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MSC INTERNAL NOTE NO. 66-EG-33

PROJECT APOLLO

QUICK LOOK RESULTS OF A SIMULATION STUDY OF ENTRY RANGING USING THE CM BLOCK II ENTRY MONITORING SYSTEM (EMS)

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JULY 6, 1966

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SUMMARY

A piloted simulation of the CM Block II entry has been conducted to evaluate the feasibility of using the entry monitor system (EMS) as a backup ranging device in the event of a primary G&N malfunction. The results of the study indicate that the addition of some backup ranging lines on the EMS scroll provides the crew with the capability of maneuvering the spacecraft to a preselected landing site following a G&N failure. Action has been taken to try and have these backup ranging lines included in the Block II CM series. Simulation results indicated that there is an 89% probability that the spacecraft will land within 161 n. mi. of the mean miss distance (50 n. mi.) if the pilot uses the EMS backup mode for entry ranging.

INTRODUCTION

The Block II CM has an EMS that will be used to monitor primary guidance and navigation(G&N) during the atmospheric entry portion of the mission. The EMS provides a simple but highly reliable means for the crew to monitor CM entry while in the automatic or manual G&N modes. In the past, there have been man-in-the-loop simulations conducted at both MSC and NAA where the EMS has been evaluated as a means of detecting G&N malfunctions and also as a means of performing safe (constant g) entries once a malfunction has been detected. These simulations have led to the speculation that the EMS might also be used as a backup entry ranging device in the event of a G&N malfunction. To determine if this is a feasible conception, the Guidance and Control Division has performed a six-degree-of-freedom entry simulation study (reference 1).

SIMULATION IMPLEMENTATION

The implementation of the CM entry ranging simulation using the Block II EMS was accomplished by coupling the analog solution of the spacecraft equations of motion and digital solution of the MIT guidance to a fixed base simulation of the CM. The simulator contained an astronaut couch, rotational hand controller, and main display console enclosed in a mockup of the CM. The main display console contained those switches and instruments needed to perform the entry simulation (Table 1 and figure 1). The EMS, as described in reference 2, was closely approximated by constructing NAA monitor lines (figure 2) on pressure sensitive paper which moved vertically in accordance with the EMS velocity output and a stylus which moved horizontally in accordance with the EMS g output.

EMS RANGING LINES

Since the lines which are presently on the EMS scroll (figure 2) are for monitoring the G&N system only, a new set of lines had to be developed and superimposed on the scroll for the purpose of performing entry ranging in the event of a G&N malfunction (figure 3). The ranging lines can be broken down into two sets. The first set is for the supercircular portion of the entry (first pass into the atmosphere). The second is for the subcircular portion of the entry (second pass into the atmosphere). The first set of lines begin at an entry velocity of 36,300 ft/sec. The top line is simply an EMS scroll trace of a guided entry from an initial flight angle (γ_I) of 6.4° and a downrange target of 2,500 n. mi. from an altitude of 400,000 feet. The lower line is a guided entry with initial conditions of $\gamma_I = 7.12^\circ$ and range-to-go (RTG) = 1,500 n. mi. There is also a line which branches off the lower trace which is a guided entry with initial conditions of $\gamma_I = 7.12^\circ$ and RTG = 2,000 n. mi. The second set of lines begin at an EMS scroll velocity of approximately 24,000 ft/sec and continue to the end of the scroll (4,000 ft/sec). These lines are marked every few inches with numbers (8,6,4,3,2,1,0.5) which represent hundreds of miles to go to the target. These lines are potential range lines and indicate to the pilot how much farther the spacecraft will travel if the pilot holds the present constant g level. For example, if the G vs V trace crosses the line marked "3", it would indicate to the pilot that the spacecraft will travel 300 n. mi. further if he held the present g level constant for the rest of the flight. The simulation pilots were also given a chart which presented a plot of maximum g load vs initial flight path angle for liftup trajectories (figure 4). This chart was useful to determine the lift vector orientation during the first pass into the atmosphere. However, the flight crew probably will have memorized the plot by flight time, and therefore, it would be superfluous to carry it along on the mission.

Use of EMS Ranging Lines

The pilot in an actual entry will receive various information from the ground prior to entry. In part, this information will consist of inertial velocity, γ_I, RTG from 400,000 feet, RTG from 0.05 g altitude (297,431 feet), and crossrange to the right or left of the target. He will then enter the inertial velocity on the EMS scroll and the RTG from the 0.05 g altitude in the RTG meter as described in reference 2. If there has been a G&N failure prior to entry and the pilot uses the EMS ranging lines, he should do the following:

1. Aline the spacecraft in the entry position automatically or manually.

2. Check the plot of maximum g vs γ_I to determine what g loading will be encountered if a liftup entry is flown.

3. At 0.05 g, fly liftup if γ_I is steeper than -5.84° and fly liftdown if it is shallower than -5.84° (Liftup or liftdown should be verified with the corridor verification lights).

4. If (2) above indicates that more than 5g will be obtained for a liftup entry, then hold liftup and level off at 5g as the g level decreases through that point. If γ_I is steeper than -5.84° but (2) above indicates that 5 g will not be reached with liftup, then modulate the lift vector (starting just before the maximum liftup g is obtained) and level off at 5g. If γ_I is shallower than -5.84°, hold liftdown and level off at 5g.

5. Continue to hold a 5g level until the G vs V trace approaches the exit rays (2,500 n. mi., 2,000 n. mi., and 1,500 n. mi.). Then, depending on the ground information as to the RTG from 400,000 feet, allow the g level to decrease so that the EMS trace of G vs V follows the appropriate line. For example, if the RTG is 2,200 n. mi. at 400,000 feet, modulate the lift vector such that the trace will pass parallel to and between the 2,500 n. mi. and the 2,000 n. mi. exit rays. This assures that the spacecraft will have the correct flight path angle and velocity during the ballistic portion of the trajectory (between the first and second pass into the atmosphere).

6. During the ballistic portion of the flight (less than 1g) hold either a $+90^\circ$ or -90° lift vector orientation if the G vs V trace paralled the correct exit ray and was essentially in the correct location. If the G vs V trace was above the correct location, fly liftdown. If the trace is low, fly liftup. Hold the above lift vector orientation until the g level begins to build up again. Of course, there may be some trajectories to short targets where the spacecraft never gets below a 1g level after entering the atmosphere.

7. Once the g level starts to build up during the second pass into the atmosphere, fly liftup until the g level builds to a maximum. At this point, check the RTG meter against the potential RTG lines. If they agree, hold that g level to the end of the run. Of course, small adjustments in g level can be made as the trace passes through the successive potential RTG lines. If the RTG meter and the potential RTG lines do not agree, modulate the lift vector until they do agree and then try to hold a constant g level to the end of the flight. The EMS scroll ends at a velocity of 4,000 ft/sec. However, the flight path angle of the spacecraft is almost -90° at that point, and there is very little ranging that can be done from that point on.

It should be noted that there is no crossrange indication onboard the spacecraft during a G&N failure, and therefore, the pilot must "mentally integrate" this quantity during the flight and modulate the lift vector from side to side to hold the crossrange error at a minimum. Also, for long range targets, the spacecraft may skip (pass up through the 0.05 g altitude) and the pilot should then go to an entry attitude position with the lift vector up (either automatically or manually) until the 0.05 g light comes on again. An EMS scroll trace for an entry of γ_I = 6.4 and RTG = 2,200 n. mi. using the EMS for backup ranging is shown in figure 5.

TEST RUNS

The simulation test runs began at an altitude of 400,000 feet and an inertial velocity of 36,300 ft/sec. The vehicle was assumed to be at the correct entry attitude in pitch and yaw with the liftup. The only conditions that were varied were initial flight path angle (γ_I) and range-to-go to the target (RTG). All piloted runs were flown under manual control utilizing single-system RCS. Manual control was exercised with either G&N roll steering signals (EMS for monitoring), which was termed "Manual G&N mode", or without G&N roll steering signals (EMS for prime control), which was termed "EMS backup mode".

Various G&N failures were also introduced during the manual G&N modes. The first matrix of test runs assumed that the G&N has failed prior to 0.05g, but the attitude hold capability still existed (above 0.05g). The test subjects flew all these runs in the EMS backup mode. The γ_I was varied from -5.2° to -7.12° and the RTG was varied from 1,500 n. mi. to 2,500 n. mi. (total of 35 runs for each simulation pilot). There were four test subjects (three from FCSD and one from G&CD). Each pilot was given ample training time to familiarize himself with the system before he started the test run matrix. In addition to the G&N failure prior to 0.05g there were a number of runs where the G&N failure was introduced after 0.05g. These runs were broken down into two categories: (1) complete G&N failures (loss of computer), and (2) erroneous steering commands.

It should be noted that the G&N failures in category (2) do not necessarily violate NAA monitor lines. For example, the target may be at a RTG of 2,500 n. mi. and the steering signals could direct the vehicle to a RTG of 1,500 n. mi. without violating the NAA monitor lines. However, the G vs V trace over the EMS ranging lines would indicate a G&N malfunction quite early in the entry.

DISCUSSION OF RESULTS

G&N Malfunctions Prior to 0.05g

The results of the study of G&N malfunctions prior to 0.05g are based on four pilots who made 35 runs each. The data were statistically evaluated and are presented as the mean, 1 σ, and 3 σ miss distances for downrange (DR), crossrange (CR), and total vector $\left[(DR)^2 + (CR)^2 \right]^{\frac{1}{2}}$ (Table II). For comparison, the same miss distances are also presented for automatic G&N entries.

A normality check of the miss distance data performed by G&CD showed the data to be not-normal. Therefore, a 3 σ deviation can only be considered an 89% probability of occurrence rather than 99.74%. Or more specifically, if a G&N failure occurs prior to 0.05g and the pilot uses the EMS backup mode for entry ranging, there is an 89% probability that the spacecraft will land within 161 n. mi. of the mean miss distance (50 n. mi.).

The above miss distances are considered quite accurate; however, there are some qualifications that must be considered:

1. During the simulation, it was assumed that all other active systems (except the G&N) were operational. For example, control of the spacecraft would become quite difficult if the RCS system failed while flying the EMS backup mode.

2. The L/D used in the simulation was a constant .341. However, L/D values from .25 to .4 were tested. L/D values below .3 were difficult to fly and increased the miss distances. L/D above .341 increased the response of the spacecraft to lift vector orientations and made the control task easier. (Changes in L/D from .3 to .5 do not change the EMS backup ranging lines.)

