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AN ENVELOPE OF SATURN V MALFUNCTION TRAJECTORIES WHICH CAN ACHIEVE ORBIT

TRW Systems Group and Flight Analysis Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
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PROJECT APOLLO

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MSC Task Monitor: C. T. Hyle

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NOMENCLATURE

CSM	command service module
EDS	emergency detection system
SLVS	Saturn launch vehicle simulation
OT	operational trajectory
SA	Saturn Apollo vehicle
S-IC	first stage of Saturn V booster
S-II	second stage of Saturn V booster
S-IVB	third stage of Saturn V booster
MSFC	Marshall Space Flight Center
V	inertial velocity
γ	inertial flight-path angle

AN ENVELOPE OF SATURN V MALFUNCTION

TRAJECTORIES WHICH CAN ACHIEVE ORBIT

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1. SUMMARY

Abort envelopes on the Flight Dynamics Officer's plotboards which provide an early warning of an impending abort situation are presented for the AS-503/CSM-103 launch trajectory. These abort envelopes represent the limit of the capability of a malfunctioning vehicle to attain a contingency orbit. The envelopes have been constructed so that there is negligible probability of the trajectory penetrating the envelope and then reaching a contingency orbit.

The specific malfunctions which were considered in defining the abort envelope are loss of inertial attitude reference, platform gyro drift, first and second stage engine actuator hardover, loss of X-axis accelerometer, failure of second stage engine to ignite, and premature shutdown of first stage engine. Abort limit lines, which represent the combined effects of these failures, are presented for the inertial flight-path angle versus inertial velocity (V-γ) and altitude versus range plotboards.

The baseline trajectory used in the production of this document was the June Mission D operational trajectory. Since there are only minor differences in the Apollo 8 (AS-503/CSM-103) launch trajectory, the information presented herein is intended for use during the Apollo 8 launch.

2. INTRODUCTION

The purpose of this investigation is to determine limit lines on the V-γ and altitude-range plots which provide the Flight Dynamics Officer with an early indication of an impending abort situation. These limit lines are derived by considering vehicle malfunctions which cause the trajectory to slowly diverge from nominal. Malfunctions which are directly monitored by the Emergency Detection System (EDS) and which cause an immediate abort situation are not considered here.

Vehicle malfunctions may be catagorized as follows:

a. Those which are monitored by the EDS and which lead to an immediate abort situation

b. Those which are monitored by EDS but which cause the booster to deviate slowly from the nominal trajectory

c. Those which are not monitored by the EDS

Since the present investigation is concerned with malfunctions which cause slow divergence from the nominal trajectory only the last two catagories are appropriate.

A previous investigation was made to determine the most critical* Saturn V malfunctions which were not monitored by the EDS (Reference 1). The data source for the study was Reference 2.

The feasibility of simulating the malfunctions in order to obtain meaningful abort limit lines was studied by using the TRW Saturn Launch Vehicle Simulation (SLVS) Program (Reference 3). The results of the feasibility study (Reference 4) indicated that malfunctions which lead to slowly divergent trajectories could be identified, and the resulting limit lines would provide the Flight Dynamics Officer with an early indication of an impending abort situation.

In defining the abort limit lines, it is assumed for the purpose of this investigation, that a successful contingency orbit is attained provided the following criteria are met.

a. The present abort limits on structural breakup, time of free-fall and limit g-loads must not be violated.

b. The actual orbital insertion altitude must be within 10 nautical miles of that specified by the operational trajectory (OT).

c. The inertial flight-path angle at orbital insertion must be within two degrees of that specified by the OT.

Since there are only minor differences in the Apollo 8 (AS-503/CSM-103) launch trajectory, the information presented herein is intended for use during the Apollo 8 launch.

*Critical and criticality in this investigation are defined as (1-Reliability) x 10^6 in keeping with Reference 2.

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3. MALFUNCTION SIMULATION RESULTS

Rather than consider only non-EDS malfunctions, the scope of the malfunctions to be considered in defining the abort limit lines has been enlarged in the present investigation to include all malfunctions which may lead to a slowly divergent trajectory. The booster malfunctions which are considered are presented in Table 1, together with the effect and criticality numbers associated with each failure. This malfunction information includes only those failures which are the top 10 single point failures per stage (Reference 2). The total flight criticality of the SA-502 booster (assumed to be the same for the SA-503) is 75,483 (Reference 2). The total criticality of the malfunctions presented in Table 1 is 19,111, or 25.6 per cent of the total criticality. The remaining 74.4 percent of the criticality is associated with malfunctions which are monitored by EDS and which result in sudden failure of the booster. The SLVS program can realistically simulate malfunctions indicated by an asterisk in Table 1 which have a criticality of 16,852 or 22.6 percent of the total flight criticality. The other malfunctions presented in Table 1 cannot be simulated directly; however, the effect of a battery failure, for instance, will result in loss of guidance which can be simulated. Most of the malfunctions which may lead to slowly divergent trajectory can be simulated, so they are considered in defining the abort limits lines.

A previous study for the S-IB configuration (Reference 5) indicated that not all the malfunctions in Table 1, which could be simulated, are active in defining the abort limit lines. Several of the malfunctions result in either rapid loss of control or a trajectory which is so close to nominal that it is not active in defining the abort limit lines. On the basis of Reference 3, the following malfunctions are considered in the present study:

a. Loss of inertial attitude reference

b. Inertial platform gyro drift

c. First stage actuator hardover

d. X-axis platform accelerometer failure

In addition, the following malfunctions, which are applicable to Saturn V launches, are considered:

e. Second stage actuator hardover

f. S-II engine out

g. S-IC engine out

The malfunction simulations were performed by using the TRW Saturn Launch Vehicle Simulation (SLVS) Program (Reference 3). The nominal trajectory as determined from SLVS is compared to the operational trajectory for AS-503 (Reference 6). It is concluded that the SLVS program has adequately simulated the AS-503 vehicle control dynamics and guidance during the launch phase from lift-off to earth orbit insertion (Reference 6). The trajectory simulation includes the wind-biased trajectory together with the mean December-to-March launch winds. Trajectory dispersions due to wind have not been considered in this study.

