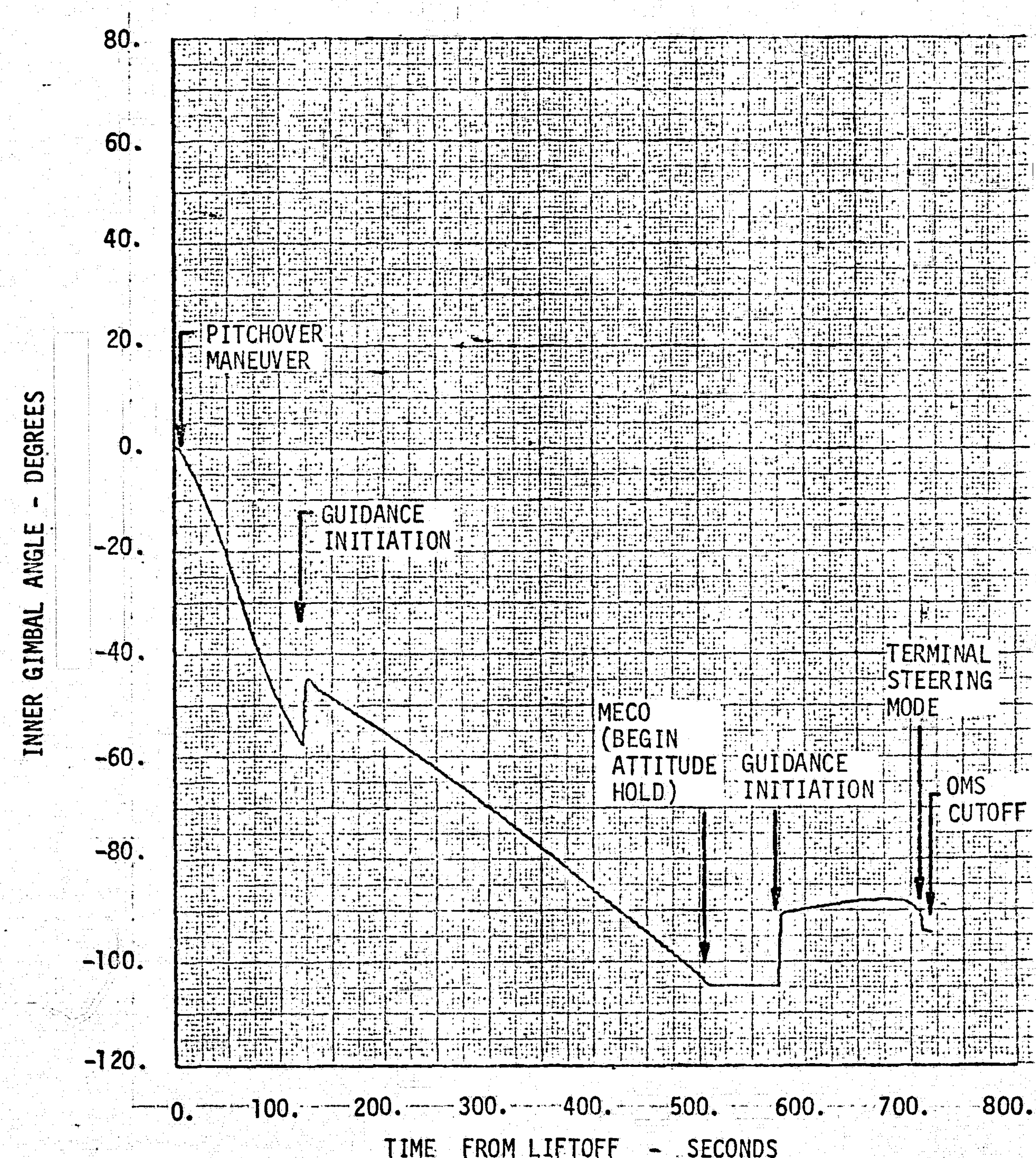


FIGURE 28 INNER GIMBAL ANGLE HISTORY

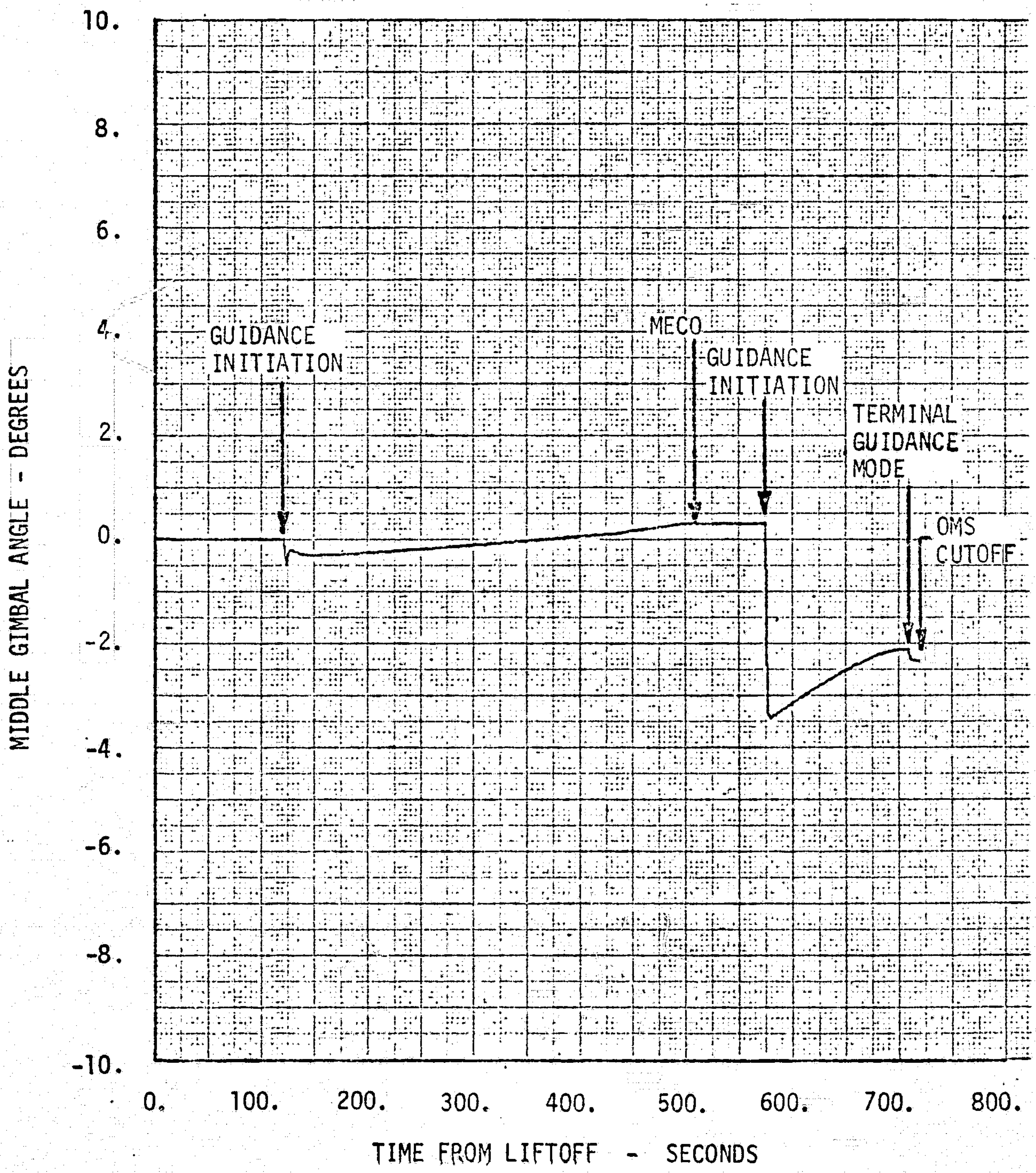


FIGURE 29 MIDDLE GIMBAL ANGLE HISTORY

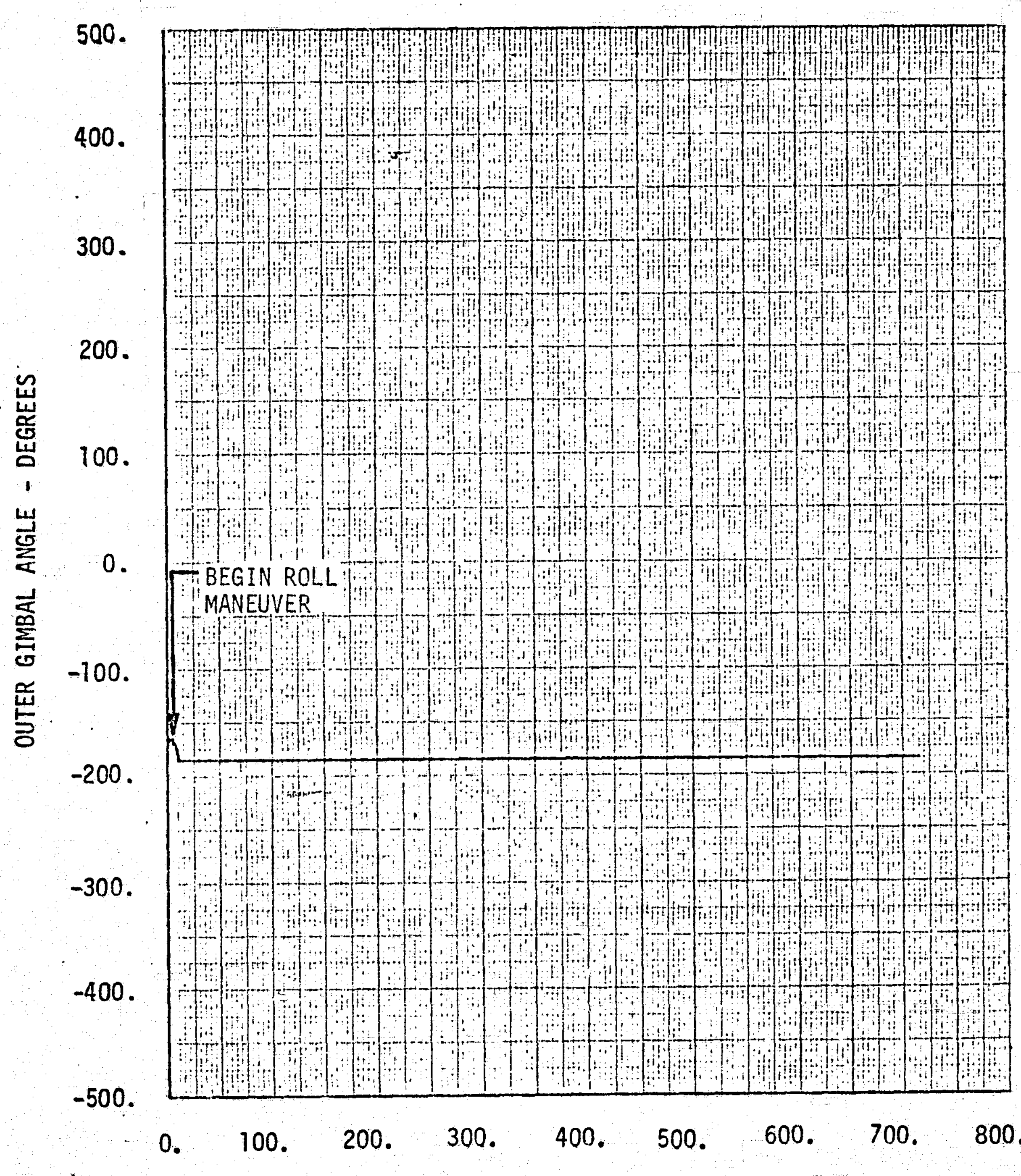


FIGURE 30 OUTER GIMBAL ANGLE HISTORY

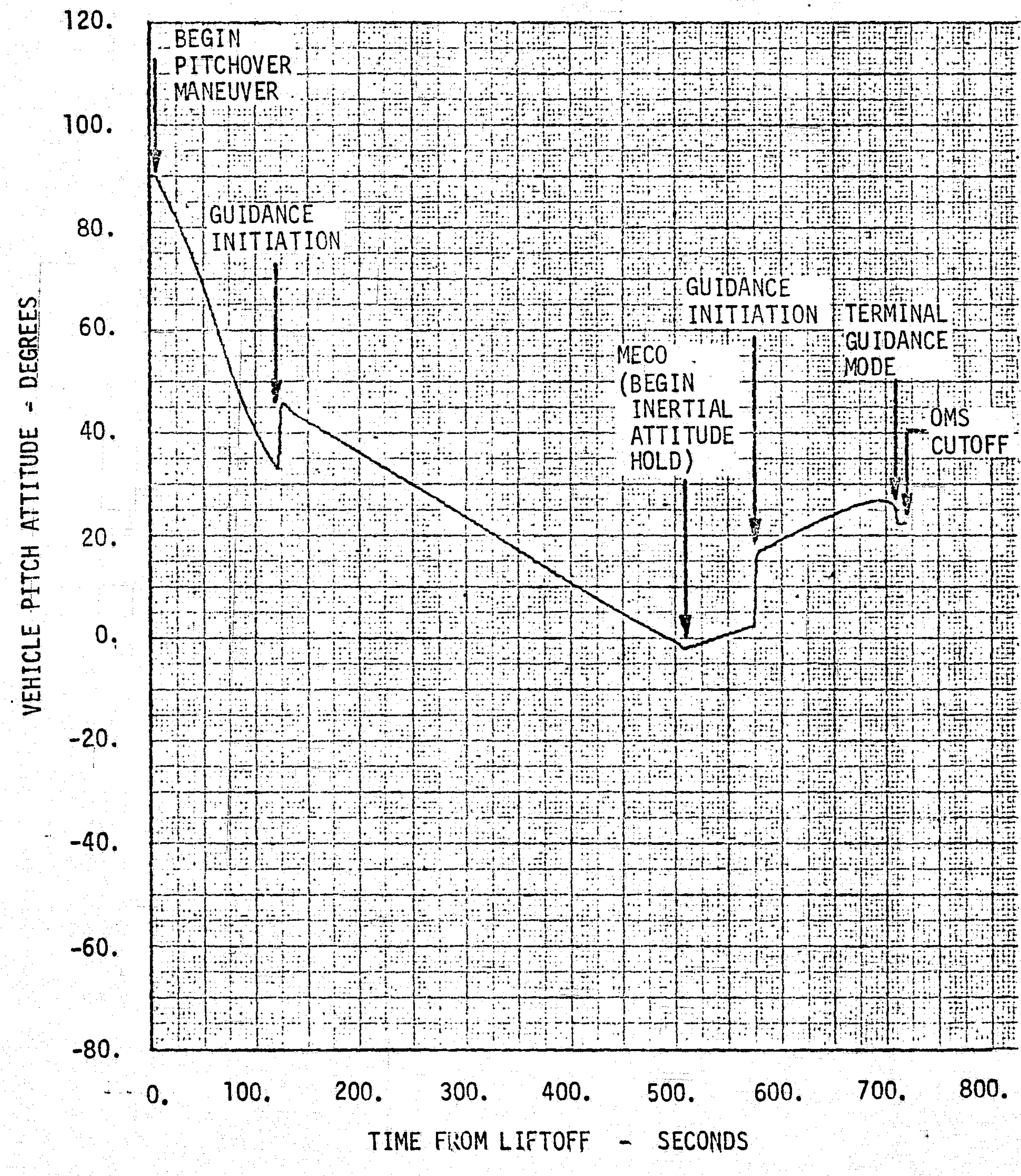


FIGURE 31 VEHICLE PITCH ATTITUDE HISTORY

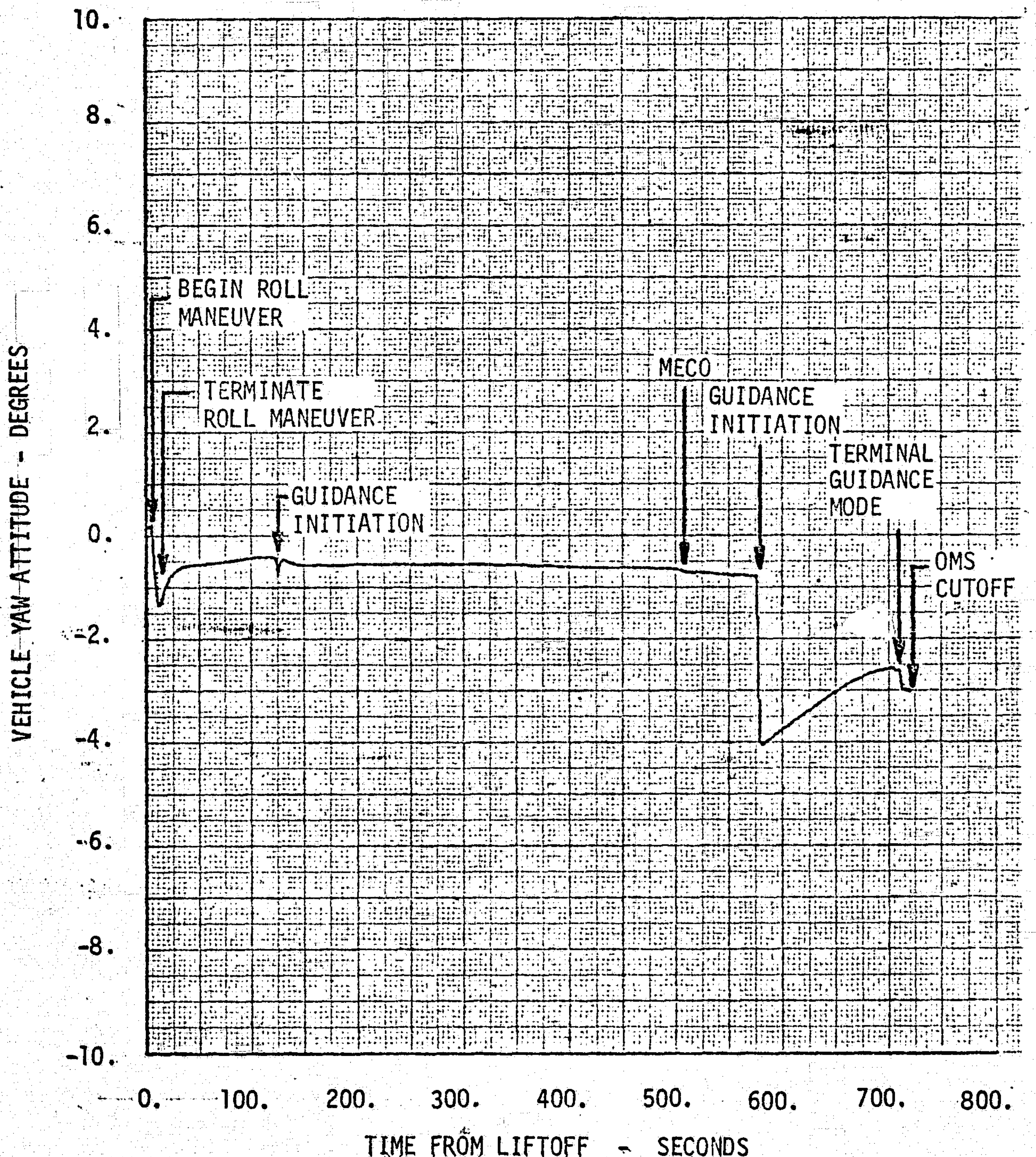


FIGURE 32 VEHICLE YAW ATTITUDE HISTORY

TABLE IV PARAMETER DEFINITION

Altitude	Vehicle altitude above the reference ellipsoid measured along the geodetic radius vector.
Atmospheric thrust	Vacuum thrust corrected for atmospheric pressure effects
