No

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RESULTS OF SIMULATION OF LM RENDEZVOUS USING GRAPHICAL CHARTS

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MANNED SPACECRAFT CENTER

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RESULTS OF SIMULATION OF

LM RENDEZVOUS USING GRAPHICAL CHARTS

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1.0 SUMMARY

A man-in-the-loop simulation study of LM terminal phase rendezvous in earth orbit was conducted on the Lunar Module Procedures Simulator (LMPS) to establish the adequacy of graphical rendezvous charts as a backup and monitor of the PGNS and AGS. A total of 30 runs were made with 6 sets of initial conditions starting approximately 14 minutes prior to terminal phase initiation, and ending after establishing formation flying at a range of 50 to 100 feet. The resulting data indicated the mean propellant quantity required to accomplish a 15 n.m. Δh rendezvous from below to be 126.8 pounds, with a maximum propellant requirement of 150.3 pounds and a minimum of 112.1 pounds. Assuming a statistically normal distribution of propellant resulted in a computed standard deviation of 15.5 pounds in the total propellant used.

2.0 INTRODUCTION

2.1 Assumptions

The simulation runs were based on the following assumptions:

(1) Near inplane conditions existed at TPI.

(2) Information available for performing maneuvers was as follows:

DATA	SYMBOL	SOURCE/DISPLAY		SYSTEM ERRORS
Pitch angle	$\theta \sim .01$ DEG	AGS	DEDA	None
Body axis velocity increments	$\Delta V_{x, y, z} \sim$ FPS	AGS	DEDA	None
Range	R, NM/FT	RR	Tapemeter	$\pm 0.5_{NM}$ NM random R<10
Range rate	$\dot{R}$, FPS	RR	Tapemeter	2 FPS bias $\dot{R}$<50 FPS
Target line-of-sight rates	$\dot{\theta}_I, \dot{\Psi}_I \sim m$ RAD/SEC	RR	Crosspointers	None

(3) All thrusting was done along the LOS and/or normal to the LOS.

(4) The only AGS data used was Address 307 (the positive angle between the $+Z_{LM}$ axis and local horizontal).

(5) The AGS autopilot provided attitude hold and pulse mode for control.

2.2 Subjects

The simulations were run by two teams consisting of two simulation subjects each who alternated in the roles of left and right-hand pilots.

2.3 Initial Conditions

Six sets of initial conditions (IC's) were used--a nominal set with the LM and CSM in 165 n.m. and 180 n.m. circular orbits, respectively, and five other sets incorporating various errors in the LM state vector (see Figure 1). Neither out-of-plane velocity nor out-of-plane displacement were incorporated in any of the IC's. The LM configuration was the full ascent stage with full RCS tanks, giving it a total weight of 11,860 pounds. In this configuration, 1 pound of RCS propellant was equivalent to 0.73 FPS characteristic velocity.

2.4 Procedures

In calculating the TPI solution, the left-hand pilot used pulse mode to acquire and boresight on the CSM, then the right-hand pilot read elevation angle (Address 307) from the DEDA. Nominally, an elevation angle of 19.36 degrees occurred at TPI-8 minutes. The Event Timer (ET) was set to 8 minutes counting down and started when 307 indicated 019.36 degrees. The left-hand pilot boresighted on the CSM again at TPI-5 minutes and range and range rate were taken from the tapemeter while elevation angle was read from the DEDA. These data were then used to compute a TPI solution from the backup chart (see Appendix).

Attitude hold was used during thrusting with the pilot returning to pulse mode after thrusting was terminated.

The ET was set to count up when t = 0 and the midcourse backup charts were used to compute M/C corrections based on LOS angle data and range and range rate data taken at the times after TPI specified on the M/C charts.

After the second M/C correction, the X-pointers were used to null LOS and azimuth rates. Braking was done according to the gates shown in Figure 2.

2.5 Backup Charts

2.5.1 TPI Chart

The TPI backup chart consisted of a plot of range and range rate versus ΔV forward and another of $\Delta\theta$ and range versus ΔV up/down from which an inplane TPI burn was computed based on the backup data taken. The $\Delta\theta$ used was the (positive) change in the LOS angle from TPI-8 minutes to TPI-5 minutes.