A discussion of the individual malfunction simulation results is presented in Sections 3.1 through 3.7. The composite abort limit lines are presented in Section 4.

3.1 X-Axis Platform Accelerometer Failure

This malfunction results from failure of the ST-124-M2 inertial platform accelerometers which are integrated to determine the vehicle velocity. If the velocity word fails to satisfy a preset reasonableness test, the guidance system switches to a backup mode for calculating velocity using tabulated values of vehicle thrust and mass versus time.

The failure simulation using tabulated thrust and mass from the OT results in an almost nominal trajectory; thus, this failure is not active in defining the abort limit line.

3.2 Platform Gyro Drift

This malfunction results from failure of the pressure regulator which supplies gaseous nitrogen to the bearings of the inertial platform. The off-nominal pressure induces bearing friction which leads to gyro drift.

It was found that ± 7 degree per hour pitch drift is the maximum which results in an off-nominal trajectory which satisfies the altitude criterion. This malfunction is active in defining the abort limit lines on both the V-γ and altitude-range plots.

3.3 Loss of Inertial Attitude Reference

This malfunction results from failure of the ST-124-M2 inertial platform. The guidance system continues to compute guidance commands based on the last values of measured attitude error which satisfy a preset reasonableness test. Since guidance continues to compute, a contingency orbit cannot be achieved unless either the failure occurs late in the flight or the errors which ar frozen are such that, by chance, orbital insertion is attained.

In the present study, this malfunction is active in defining the abort limit lines for times late in the flight.

3.4 First Stage Pitch Actuator Hardover

This malfunction results from the failure of a thrust vector control subsystem servo actuator in the fully extended or fully retracted position which causes the engine to go to its fully deflected position of 5.15 degrees. The vehicle will pitch-up for pitch actuators fully extended on engines 1 and 4 and fully retracted actuators on engines 2 and 3.

The failure was simulated on engine 1 at lift-off and the resulting trajectory is active in defining the abort limit line.

3.5 Second Stage Pitch Actuator Hardover

This failure is not presented as one of the top 10 criticality items per stage in Reference 2; however, because of the importance of first stage actuator hardover in defining the abort limit lines, failure of the second stage actuator was considered. The results of the simulation study indicate that this failure does not contribute to the abort envelope.

3.6 S-II Engine Out at Ignition

This failure may be due to one of the following malfunctions:

a. "Static-inverter in no output, distorted output, and low output" mode

b. "Gas generator combuster assembly in the check valve fails to open" mode

c. "Turbopump assembly in fails to start" mode

d. "Gas generator control valve assembly in fails to open on demand" mode

e. "Ignition phase solenoid operated control valve in fails to actuate" mode

f. "Main oxidizer valve assembly in all failure" modes

g. "Mainstage solenoid operated control value in fails to actuate when energized" or "Closes during engine operation prior to engine start" modes

This malfunction is simulated at time of second stage ignition, and is found to be active in defining the abort limit lines.

3.7 S-IC Engine Out

This failure would result from a premature closure of the gas generator control valve. The malfunction was simulated by shutting engine 1 down at 3, 11, 60, and 74 seconds and engine 2 at 60 seconds after engine ignition. The simulation accounted for the chi-freeze initiation times and durations as presented in the OT. The V-γ and altitude-range plots comparing simulation results from the SLVS program with results obtained from Marshall Spaceflight Center (MSFC) for malfunctions at 3 and 60 seconds are shown in Figures 1 and 2, respectively. The SLVS and MSFN data are in qualitative agreement. The difference is attributed, at least in part, to the fact that the MSFC simulation is for the Apollo 6 booster while the simulation in the present investigation is for the D mission. The malfunction causes a large excursion from nominal on the V-γ and altitude-range plots and is active in defining the abort limit lines. The V-γ and altitude-range plots for engine 1 out at 11 and 74 seconds and engine 2 out at 60 seconds are not presented since these malfunctions are not active in defining the abort limit lines.

4. CONTINGENCY ORBIT ABORT ENVELOPES

The contingency orbit abort envelope for Saturn V launches has been determined by simulating the trajectory of a malfunctioning vehicle with the TRW Saturn Launch Vehicle Simulation Program. In this study, nominal vehicle properties such as mass, thrust, center-of-gravity location, control system constants, etc., have been used. The control system is biased for a mean December-to-March wind, and the mean wind is included.

The V-γ and altitude-range plots are shown in Figures 3 and 4, respectively with the malfunctions which are active in defining the abort limit lines.

a. S-IC pitch actuator pitch-up and pitch-down

b. S-IC engine out at 60 seconds (composite of MSFC and TRW simulations)

c. S-II engine out at S-II ignition

d. Loss of inertial attitude reference

The malfunctions which are active in defining the abort limit lines on the altitude-range plot are:

a. S-IC pitch actuator pitch-up

b. S-IC engine out at 60 seconds (MSFC simulation)

c. S-II engine out at S-II ignition

d. Platform gyro drift

The composite abort limit lines on the V-γ and altitude-range plots are presented in Figures 5 and 6, respectively. The current abort limits (Reference 7) are shown in Figure 5 for purpose of comparison. It can be seen that the abort limit lines based on capability of a malfunctioning booster to reach a contingency orbit provide the Flight Dynamics Officer with much earlier abort cue than the current limit lines.

The abort limit lines presented in the previous figures are based on nominal boost vehicle and environmental properties. It is obvious that the trajectory envelope formed by the abort limit lines would be wider if the statistical variation of vehicle and environmental properties was considered.