Commanded pitch attitude	Guidance commanded attitude of the thrust vector projection onto the plumbline pitch plane- measured negatively from the vertical
Commanded yaw attitude	Guidance commanded attitude angle from the thrust vector projection onto the plumbline pitch plane to the thrust vector
Earth fixed coordinate system	An earth centered, rotating coordinate system with Z axis directed north, X-Y plane coincident with equatorial plane. X axis is coincident with Greenwich meridian and rotates with the earth.
Inertial azimuth	Angle from instantaneous meridian plane to the projection of the inertial velocity vector onto a plane perpendicular to the geocentric radius vector - positive from north to east
Inertial coordinate system	An earth centered, inertial coordinate system with Z axis directed north, X-Y plane coincident with equatorial plane. The X-Z plane is coincident with the launch meridian at liftoff.
Inertial flight-path angle	Angle between the inertial velocity vector and its projection onto a plane perpendicular to the geocentric radius vector
Inertial range	Surface range from instantaneous launch site position to current geocentric radius vector

TABLE IV PARAMETER DEFINITION (CONTINUED)

Inertial velocity	Velocity measured in the space-fixed coordinate system
Inner gimbal angle	Euler angle defining pitch orientation in the platform system (Roll, pitch, yaw sequence) NOTE: In this simulation the platform system is initialized to the plumbline reference system.
Middle gimbal angle	Euler angle defining yaw orientation in the platform system (Roll, pitch, yaw sequence)
Outer gimbal angle	Euler angle defining roll orientation in the platform system (Roll, pitch yaw sequence)
Pitch attitude angle	Angle from the local horizontal to the vehicle longitudinal axis projection onto the relative velocity vector, geocentric radius vector plane
Pitch plane angle of attack	Angle from the pitch plane component of relative velocity vector to the projection of the vehicle longitudinal axis into the pitch plane