3. The RTG meter used in the simulation portrayed the true ground RTG of the target. Therefore, the present RTG meter error (approximately 40 n. mi.) should be added to the above numbers. However, this RTG error could be greatly reduced by either: (a) entering an RTG number transmitted from the ground that includes the curvature of the flight or (b) include some simple logic in the RTG meter that would represent the true ground RTG to the target. If (1) above is used, the RTG number (including flight curvature) should be based on the RTG from the .05g altitude (297,431 feet) to 100,000 feet. The reason for the 100,000 foot altitude limit is that the spacecraft will be coming almost straight down at that point, but the RTG meter would still be decreasing. The pilot should take the RTG meter reading at 100,000 feet and fly constant lift vector orientation of either 0° (lift downrange) or 180° (lift uprange) depending whether the spacecraft is short of the target or has passed the target. It should be noted that if the pilot holds a constant lift vector orientation of 180° from an altitude of 100,000 feet down to drogue chute deployment, the g level will not increase significantly because of the relatively low terminal velocity of the spacecraft.

4. It is, of course, essential that the EMS work correctly for the miss distances to be accurate. However, initial velocity errors (difference between spacecraft velocity and EMS scroll velocity) up to 300 ft/sec, indicated g loading errors of 5%, and off-nominal atmospheric quantities had no effect on the simulation results. These errors are well within the design specification of the EMS. It should also be noted that the EMS backup ranging lines are independent of initial velocity. Therefore, the spacecraft can enter the atmosphere at any velocity (even subcircular). As long as this velocity is entered on the EMS scroll, the backup ranging lines will still be valid.

5. Each simulation run was terminated at an altitude of 100,000 feet since at that point, the relative flight path angle is almost -90°. However, there is some ranging that can be accomplished from an altitude of 100,000 feet down to drogue chute deployment. Therefore, the EMS backup miss distances would be smaller if the simulation had been run to touchdown.

G&N Malfunctions After 0.05g

The results of G&N malfunctions after 0.05g is essentially the same as that prior to .05g as long as the malfunction is instantaneous and detectable. For example, if the spacecraft is following a nominal guided entry either in the automatic or manual G&N modes and the computer "goes out", the pilot simply takes control manually and completes the entry using the EMS backing ranging lines. The transition between the guided entry and the EMS backup entry is of no concern because the ranging lines are based on guided entries and therefore completely compatible. However, if the malfunction causes erroneous steering signals, the results are quite different. As mentioned before, the guidance could direct the spacecraft to a 1,500 n. mi. touchdown point while the desired target is 2,500 n. mi. and never violate NAA monitoring lines. The pilot probably would detect the failure even without the EMS backup ranging lines, but the addition of these lines would certainly enhance his monitoring capability. This is especially true during the terminal portion of the entry since as the G vs V trace passes over the potential ranging line, a quick check can be made with the RTG meter. Of course, it would depend upon how closely the pilot was monitoring the EMS scroll and when he would take over the guided entry, but from the simulation pilot performance, a miss distance of approximately 500 n. mi. can be detected early in the entry and 200 n. mi. during the terminal portion of the entry. Therefore, a malfunction of this type could cause a touchdown miss distance of approximately 500 n. mi.

Another type of malfunction that was investigated was an erroneous steering signal after .05g which violates NAA monitoring lines. In most cases, if the G vs V trace violates a skip line and the pilot takes over immediately, he can recover and use the EMS backup lines to guide the vehicle to the target. However, during the simulation, it was discovered that very shallow entries ($\gamma_I = 5.2^\circ$) could violate the NAA skip monitor lines early in the trajectory, and the pilot would take over and fly lift vector down and not capture the atmosphere (exit the atmosphere at a supercircular velocity). A G vs V plot of such a trajectory is shown in figure 6. To eliminate this possibly catastrophic condition, a constant (K_A) in the MIT guidance equations was changed from a value of 2 to 2.7. This required that for shallow entries the lift vector remain down until the g level reached 2.7g before a liftup command could be given. A trajectory showing this malfunction with $K_A = 2.7$ and subsequent recovery is also shown in figure 6. Another good reason to change K_A to 2.7 is heat shield limitations. Figure 7 shows a G vs V plot of two guided entires with shallow initial flight paths and long range targets using $K_A = 2$ and $K_A = 2.7$. It can be seen that the trajectory using $K_A = 2$ violates the upper heat shield boundary while the trajectory using $K_A = 2.7$ is below the boundary during most of the flight. In addition to changing K_A to 2.7, all entries shallower than $\gamma_I = -5.84^\circ$ should enter the atmosphere with liftdown initially. This will also insure that the skip lines are not violated early in the flight. The above two changes ($K_A = 2.7$ and liftdown $\gamma_I > -5.84^\circ$) are MIT software changes. Also, the g level on the EMS corridor verification lights must be set to correspond to the liftdown $\gamma_I > -5.84^\circ$ (EMS hardware change). Action will be taken to try and have these feathers included in the Block II CM series.

During previous EMS simulation studies, if the G vs V trace becomes almost parallel to a skip line, the pilot sometimes took over a good run. This was also true during the latest G&CD simulation. However, during this simulation study, the pilot would take over and make only minor corrections so the G vs V trace would parallel the correct exit ray instead of flying a constant g profile as was the procedure during the previous studies. Also, if the pilot did take over a good run, he would usually notice that the guidance commands from the computer continued to be essentially the same as the maneuvers used to fly the EMS backing ranging lines. When this situation existed, the pilot would switch back to the automatic mode and continue to monitor the entry.

G&N Malfunctions Causing Excessive g Loadings

A malfunction which causes excessive g loading can also be overcome with a simple pilot procedure. This excessive g malfunction occurs when the spacecraft is under a high g level (6g) and a liftdown command is received from the computer. If the pilot waits for the G vs V trace to violate a g line (could be 8g), the spacecraft may encounter g levels as high as 12g. A simple procedure to avoid this is to instruct the pilot when the spacecraft is at a 6g level or greater, any command other than liftup $\pm 90^\circ$ is erroneous, and he should take over manually. This would require no software change in the MIT guidance as guidance commands above 5.5 g must be between zero and positive lift.

Fuel Usage

Another result that should be mentioned is the use of fuel. There were some assumptions made in the simulation of the RCS and digital autopilot which are mentioned in reference 1. Therefore, the actual fuel numbers are not exactly correct. However, a comparison of the numbers should be of some importance. An upper limit of fuel usage for the various control modes is as follows:

(1) automatic and manual G&N $\approx$ 60 lb.

(2) constant g and EMS backup $\approx$ 100 lb.

It should be noted from the above fuel figures that safe entries (constant g) and EMS backup ranging entries use considerably more fuel than guided entries and therefore the fuel budget must be based on the backup entry mode rather than trying to minimize fuel consumption with an optimum digital-autopilot in the automatic mode.

Skip Trajectories

A few of the simulation pilots have recommended that skip trajectories (skip above the .05 g altitude) be eliminated from EMS backup ranging (references 3 and 4). The main objection seems to be that when the spacecraft passes above the 0.05 g altitude it must go into attitude hold, either automatically or manually, until the spacecraft reenters the atmosphere. Since the computer may be "out", the automatic attitude hold would not include the range angle traveled from the initial entry point to the present position. However, this can only be as large as 26° and because of the rate damping capabilities of the CM the spacecraft would attain the correct trim attitude shortly after 0.05 g on the second pass into the atmosphere (reference 5). In fact, the attitude hold maneuver during skip (either automatically or manually) is essentially the same as it would be prior to 0.05 g during the initial entry. Therefore, there seems to be no reason to eliminate the skip type entries.

CONCLUDING REMARKS

Results of the simulation study may be summarized as follows:

(1) If a detectable G&N malfunction occurs before 0.05 g and the pilot flies the EMS backup ranging lines, there is an 89% probability that the spacecraft will land within 161 n. mi. of the mean miss distance of 50 n. mi. (assuming a correct RTG meter and no other failures).

(2) If an instantaneous and detectable malfunction occurs after 0.05 g, the results are the same as (1) above.

(3) If erroneous steering commands are present during entry that do not cause violation of the NAA monitoring lines, a miss distance of approximately 500 n. mi. could be encountered.

(4) If erroneous steering commands are present during entry that do cause violation of the NAA monitoring lines and the pilot takes over immediately, he can usually maneuver the spacecraft to the target area if the following is true:

(a) The constant K_A is equal to 2.7 in the MIT guidance equations

(b) If the limiting lift down flight path angle is set at -5.84°.

(c) The EMS corridor verification lights agree with 4-b above.

(5) Trajectories using $K_A = 2.7$ do not violate the upper heat shield boundary.

(6) The EMS backup ranging lines are very useful for entry monitoring and in the event the pilot takes over a good run he can return to automatic control.

(7) Safe entries (constant g) and EMS backup ranging entries use considerably more fuel than guided entries.

RECOMMENDATIONS

The following is a list of recommendations based on the G&C simulation study of entry ranging using the CM Block II EMS:

(1) The EMS backup ranging lines (figure 3) should be included on all Block II CM-EMS. These lines should be a different color than the NAA monitor lines.

(2) Upper and lower heat shield boundary lines (figure 7) be included on all Block II CM-EMS. These lines should be a different color than the NAA monitor lines and the EMS backup ranging lines.

(3) The MIT entry guidance program be changed to include $K_A = 2.7$ and the flight path angle which determines lift up or lift down entries be set at -5.84°.

(4) The EMS corridor verification light be adjusted to reflect (3) above (EMS hardware change).

(5) The fuel budget be based on backup entries procedures.

(6) Various procedures and techniques mentioned in the text of this paper be included in the Block II flights.