The statistical variations are accounted for in the present investigation by algebraically adding the nominal dispersion in the flight parameters to the abort limit lines presented in Figures 5 and 6. This modification of the abort limit lines is shown in Figures 7 and 8 for the V-γ and altitude-range plots, respectively.

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5. CONCLUSIONS AND RECOMMENDATIONS

Abort limit lines have been determined on the Flight Dynamics Officer's V-γ and altitude-range plot boards. These limit lines represent the limit of the capability of a malfunctioning boost vehicle to achieve a contingency orbit. The purpose of the abort limit lines is to provide the Flight Dynamics Officer with an early indication that a vehicle which is slowly diverging from a nominal trajectory will not reach a contingency orbit.

The curves presented in Figures 7 and 8 include the effect of vehicle malfunctions and dispersions. It is recommended that consideration be given to incorporating these curves on the Flight Dynamics Officer's V-γ and altitude range plotboards for use as an early abort cue.

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6. White, J. J. : Updated AS-503 N-Stage Milestone Trajectory. TRW IOC 68.3351.14-5, September 12, 1968.

7. Charters, P. M. : Launch Phase Flight Dynamics Displays for Mission D/CSM-103/LM-3 Simulations. TRW Letter 68.3423.8-19, August 26, 1968.

Table I. Malfunctions Applicable

Malfunction	Failure Effect	Total Criticality
Inertial platform failure*	Loss of inertial attitude or inertial velocity signals	4495
S-IVB APS bladder failure*	Loss of one S-IVB APS engine	2196
Failure of start or internal shaft seal leakage on turbopump assembly*	S-II engine fails to start	1975
S-IVB propellant utilization valve failure*	Non-nominal S-IVB thrust	1713
Failure of check valve to open in gas generator combustor assembly*	S-II engine fails to start	1680
No output from S-II static invertic*	S-II engine fails to start	1485
D-20 battery failure	Gradual loss of guidance and control	1416
Failure of main oxidizer valve assembly in all modes*	S-II engine fails to start	1040
Flight control computer failure*	Saturation or loss of attitude error signals	570
S-IC servoactuator failure*	Actuator hardover, slow response or null	528
Platform bearing pressure regulator failure*	Platform gyro drift	368
Platform electronics assembly failure	Erroneous velocity signals or loss of flight control	365

*Refer to Section 3

Table I. Malfunctions Applicable (Continued)

Malfunction	Failure Effect	Total Criticality
Failure of gas generator control valve assembly to open*	S-II engine fails to start	305
Failure of ignition phase control valve to actuate*	S-II engine fails to start	209
D-30 battery failure	Flight control computer receives incorrect constants	191
Excessive internal leakage in mainstage control valve*	S-II engine fails to start	179
Plotform AC power supply failure	Erroneous attitude signals	178
56-volt power supply failure*	Loss of inertial reference, erroneous gimbal, velocity signals	109
Quick disconnect failure	Gradual guidance and control failure	109