Relative flight-path angle	Angle between the relative velocity vector and its projection onto a plane perpendicular to the geocentric radius vector
Relative velocity	Velocity measured in the earth-fixed coordinate system
Throttle setting	Ratio of actual atmospheric thrust to nominal (100%) atmospheric thrust
Time to go	Guidance determined prediction of time remaining before satisfying guidance target conditions

TABLE IV PARAMETER DEFINITION (CONCLUDED)

Sensed acceleration	Ratio of sum of all forces acting on the vehicle to the vehicle mass
Yaw attitude angle	Angle from the vehicle longitudinal axis projection onto the relative velocity vector, geocentric radius vector plane to the vehicle longitudinal axis

REFERENCES

1. NASA Memorandum FM72 (74 - 158),
   Mission 3B MECO Conditions Selection Trade Study, dated 4 September 1974.

2. NASA Memorandum FM13 (74 - 200),
   Space Shuttle Baseline Reference Missions Initialization Package,
   dated 23 October 1974

3. JSC Internal Note, Space Shuttle System Baseline Reference Missions,
   Volume III - Mission 3A and Mission 3B, Revision 2, to be released.

4. MDTSC Design Note, 1.4-7-2, Pitch Turning Rate During OMS Insertion Burn for
   Mission 3B, dated 31 January 1975.

5. JSC Memorandum FM13 (74 - 22) Mission Planning and Analysis Division
   Shuttle Data Tape Common Format, dated 11 February 1974.