REFERENCES

1. Presimulation report entitled, "Simulation Study of Entry Ranging Using the CM Block II Entry Monitoring System (EMS)", dated December 9, 1965

2. TRW Submittal X-35 and X-36 entitled, "Apollo Block II CSM Guidance and Control Data Book (Revised)", dated September 7, 1965

3. NAA memorandum ATO-D-APT-66-36 entitled, "Pilot Report--Apollo Block II Entry Monitor System, Entry Ranging", dated April 21, 1966

4. MSC memorandum CF325-6M-246 from CF325 to CF32 entitled, "Entry Monitor System Simulation", dated June 3, 1966

5. MSC memorandum EG27-66-58 from EG27 to EG2 entitled, "NAA Pilot Report on EMS Entry Ranging", dated May 5, 1966

TABLE I. - DISPLAYS AND SWITCHES USED IN THE SIMULATION

Switches and Displays	Simulation Nomenclature	Simulation Active	Pre .05g		Post .05g	
			Position	Direction	Position	Direction
MODE SELECT	S-1	No	ENTRY	ENTRY		
EMS AUTO-MAN	S-2	No	EMS AUTO	UP		
CMC ATT	S-3	No	IMU	UP		
FDAI SCALE	S-4	Yes	5/5	CENTER	50/10	DOWN
FDAI SELECT	S-5	No	1	DOWN		
FDAI SOURCE	S-6	No	GDC	DOWN	ATT SET	CENTER
ATT SET	S-7	No	IMU	UP		
MA ROLL	S-8	Yes	RATE CMD	CENTER		
MA PITCH	S-9	Yes	RATE CMD	CENTER		
MA YAW	S-10	Yes	RATE CMD	CENTER		
LIMIT CYCLE	S-11	No	ON	UP	OFF	DOWN