*Refer to Section 3

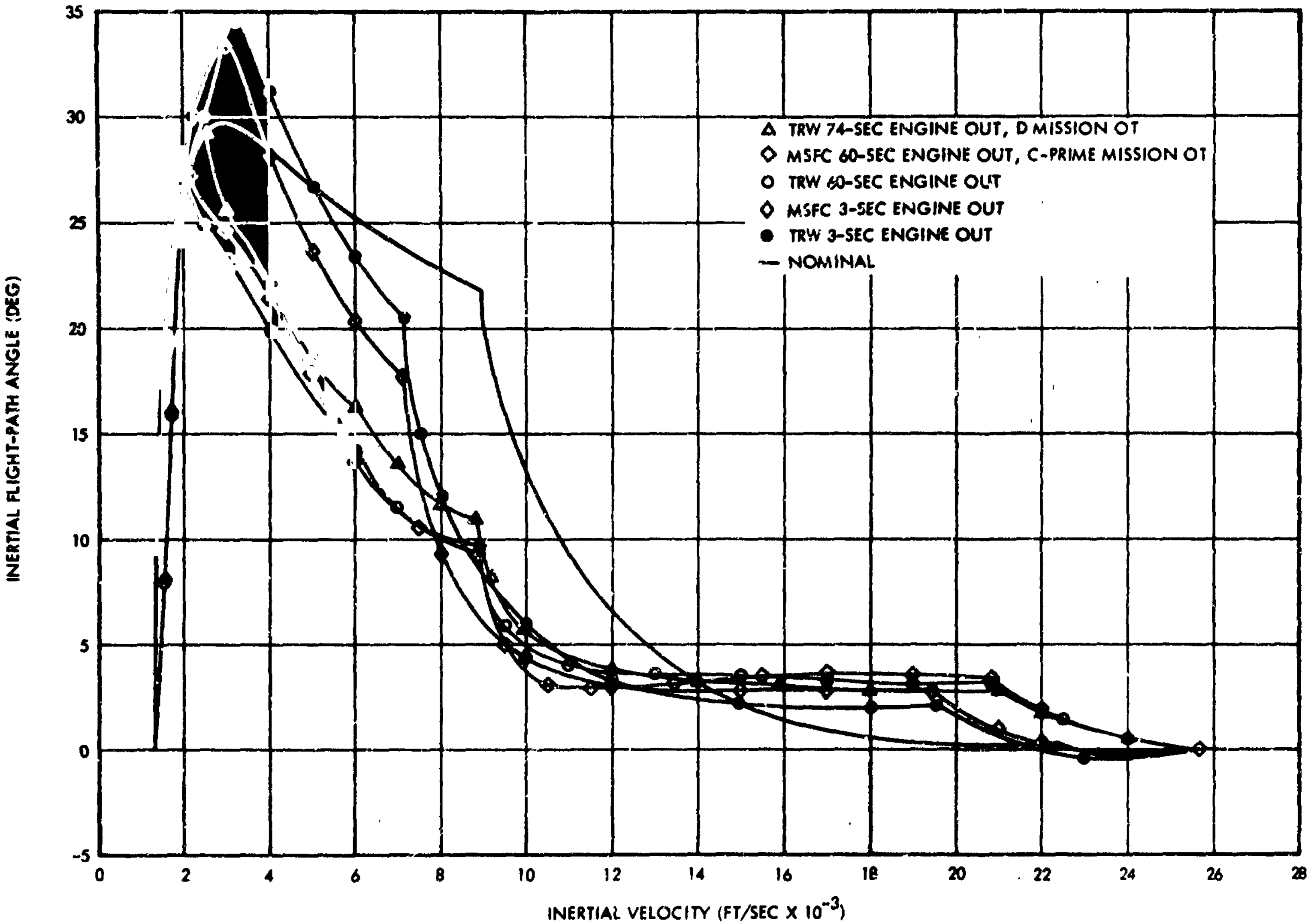

Figure 1. Inertial Velocity versus Inertial Flight-Path Angle for S-IC Engine 1 Out at 3, 60, and 74 Seconds