2.5.2 M/C Charts

Two types of backup M/C charts were used. Both are shown in the Appendix. The first type required that the LOS angle θ be read at 4, $4\frac{1}{2}$, $7\frac{1}{2}$, and 8 minutes after TPI for the first M/C and at 15, $15\frac{1}{2}$, $18\frac{1}{2}$, and 19 minutes after TPI for the second M/C. Range and range rate data were taken at 6 and 17 minutes after TPI for each of the two M/C's. For each M/C, the difference in the sums of the first two and last two

LOS angle readings was calculated to get an "average" 2 $\Delta\theta$. This was done to reduce the effects of tracking errors. This was used in a plot of 2 $\Delta\theta$, range, and the last value of θ taken versus ΔV up/down to get an up/down correction. The fore/aft correction was computed from a plot of range and θ versus ΔV fore/aft. The second type of M/C chart used was similar to the TPI chart in that it required only two measurements of θ LOS (one at TPI+15 minutes and the other at TPI+18 minutes) and one reading each of range and range rate (taken at the second reading of θ LOS). Otherwise, the graphical solutions for ΔV fore/aft and ΔV up/down were similar to those used on the other type of chart. Where this second type of backup M/C chart was used, only one M/C correction was made.

3.0 DISCUSSION

3.1 Propellant Usage

A total of 19 familiarization runs and 30 data runs were made during the study. The familiarization runs are not included in the results since they were made to develop pilot proficiency. Figure 3 is a breakdown of the mean propellent requirements for each of the six cases individually and the six cases as a whole. The theoretical minimum propellant usage is the two-impulse burn as computed by the AGS computer. A summary of the results of the simulations in terms of total propellant used is also given in Figure 4. Case I required the greatest amount of propellant, while Case IV was the most economical. This was due to the LM being below its nominal altitude with its altitude decreasing in Case I; whereas in Case IV, the LM was over a mile higher than nominal and slowly losing altitude. The remaining IC's represented various cases between these two extremes.

3.1.1 TPI

The propellant required for TPI by the various cases is given in Figure 5. Note that only Case IV showed a consistent trend to deviate from the mean TPI propellant requirement, the trend being to require less than the nominal amount of propellant. This would be expected with the Δh at TPI being less than nominal for Case IV.

3.1.2 M/C's

Figures 6 and 7 are graphic representations of the propellant requirements for the M/C's that were made. The mean M/C correction in terms of pounds of propellant is given on each figure. The ellipses were generated using the formula for the standard deviation of data about the mean value. The graphs use the sign convention that up and forward are positive burns with aft and down representing negative burns. For instance, the mean first M/C burn was 1.3 pounds up and 0.2 pounds aft, and the mean second M/C burn was 1.9 pounds up and 0.9 pounds forward.

3.1.3 Braking and LOS Control

The propellant requirements for braking and for nulling of LOS rates are given in Figures 8 and 9. LOS control consisted of nulling elevation and azimuth rates as indicated by the crosspointers, and the data of Figure 9 are totals required to null both rates. The braking gates given in Figure 2 were utilized by all of the simulator subjects. Wide variations in the quantity of propellant for braking can be noted in each case, but Case V was consistently less expensive than any other. Likewise, there was a wide variation in each case of the propellant required to control LOS rates with Case IV being far cheaper than any other case.

3.2 Accuracy of Charts

The charts used in this study proved to be an adequate means of computing a TPI and M/C burns independently of the PGNS and AGS. However, the charts were susceptible to various errors that limit their solutions to an accuracy of ± 1 FPS. Errors in the measurement of LOS angle are a function of the precision with which the pilot can boresight on the target which is on the order of ± 0.1 degrees using the error needles. Also, while the range rate tapemeter could be read accurately to within 0.5 FPS, the range tapemeter could only be read to the nearest 0.5 n.m. on the largest scale and to within 100 feet on the intermediate scale. The error in θ LOS when boresighting represented an uncertainty of 1 FPS UP/DWN at TPI and at the M/C's. The error in reading range was equivalent to an uncertainty of 2 FPS in the first M/C and 0.5 FPS in the second M/C. Additional errors in range data were caused by a tendency of the range tapemeter to slip when driven to the reset point. Frequent checks on the tapemeter were made from within the crew station, and several times it was found to be off by 0.5 n.m. at the point in the run where the first M/C was being computed. The error due to slippage became less critical, however, as the tapemeter progressed to the intermediate and lower scales. The presence of these uncertainties in the backup charts led to the decision not to apply any computed burns of 1 FPS or less.

4.0 CONCLUSIONS

The simulation study made led to the following conclusions:

(1) The charts and procedures used consistently resulted in a successful LM terminal phase rendezvous.

(2) The mean propellant required for terminal phase was 126.8 pounds, and it was felt that with more experience on the part of the simulator subjects this total could be reduced perhaps as much as 10 pounds.