ATT DEADBAND	S-12	No	MAX	UP		
RATE DEADBAND	S-13	No	HIGH	UP		
DIRECT RCS	S-14	No	ON	UP		
SCS ROLL A/C	S-15	No	ON	UP		
SCS ROLL B/D	S-16	No	ON	UP		
SCS PITCH	S-17	No	ON	UP		
SCS YAW	S-18	No	ON	UP		
SCS CONTROL SOURCE	S-19	No	SCS	CENTER		
BMAG ROLL	S-20	No	ATT 1 RATE 2	CENTER		
BMAG PITCH	S-21	No	ATT 1 RATE 2	CENTER		
BMAG YAW	S-22	No	ATT 1 RATE 2	CENTER		
EMS ROLL	S-23	Yes	OFF	DOWN	ON	UP
ENTRY .05G	S-24	Yes	OFF	DOWN	ON	
ALTIMETER	M-1	Yes				
G-V PLOTTER	M-2	Yes				
RANGE TO GO	M-3	Yes				
ROLL ATT	M-4	Yes				
G-METER	M-5	Yes				
FDAI	M-6	Yes				
PHASE TIME	M-7	Yes				
G LIMITER	L-1	Yes				
SKIP LIMITER	L-2	Yes				
.05G INDICATOR	L-3	Yes				

TABLE II - MEAN, STANDARD, AND 3σ MISS DISTANCES FOR EMS BACKUP AND AUTOMATIC RANGING

Mode Target Error	Mean n mi	Standard Deviation n mi	3σ n mi
EMS Backup			
Downrange	33.9	56.2	168.6
Crossrange	25.1	20.8	62.4
Vector	49.9	53.6	160.8
Automatic			
Downrange	5.17	6.13	18.39
Crossrange	4.18	1.8	5.4
Vector	8.02	4.5	13.5

Legend

Note: *Active displays and switches

Free hand lettering denotes simulation nomenclature

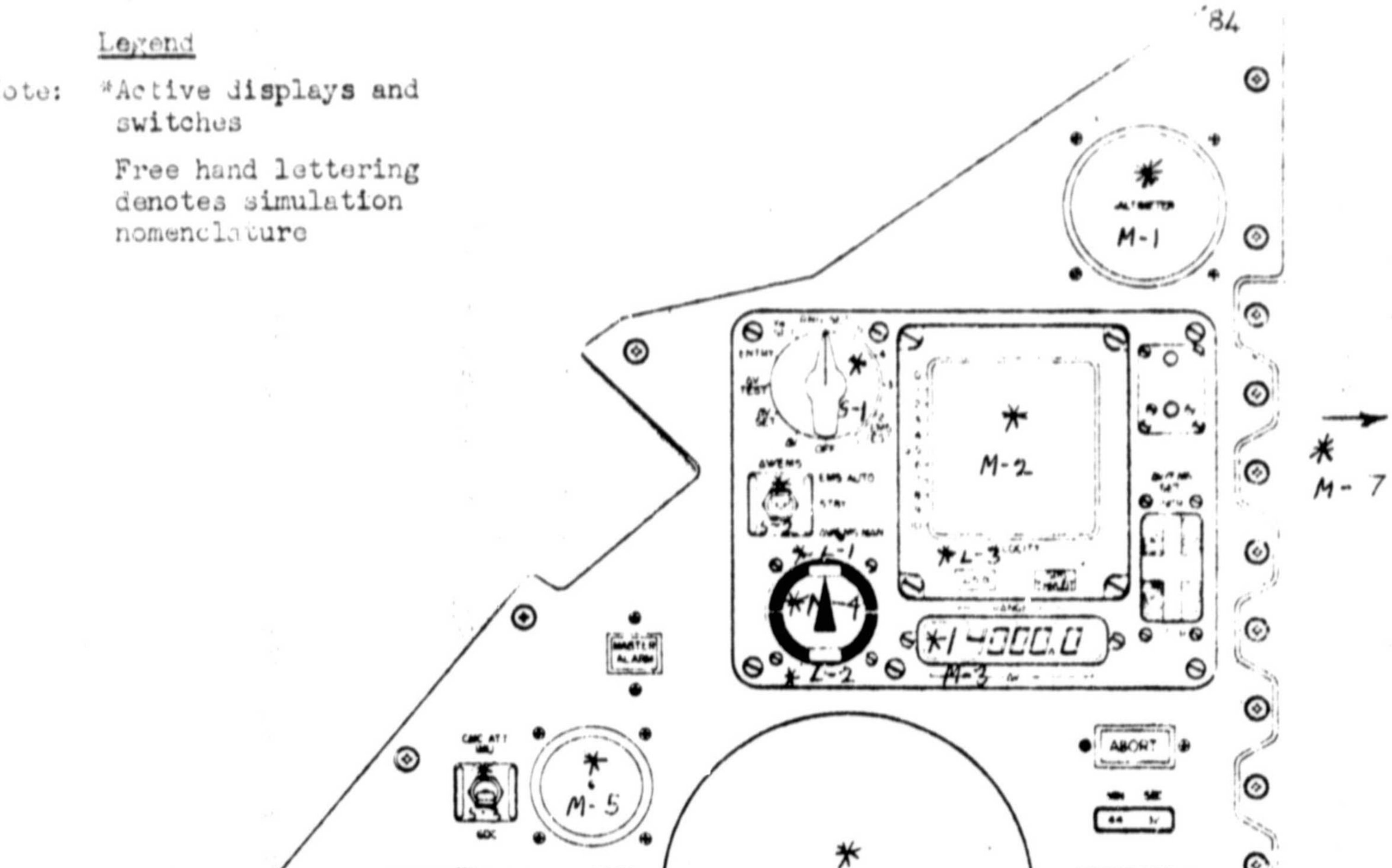


Figure 1.- Main display console

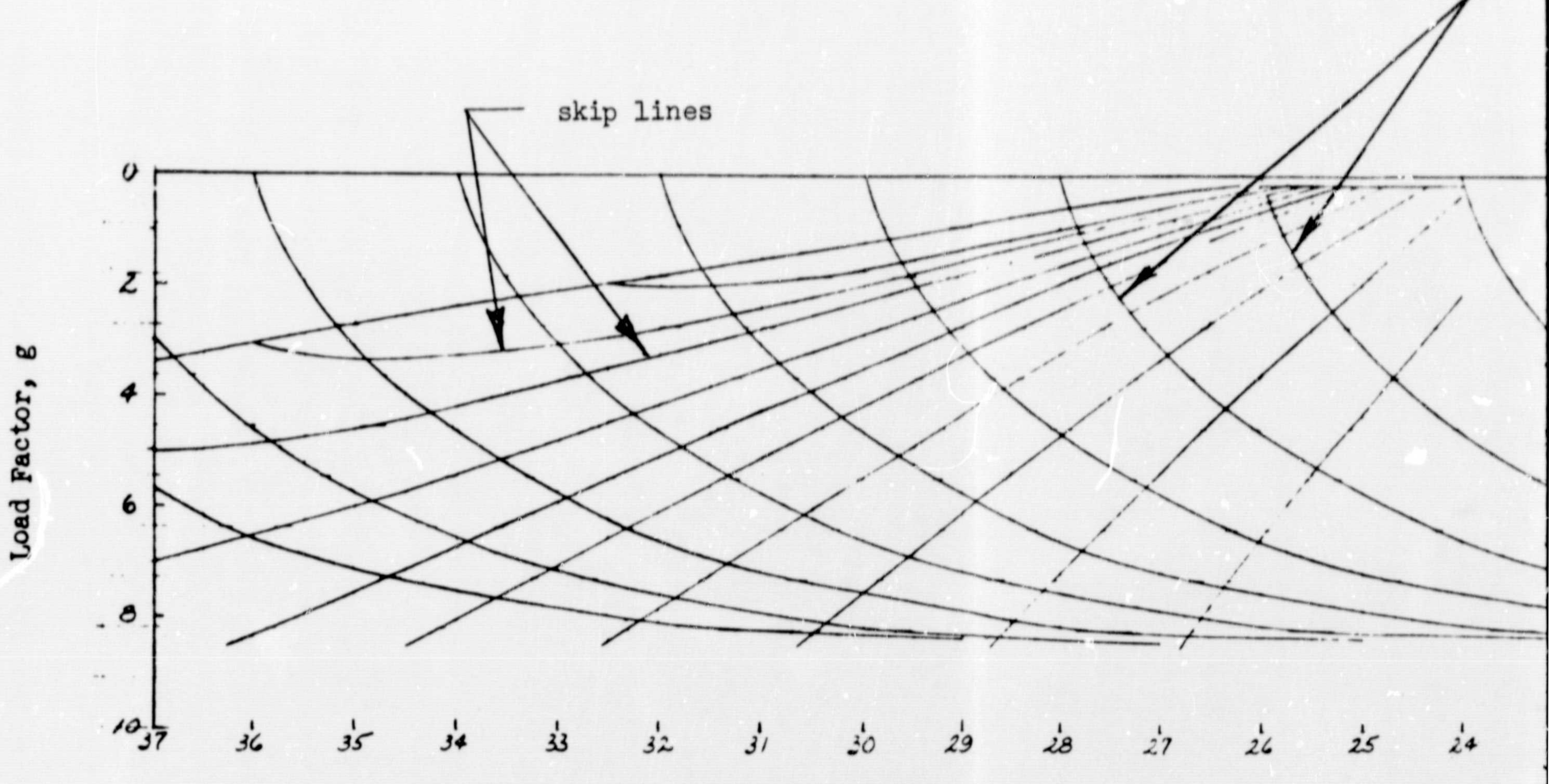
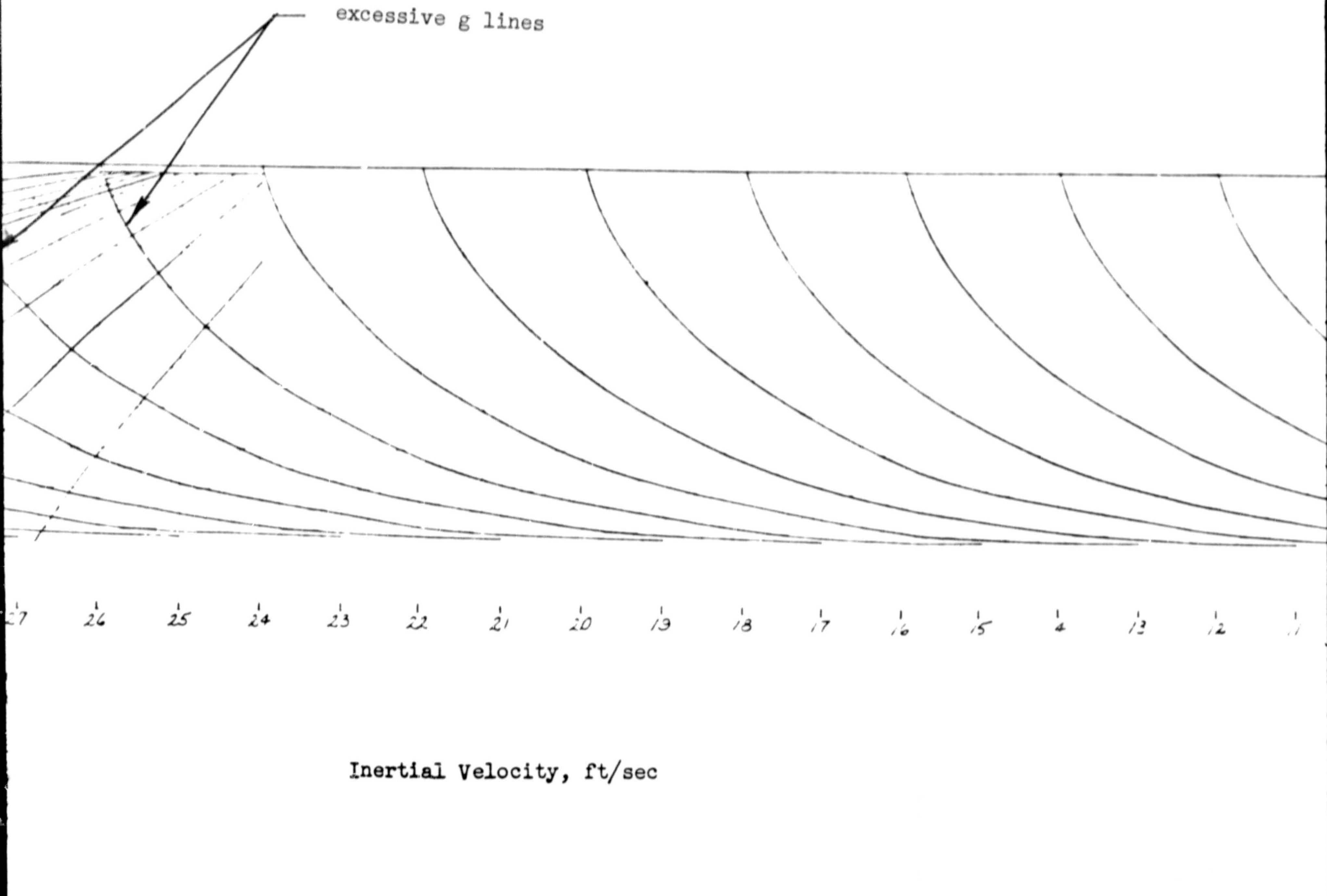