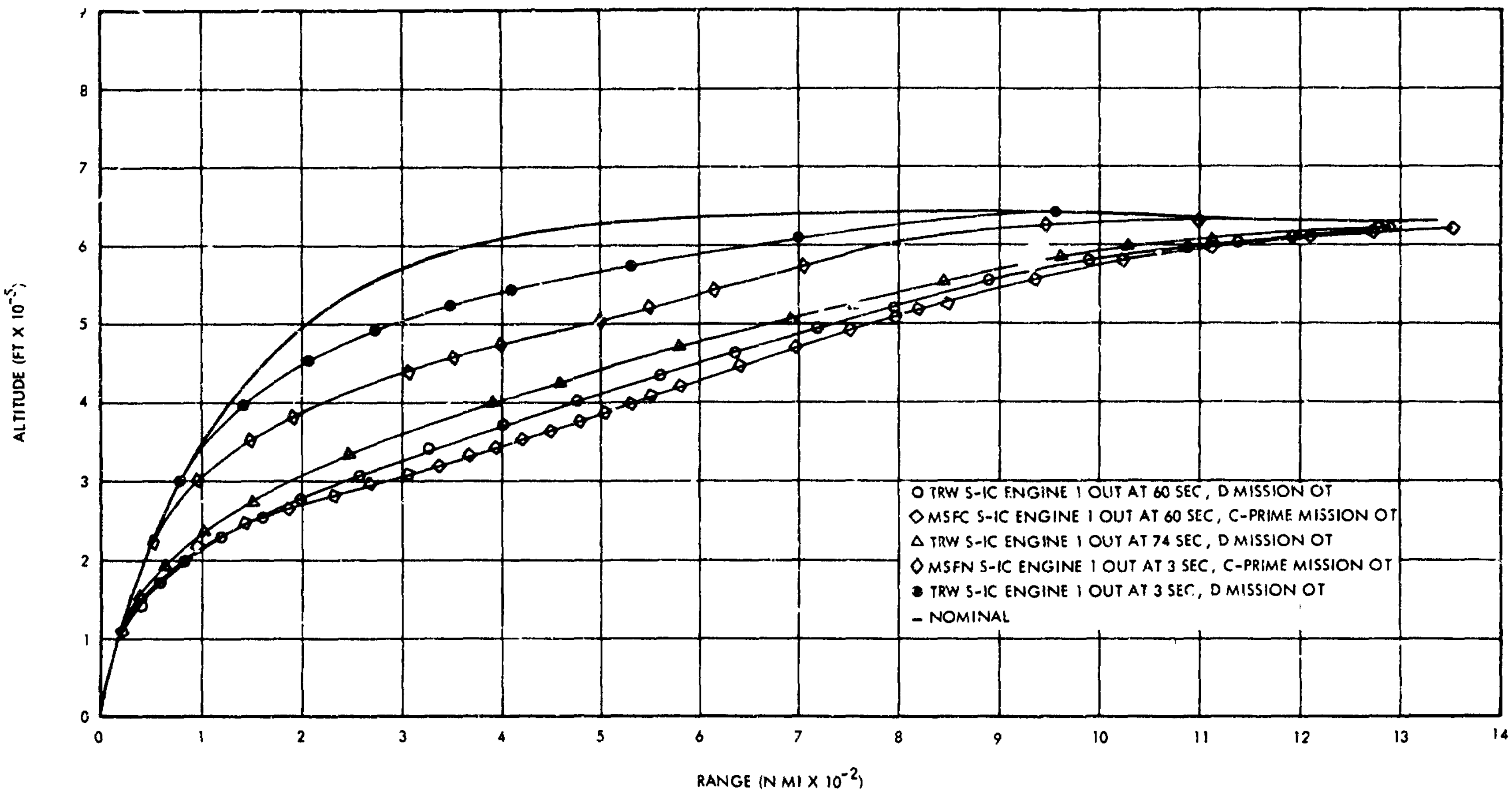

Figure 2. Altitude versus Range for S-IC Engine 1 Out at 3, 60, and 74 Seconds

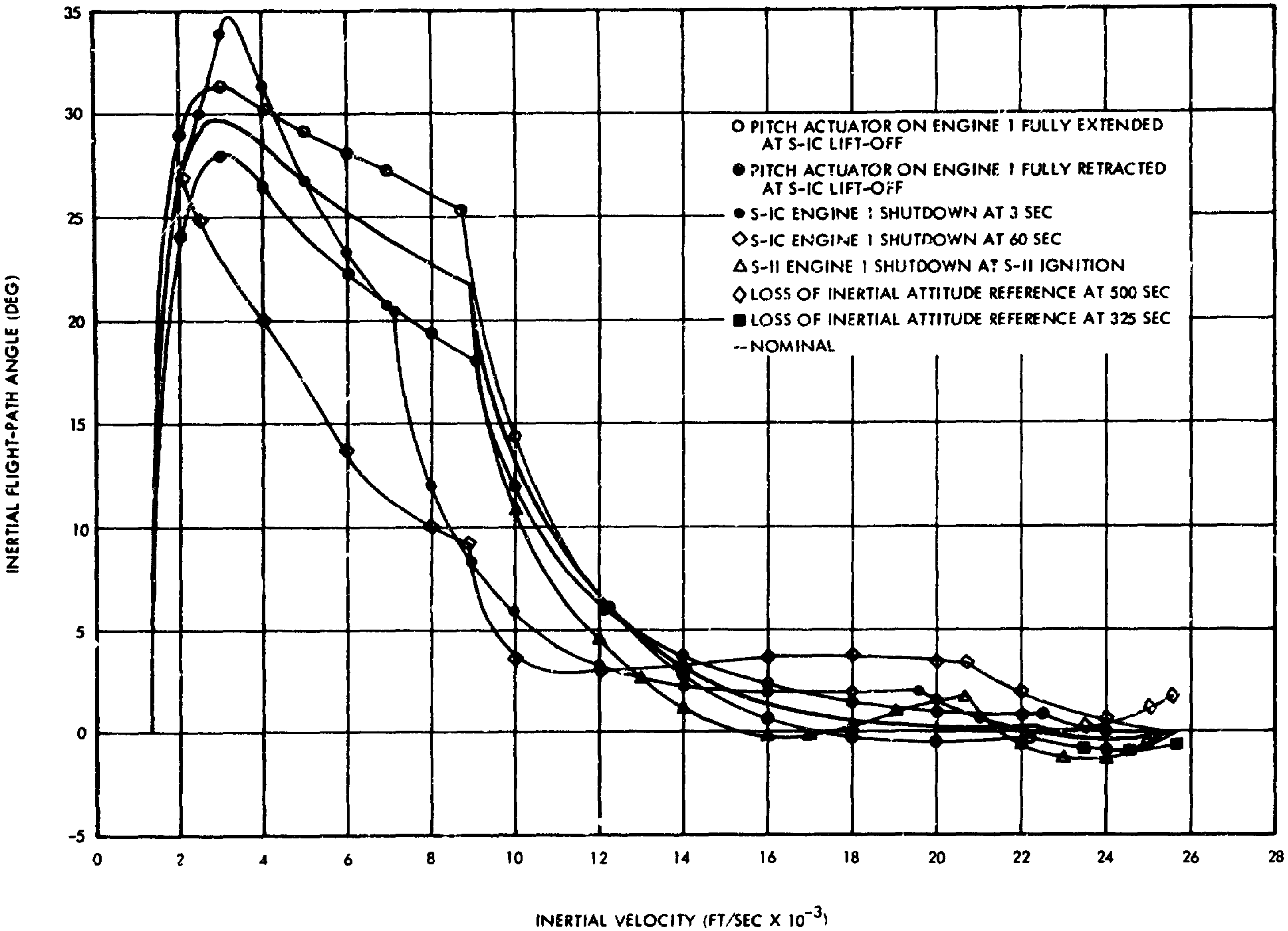

Figure 3. Inertial Velocity versus Flight-Path Angle for Individual Malfunctions Contributing to the Saturn V Envelope