(3) Corrections of 1 FPS or less should not be applied.

(4) The mean value of TPI was 44.5 pounds along the line-of-sight.

(5) The mean value of the first M/C was 1.3 pounds up and 0.3 pounds aft.

(6) The mean value of the second M/C was 0.8 pounds forward and 1.9 pounds up.

FIGURE 1

INITIAL CONDITIONS

CASE	R(NM)	$\dot{R}$(F/S)	Θ_{LOS} (DEG)	H_{LM} (NM)	$\dot{H}_{LM}$ (F/S)
NOM	52.9	-151.0	16.0	165.0	0.0
I	52.8	-153.6	16.7	164.4	-2.1
II	54.4	-166.0	17.1	163.5	1.8
III	52.1	-154.9	16.7	164.5	-2.8
IV	46.1	-136.5	16.9	166.2	-0.3
V	53.12	-163.8	17.3	163.7	3.8

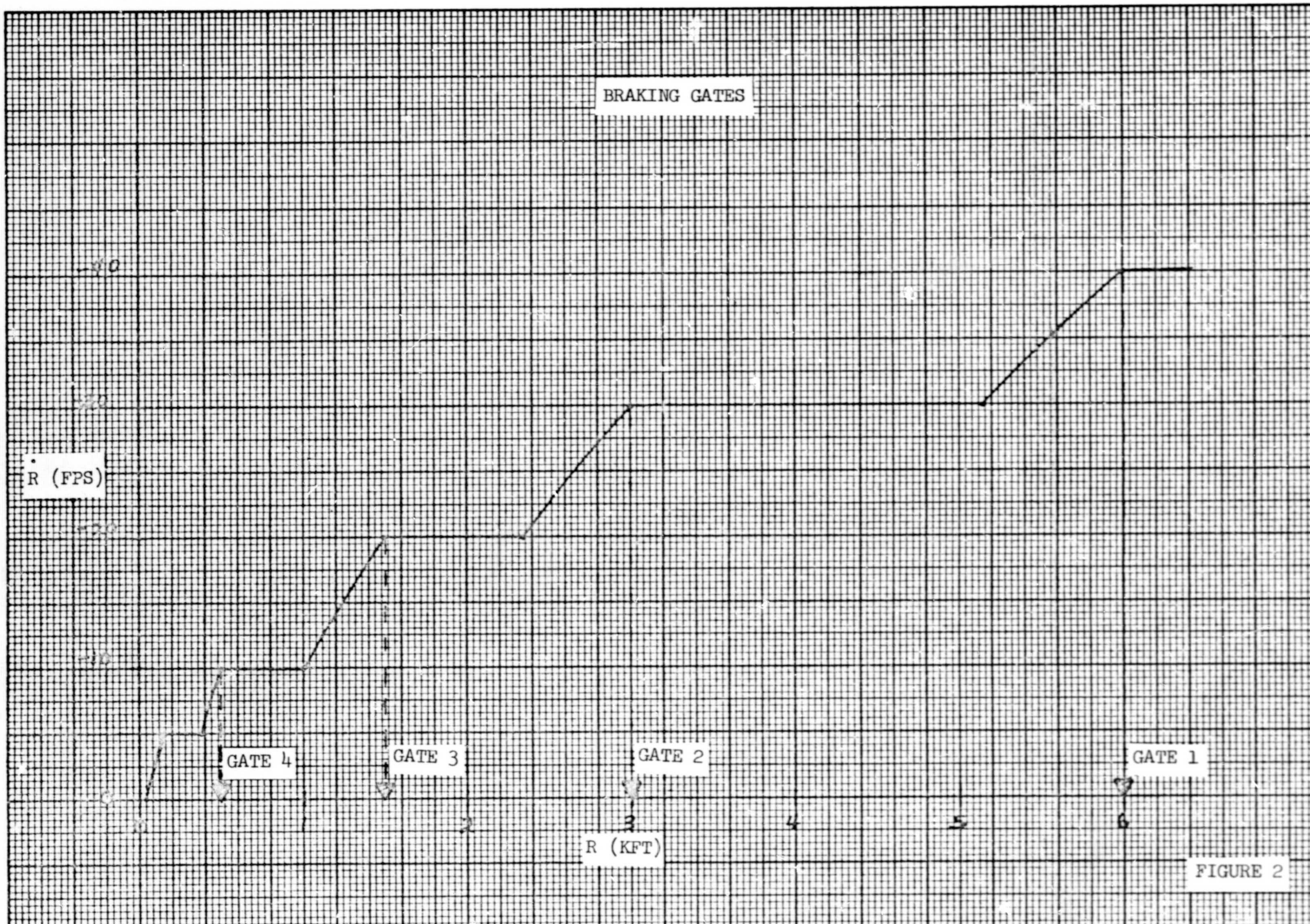

BRAKING GATES
-40
-30
-20
-10
0
$\dot{R}$ (FPS)
GATE 4
GATE 3
GATE 2
GATE 1
0
1
2
3
4
5
6
R (KFT)