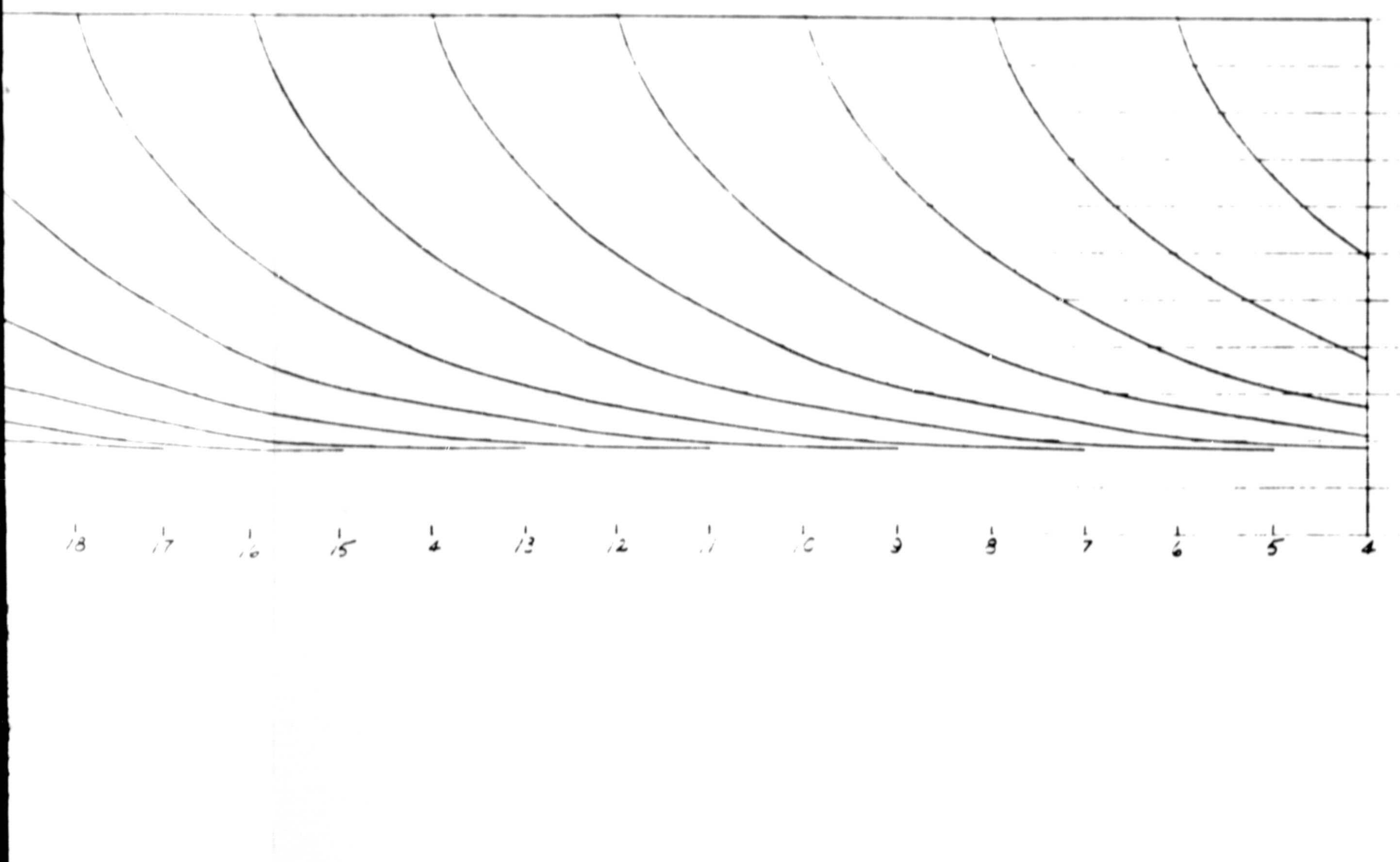
Figure 2 - NAA G&N monitor lines

FOLDOUT FRAME 1



Inertial Velocity, ft/sec

FOLDOUT FRAME 2



ME 2

FOLDOUT FRAME 3

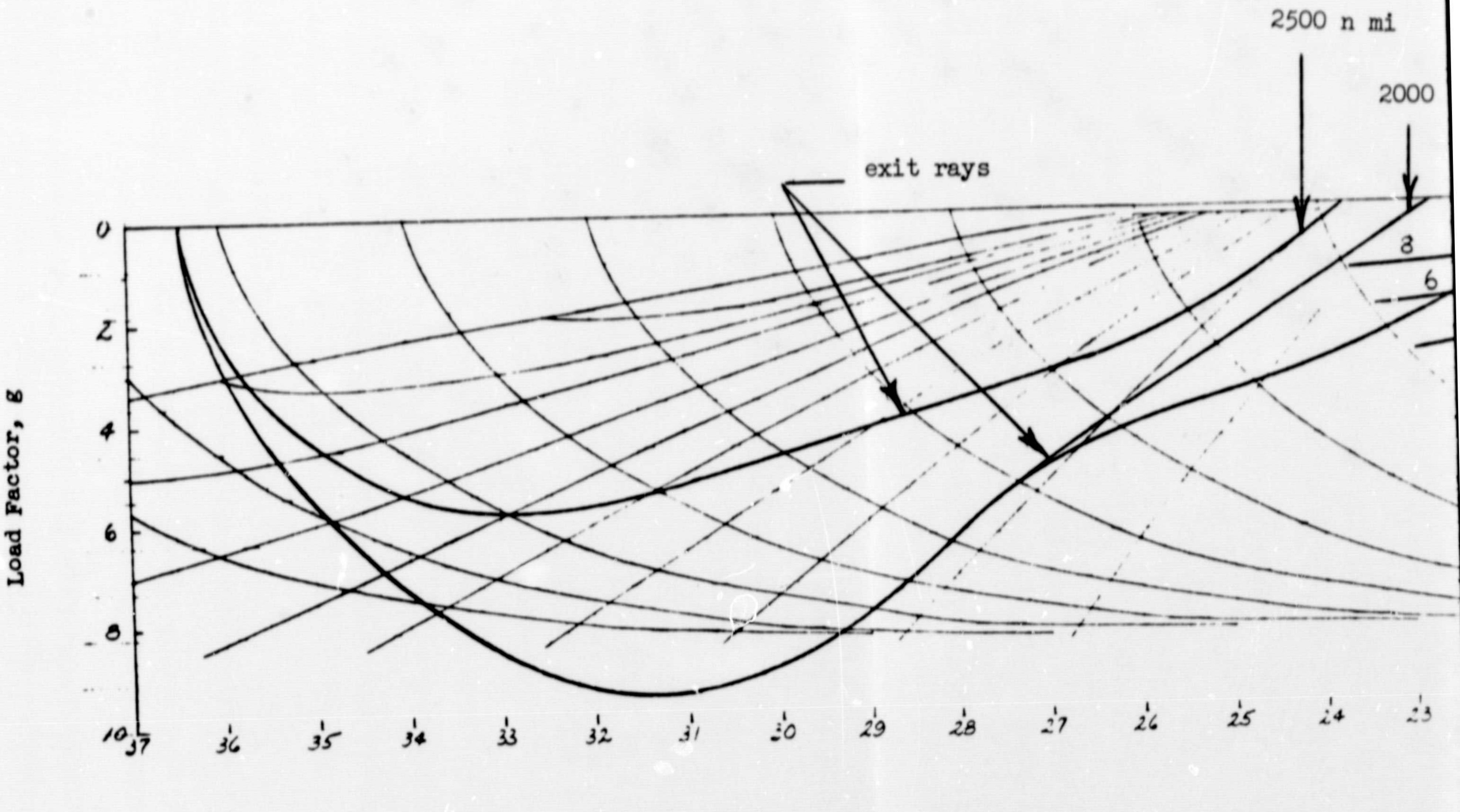
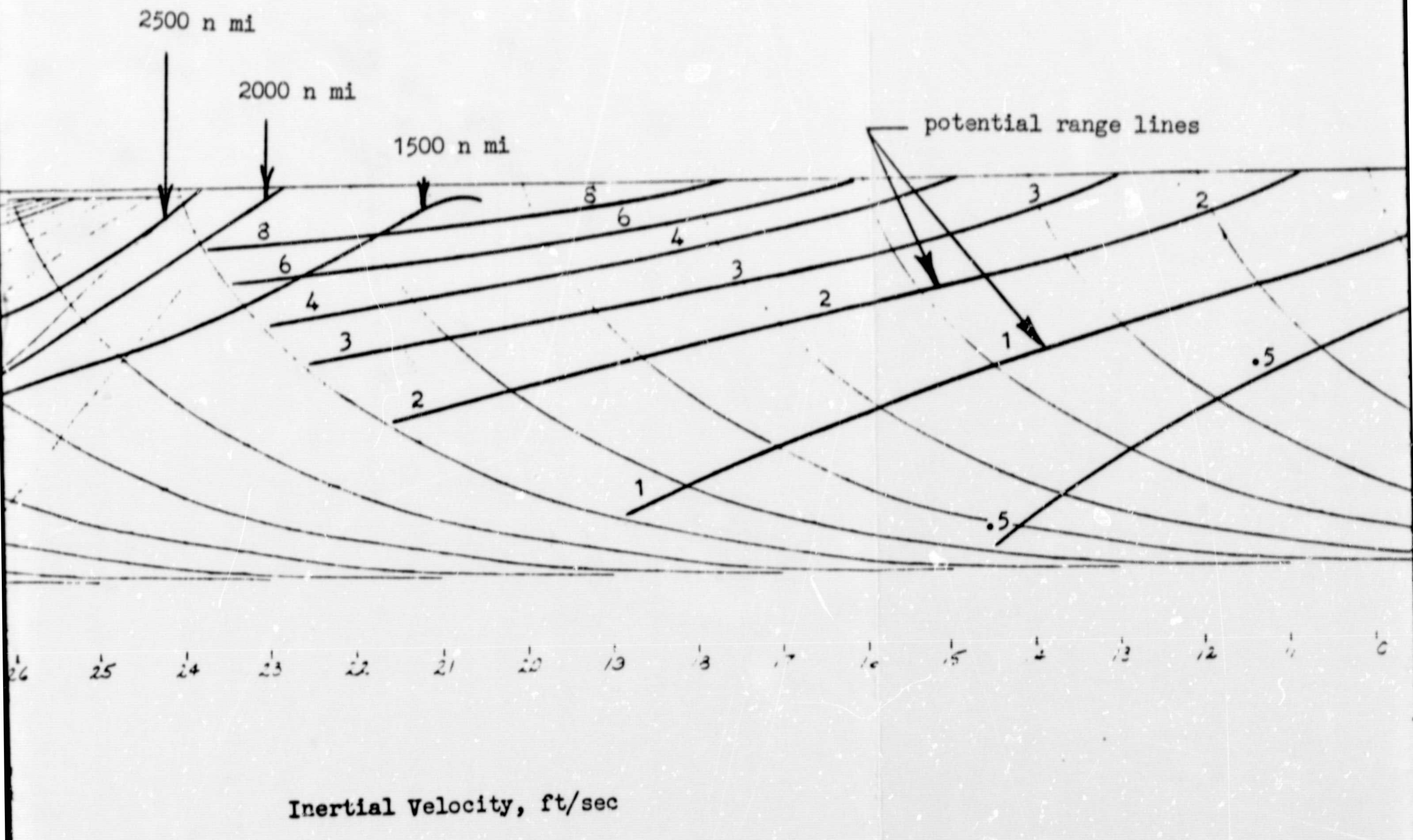


Figure 3 - EMS backup ranging lines

FOLDOUT FRAME 1



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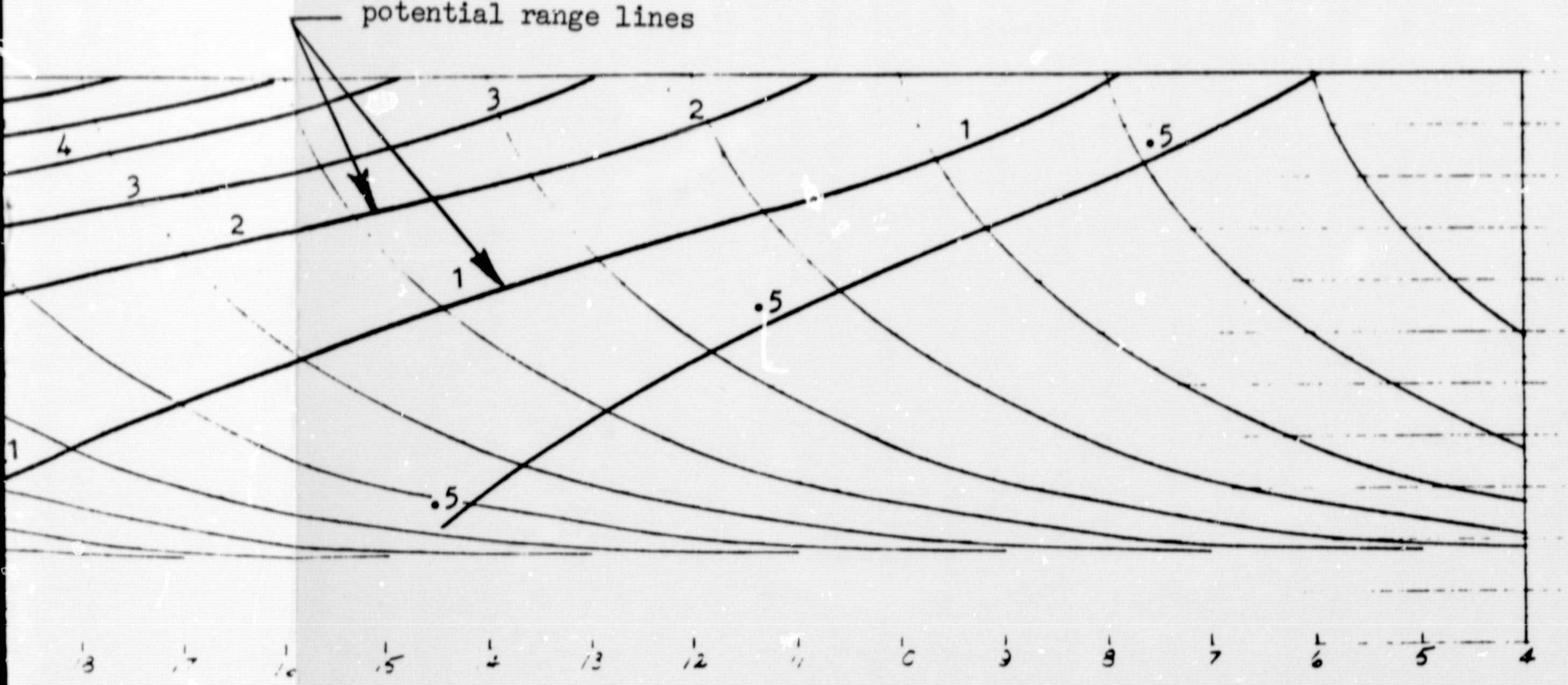