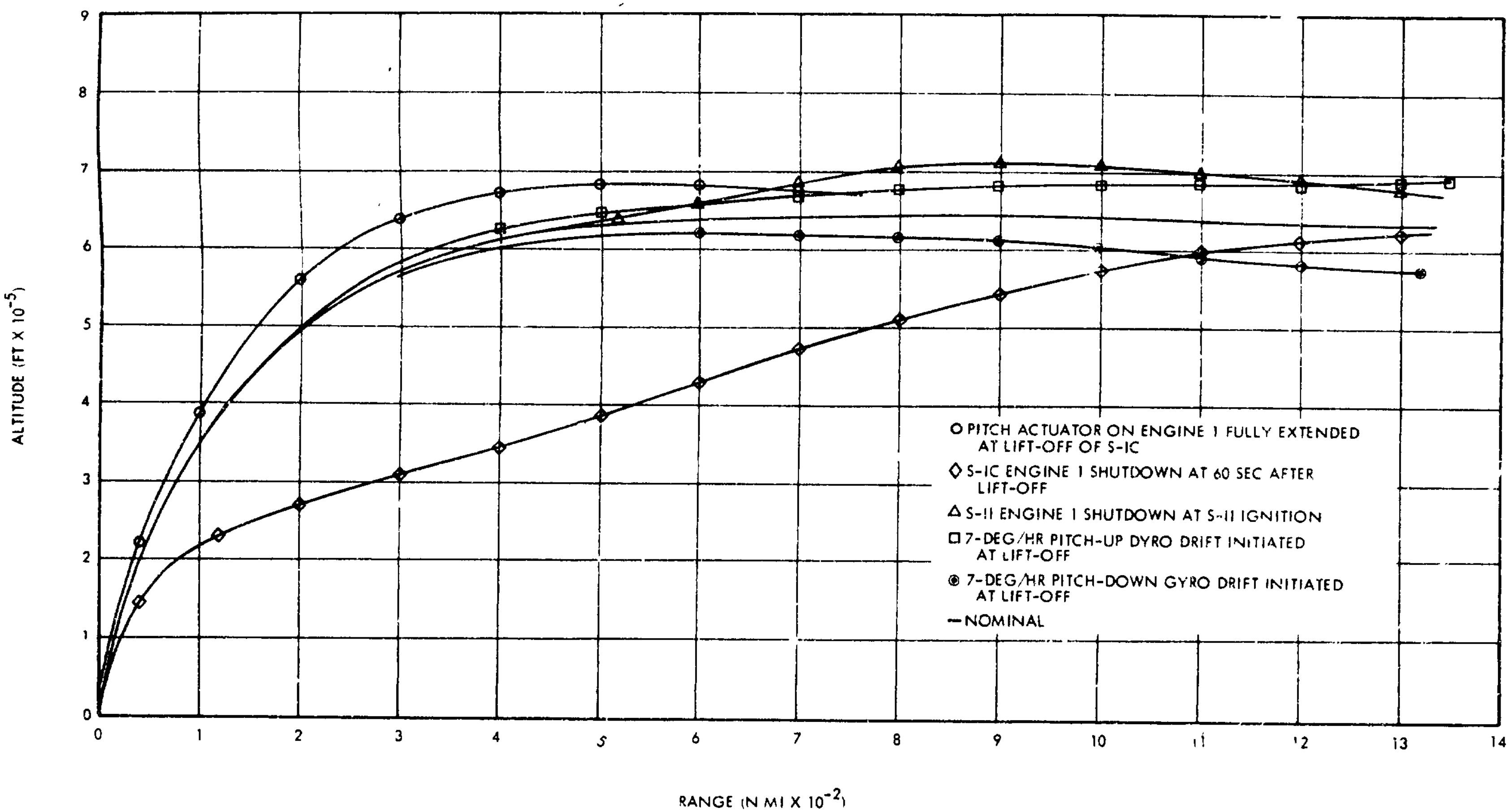

Figure 4. Altitude versus Range for Individual Malfunctions which Contribute to the Saturn V Envelope

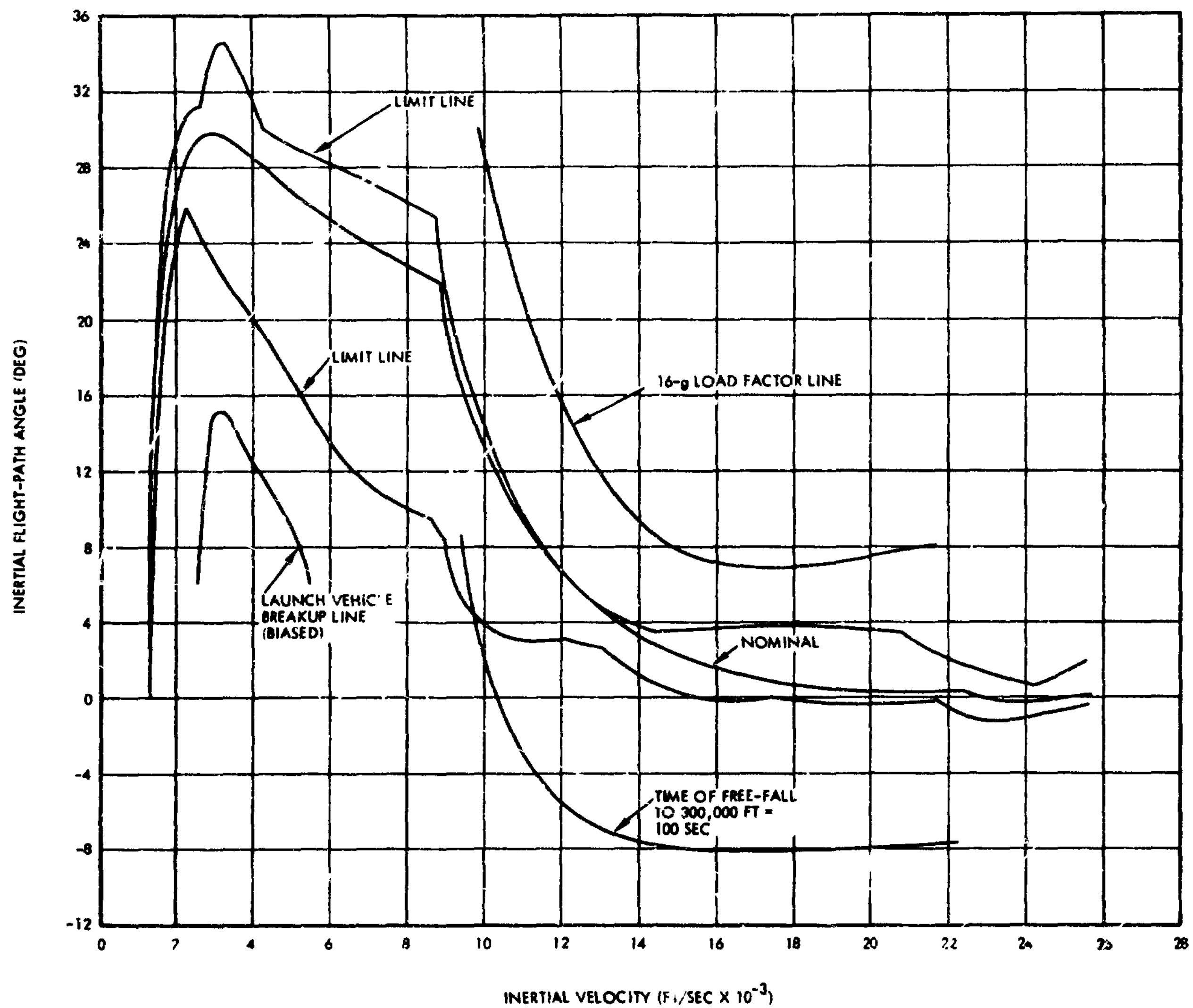

Figure 5. Inertial Velocity versus Flight-Path Angle Composite Envelope for Saturn V