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FOLDOUT FRAME 3

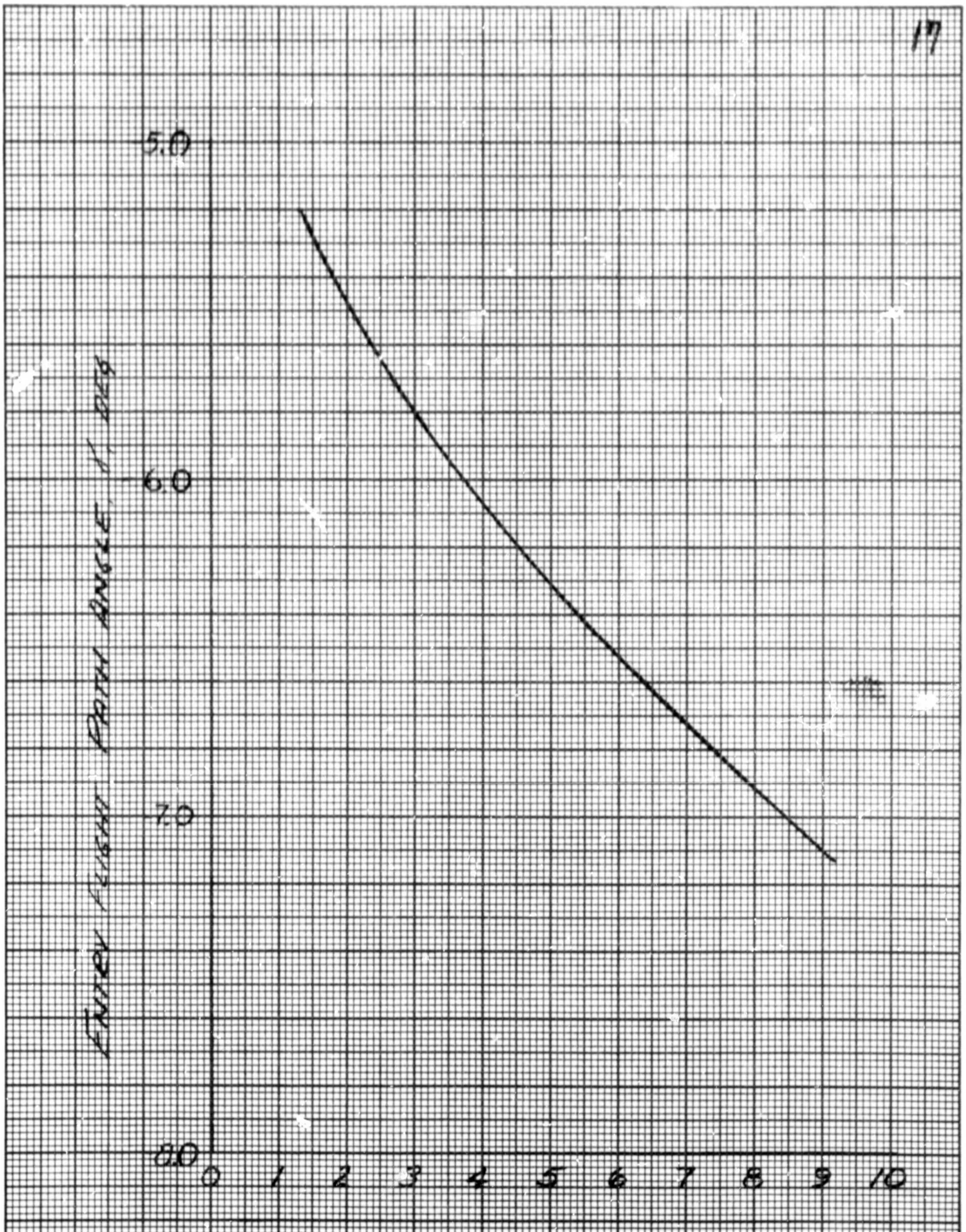


Figure 4 - Maximum g force vs flight path angle for lift-up entries

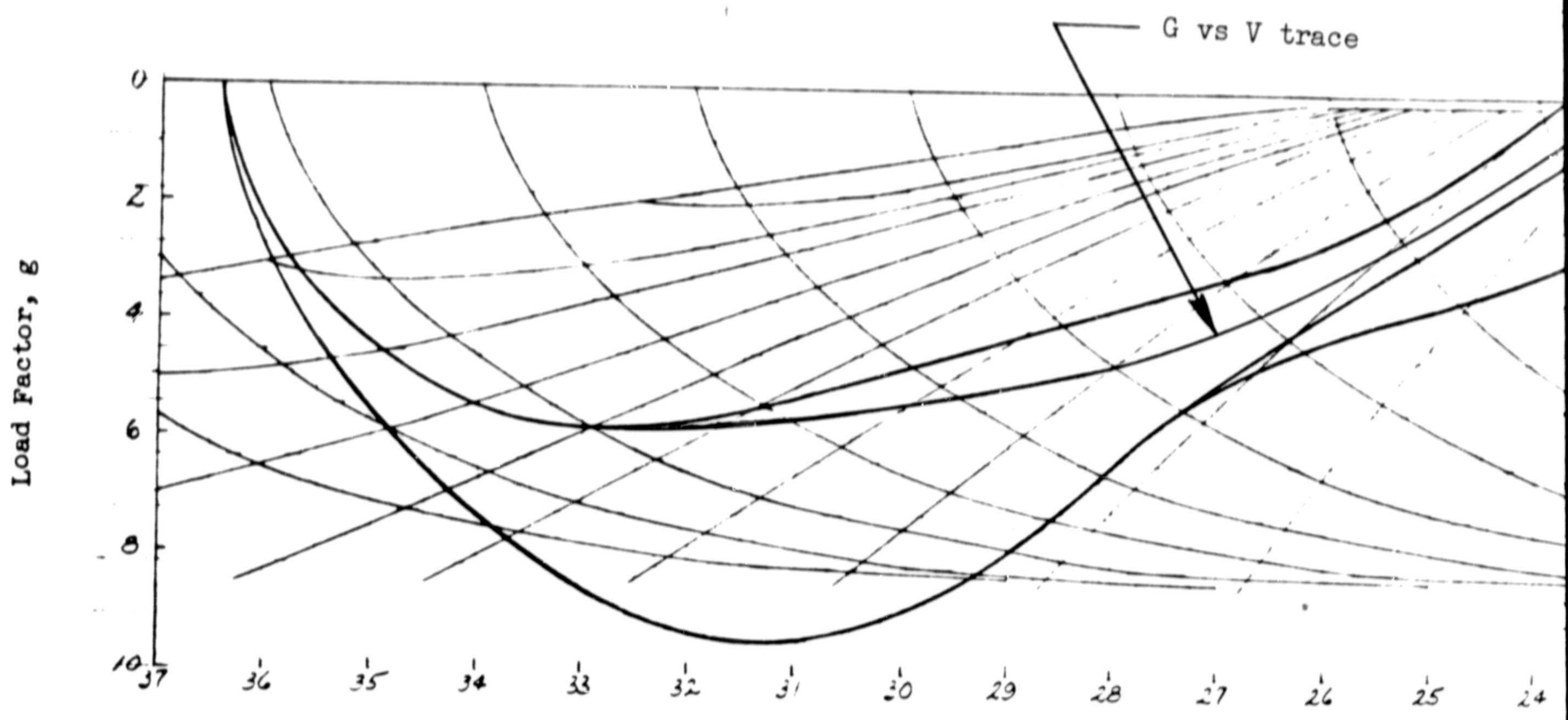
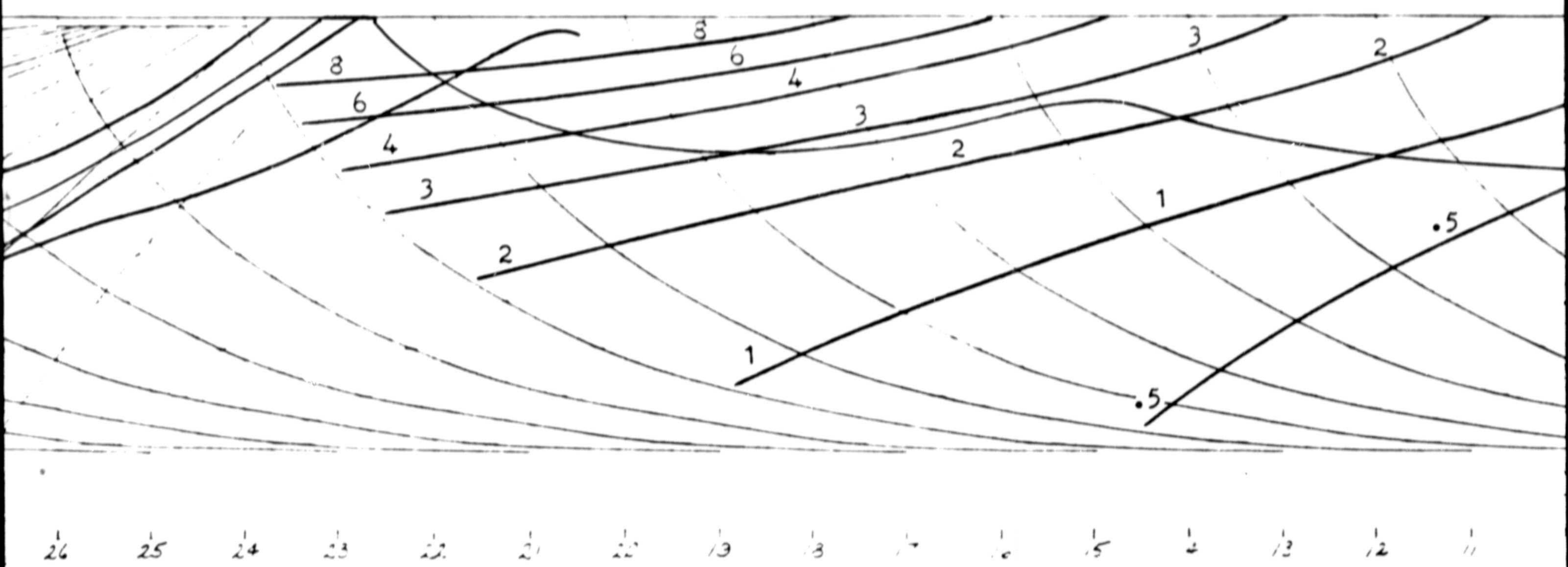


Figure 5 - G vs V trace for $\gamma_I = -6.4^{\circ}$ and RTG = 2200 n mi

FOLDOUT FRAME 1

trace



Inertial Velocity, ft/sec

FOLDOUT FRAME 2

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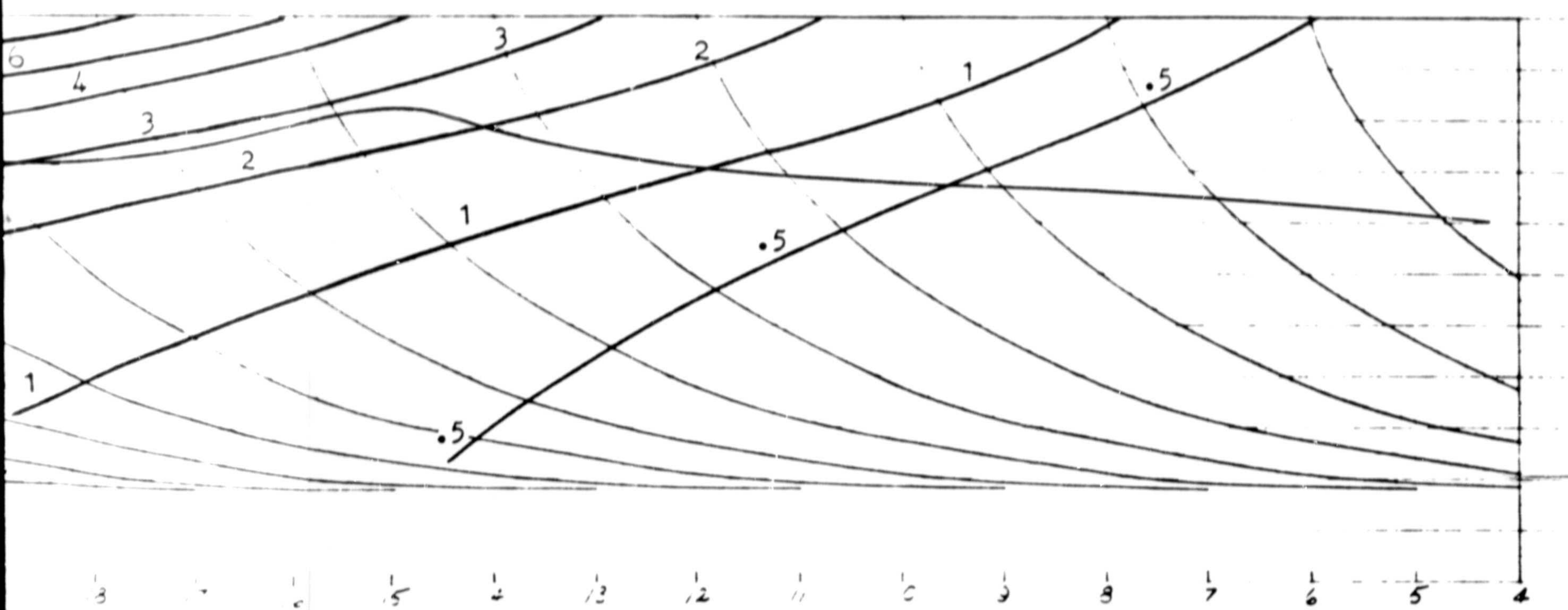

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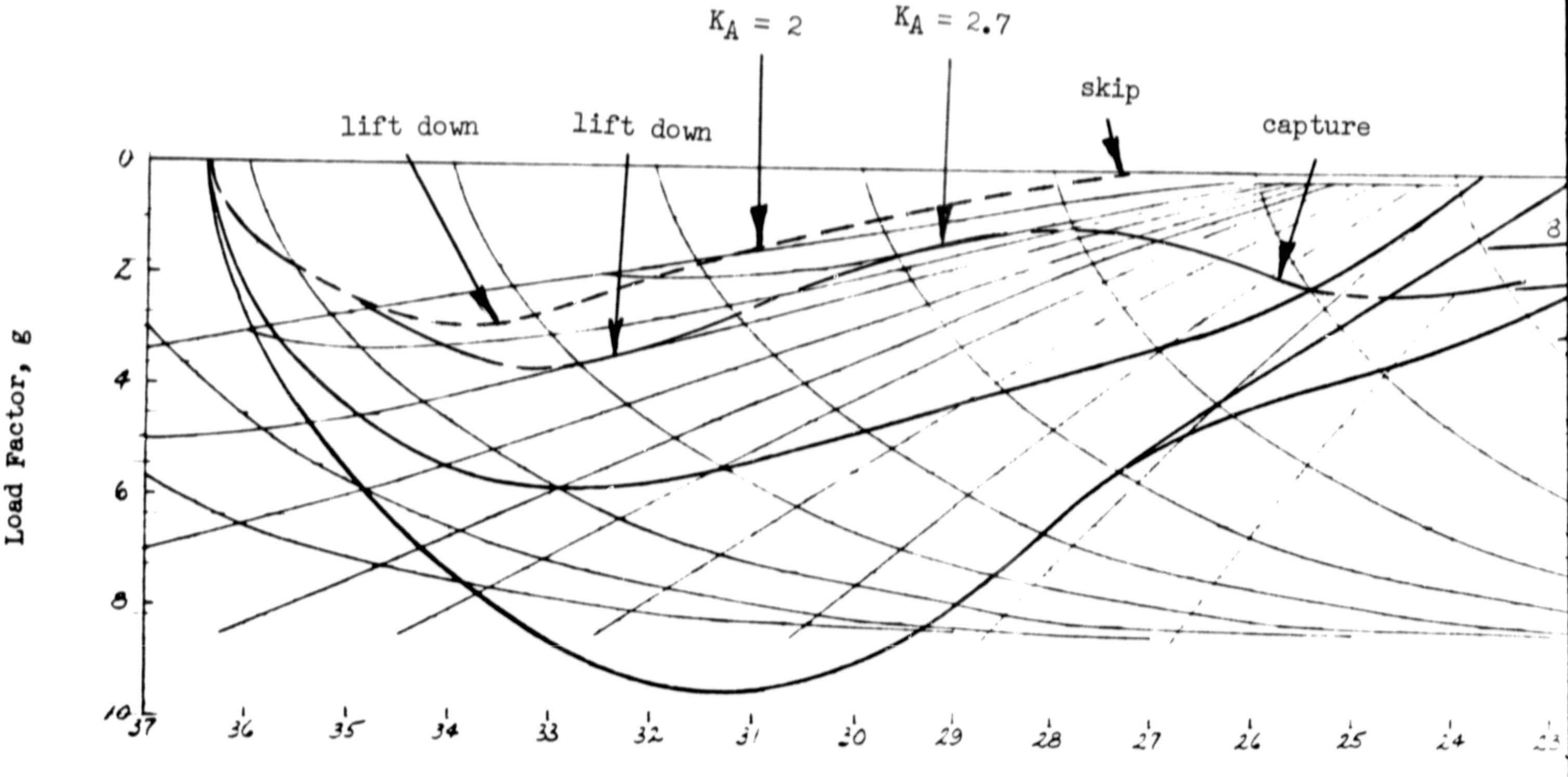
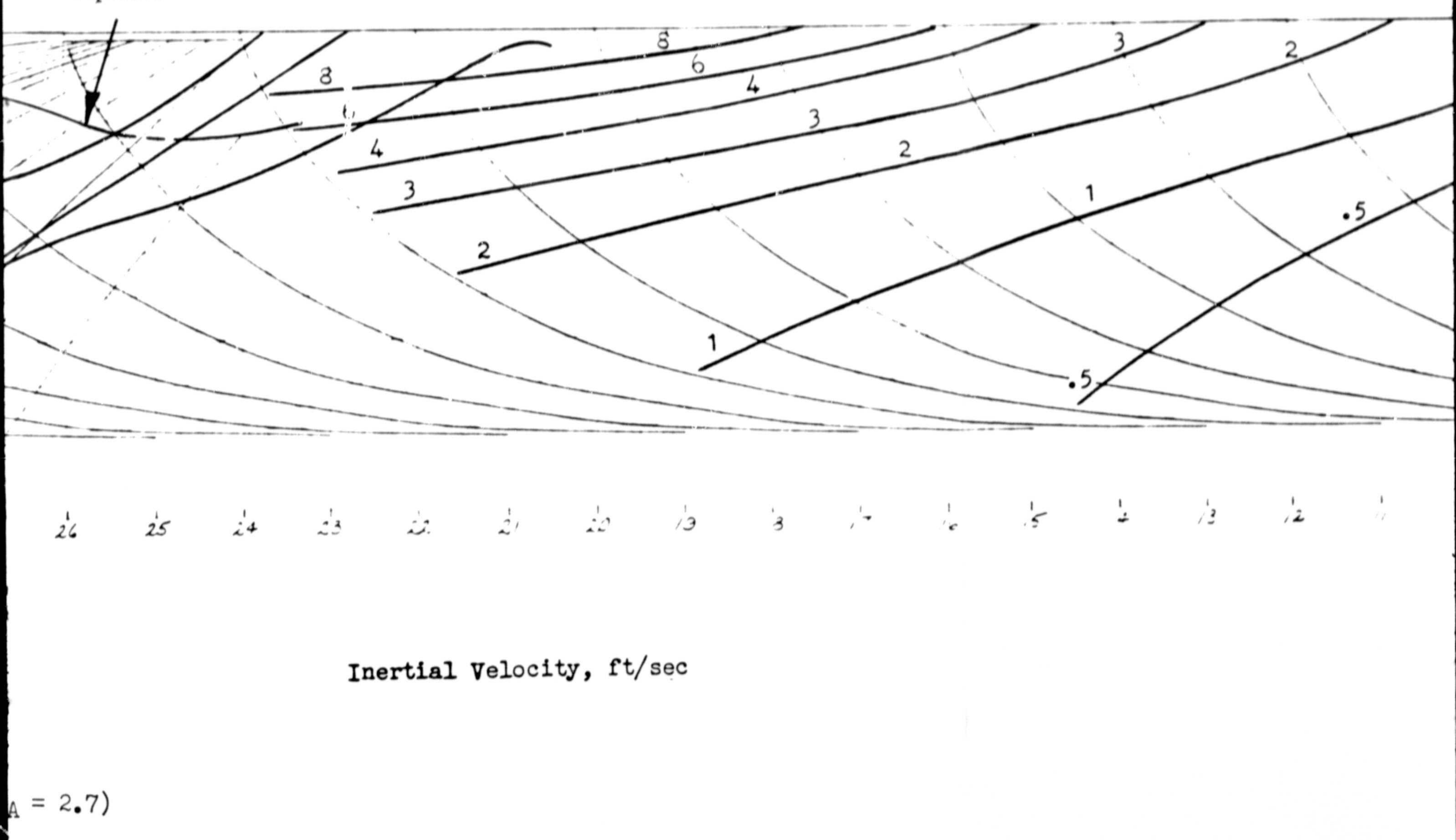


Figure 6 - G vs V trace for shallow entry and long target ($K_A = 2$, $K_A = 2.7$)

FOLDOUT FRAME 1

capture

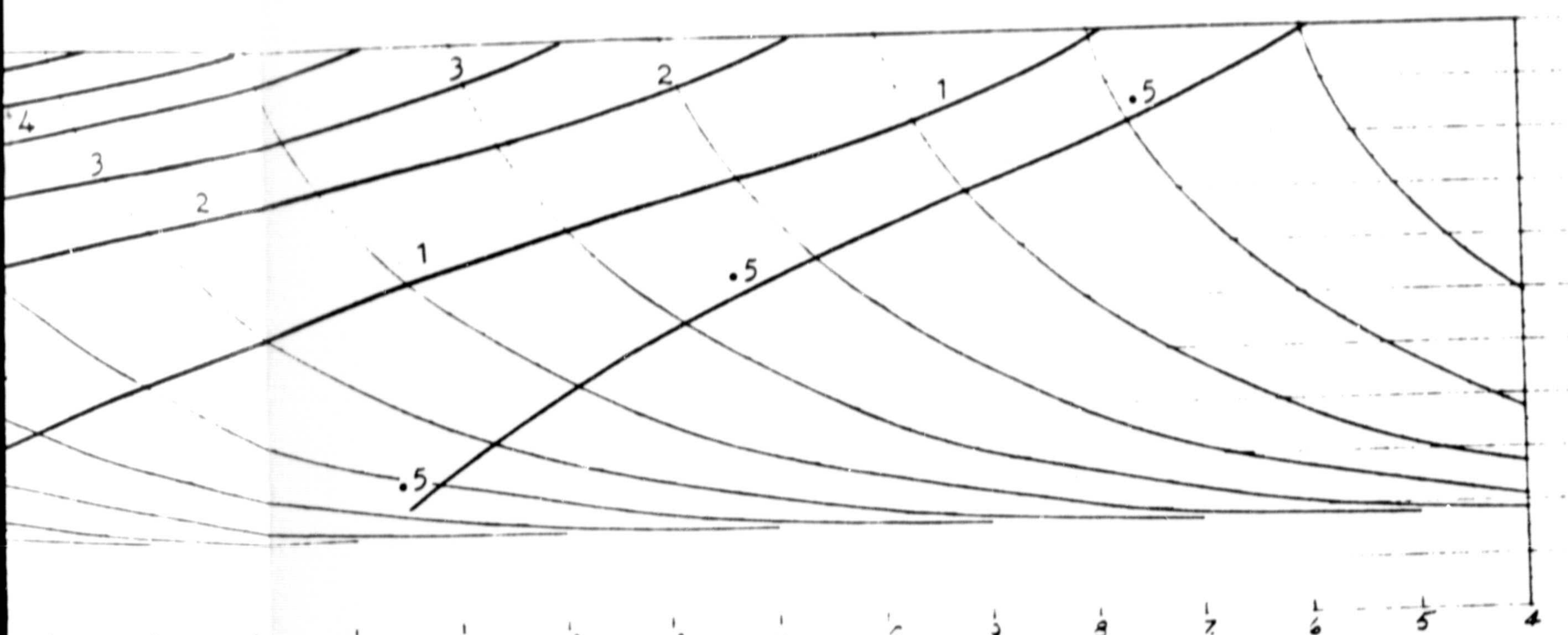


Inertial Velocity, ft/sec

A = 2.7)