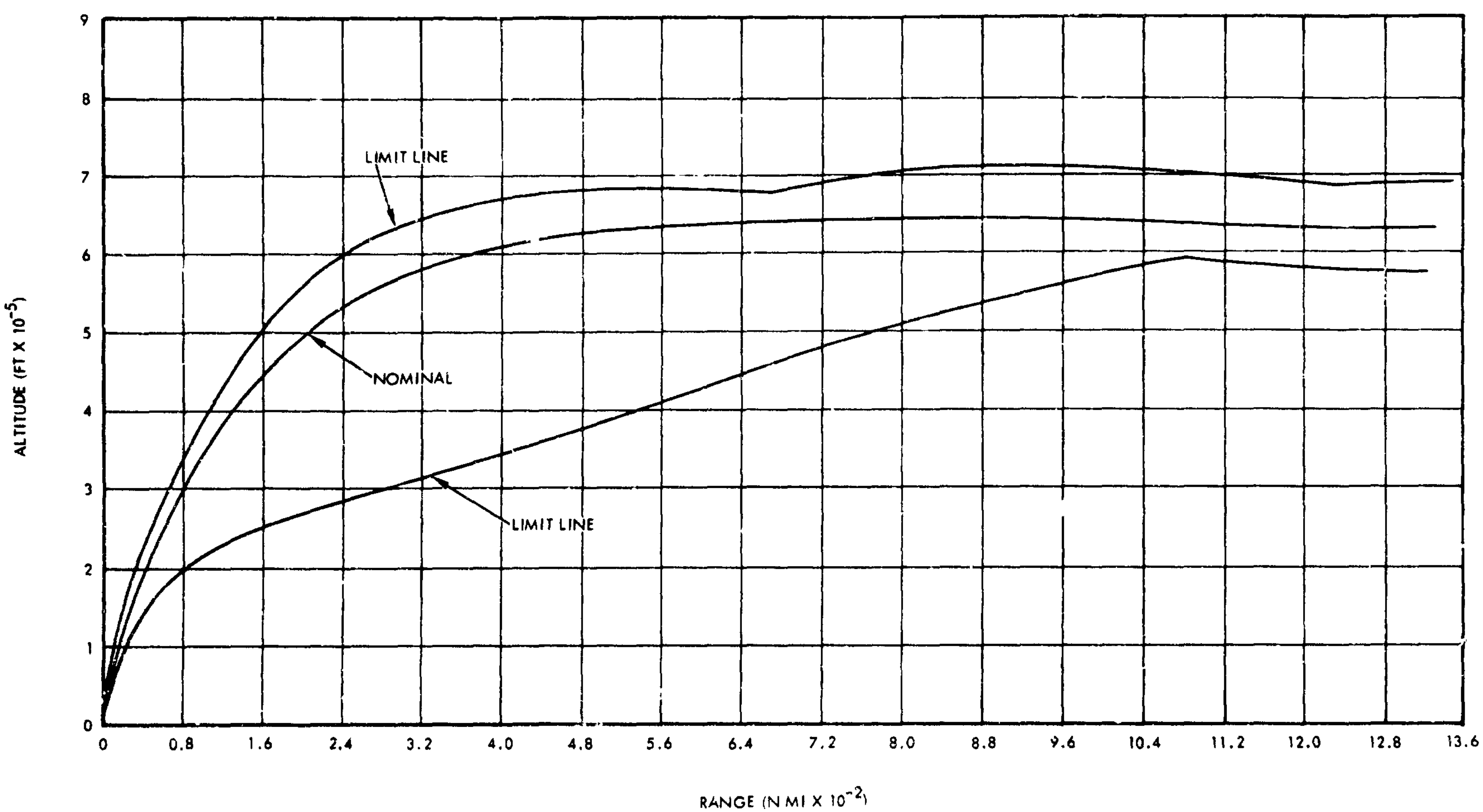

Figure 6. Altitude versus Range Composite Abort Limit Lines for the Saturn V Envelope