FOLDOUT FRAME 2

19



FOLDOUT FRAME 3

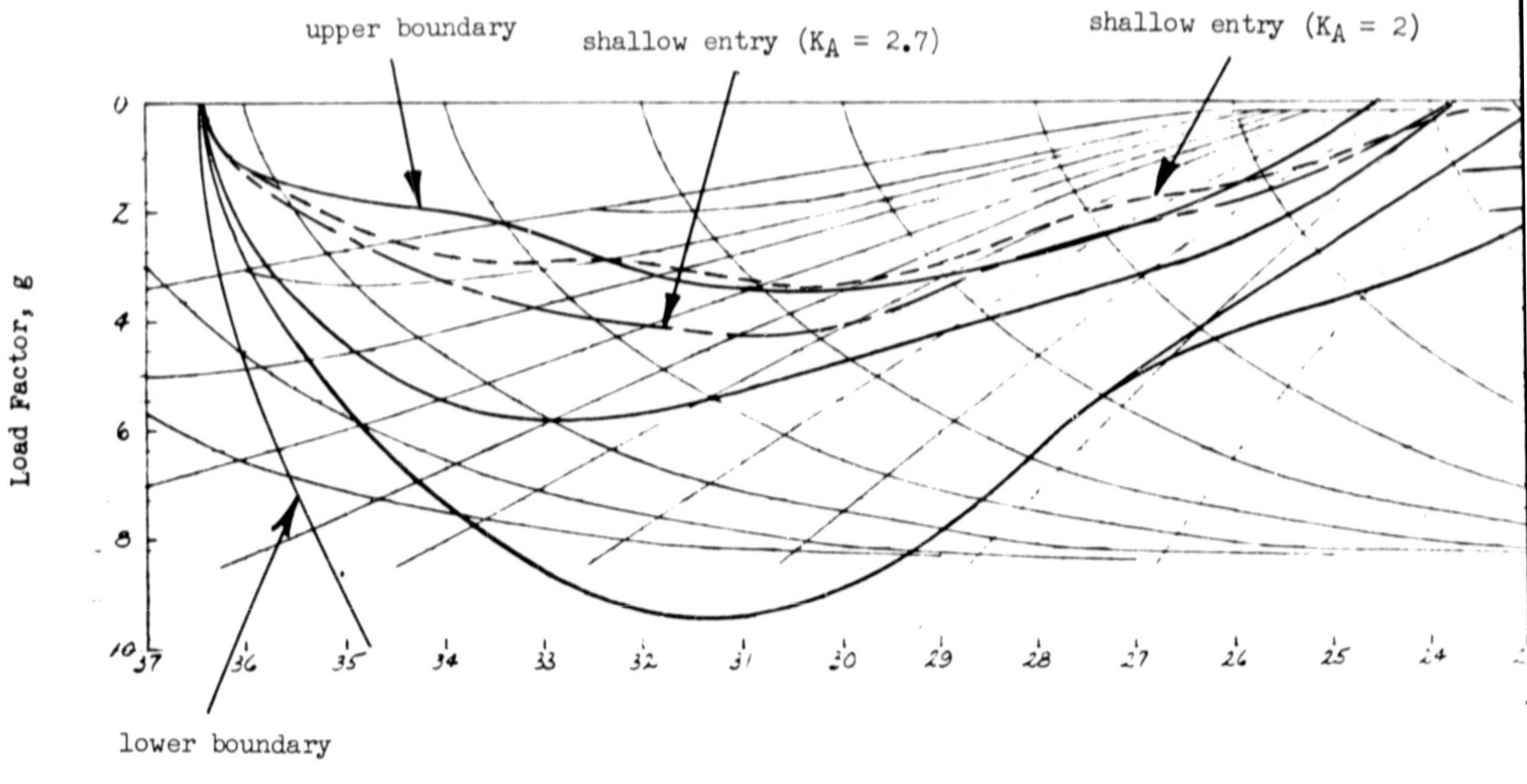
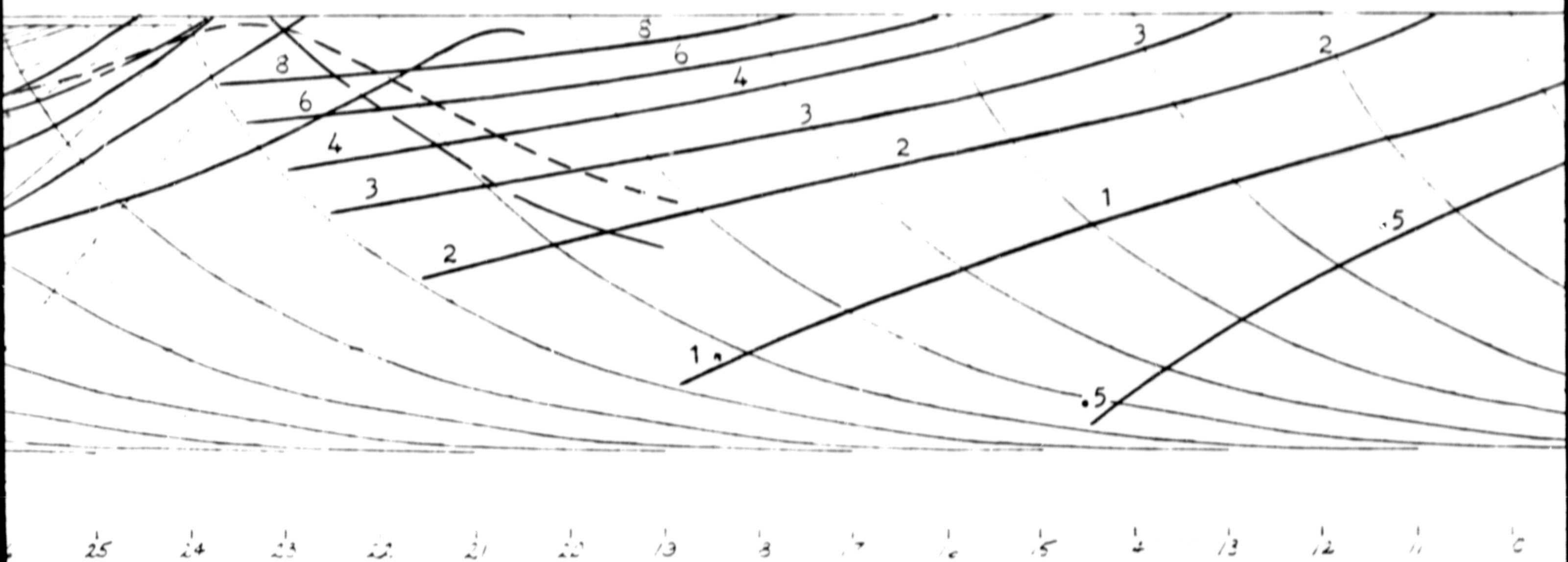


Figure 7 - Upper and lower heat shield boundaries

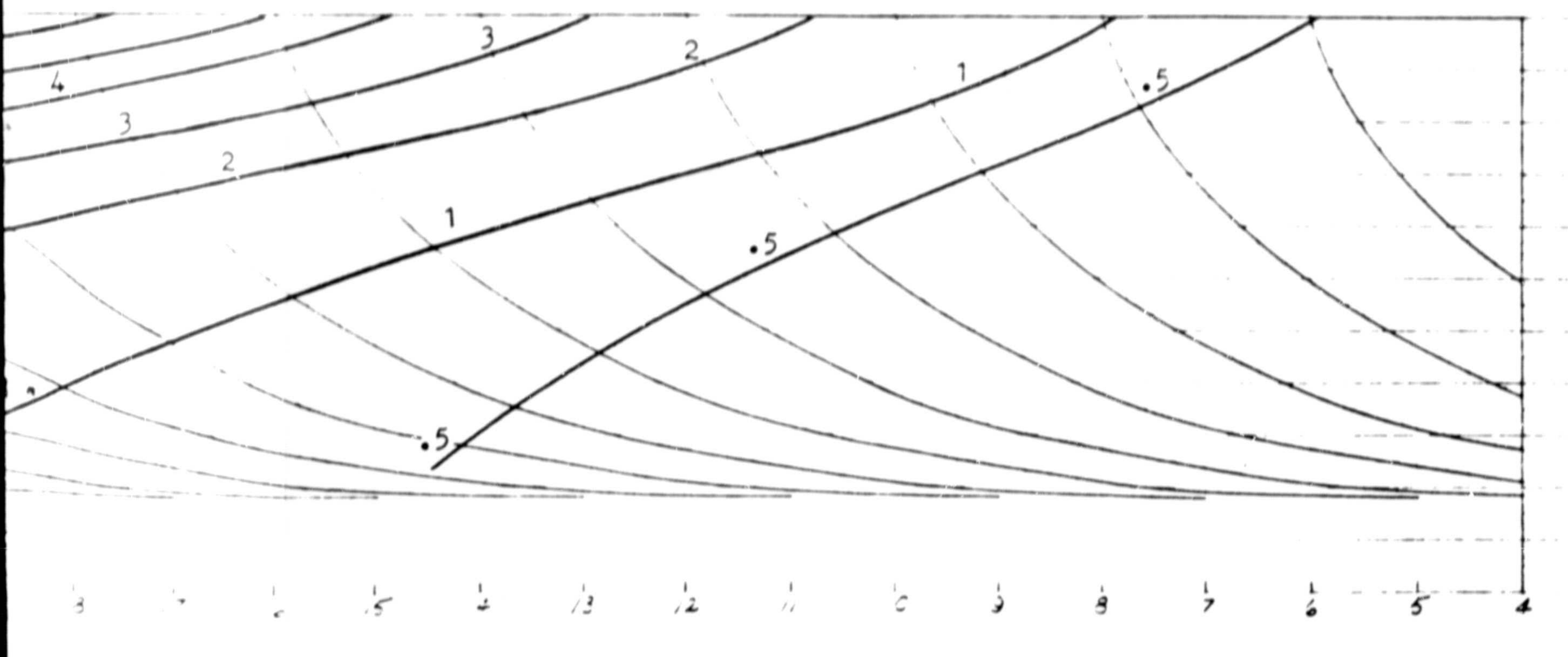
FOLDOUT FRAME 2

try (K_A = 2)



Inertial Velocity, ft/sec

FOLDOUT FRAME 2



FOLDOUT FRAME 3