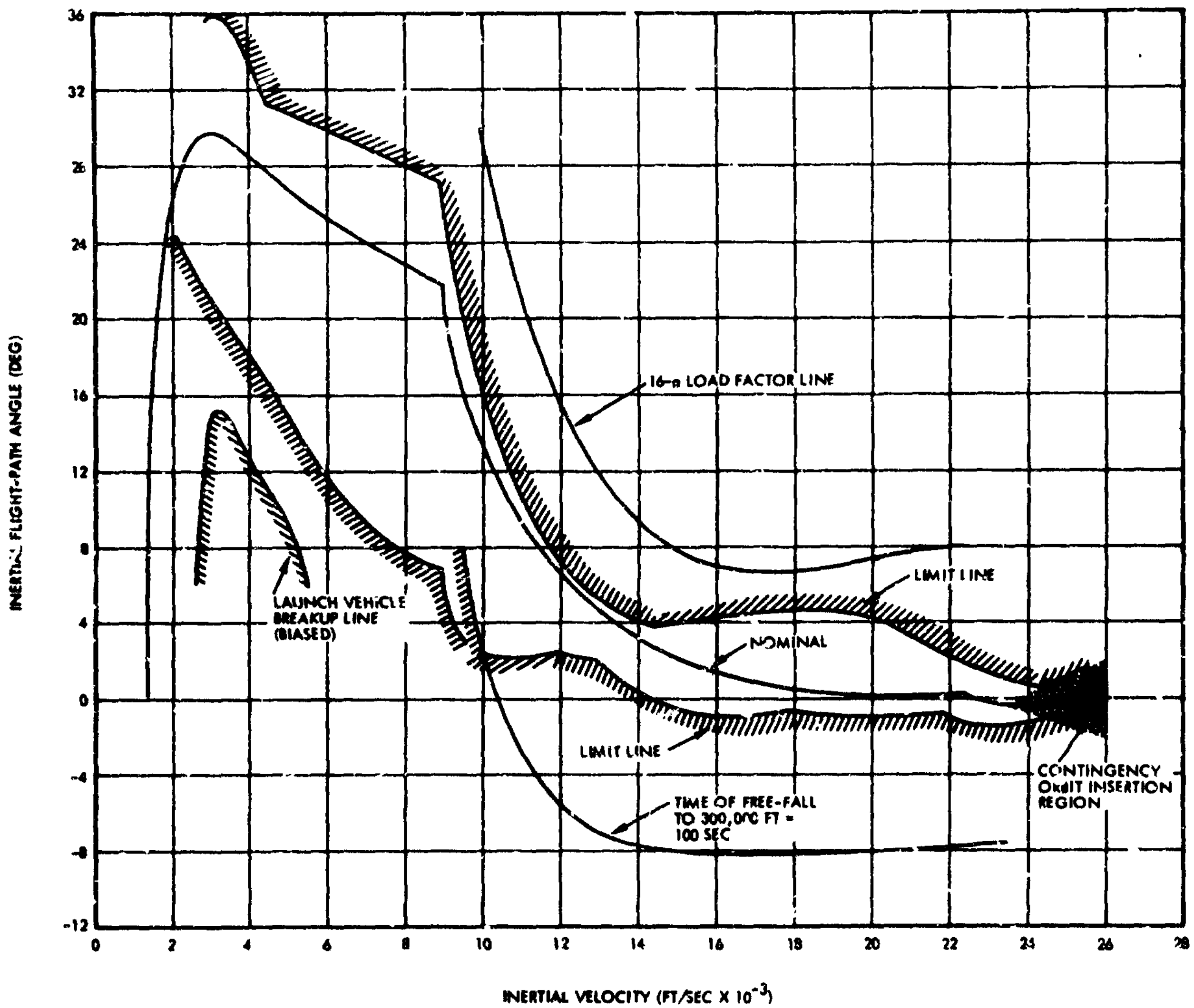

Figure 7. Inertial Velocity versus Flight-Path Angle Abort Limit Lines Incorporating Dispersion Data for the Saturn V Envelope

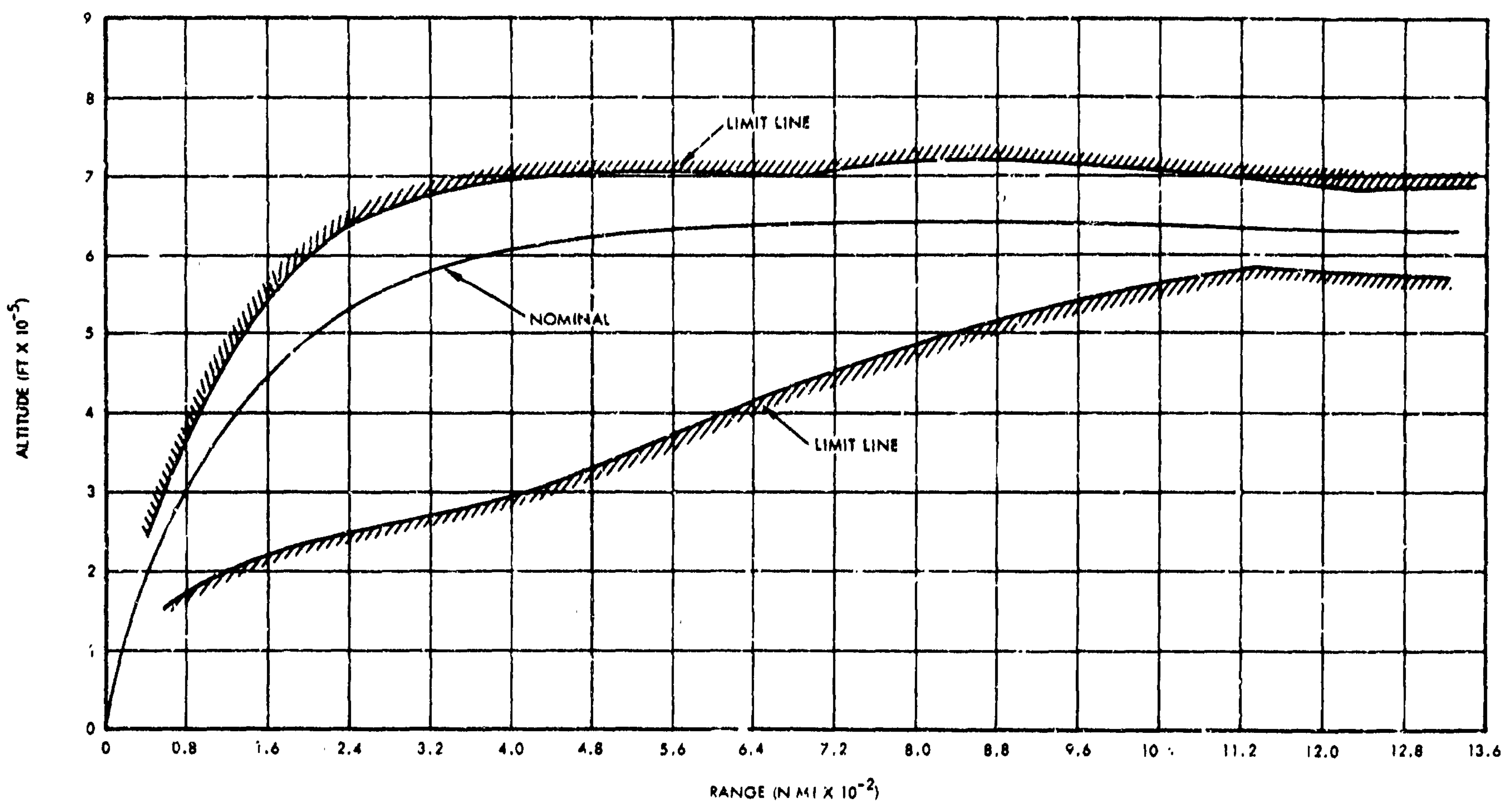

Figure 8. Altitude versus Range Abort Limit Lines Including Nominal Dispersions for the Saturn V Envelope