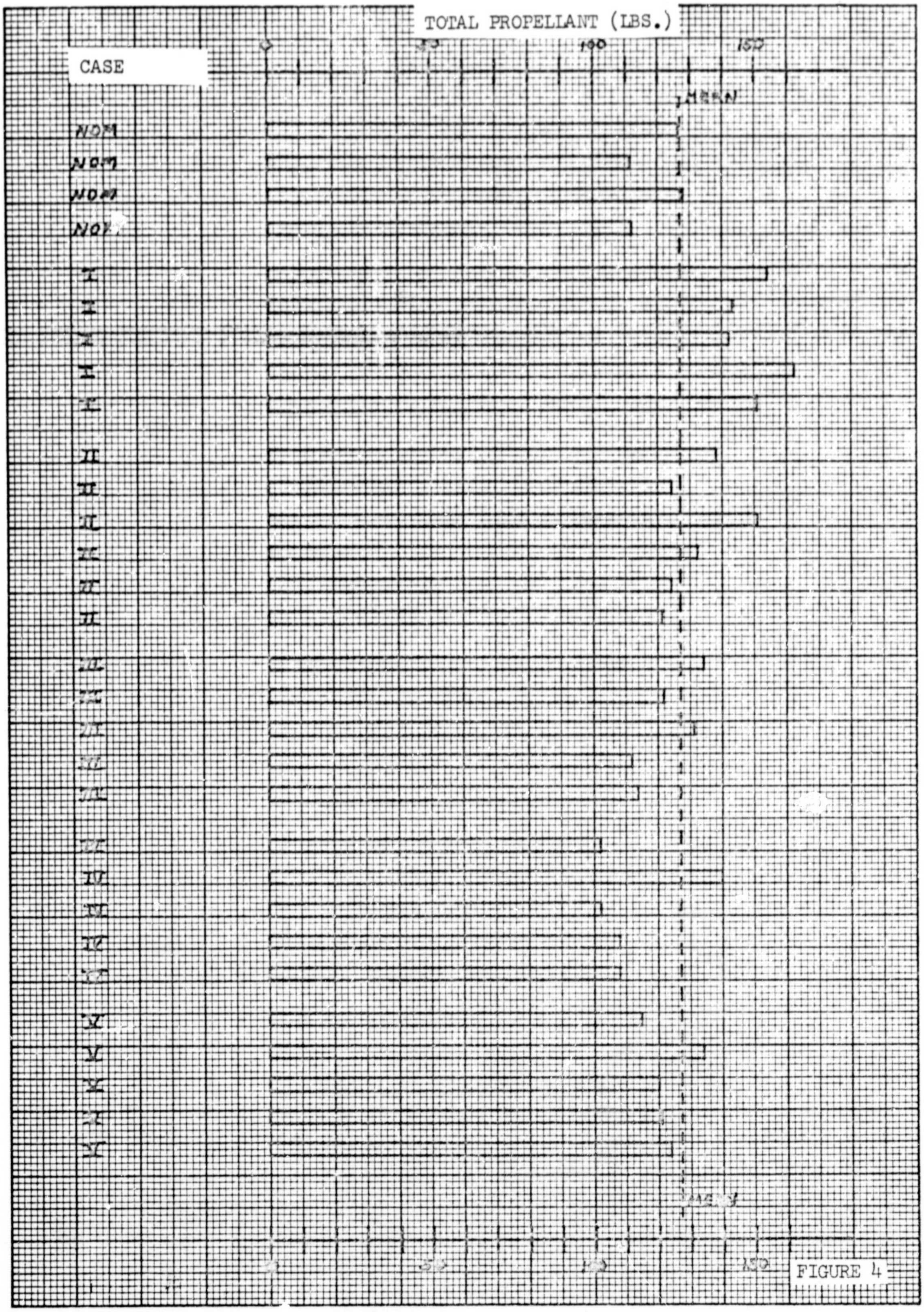
FIGURE 2

MEAN PROPELLANT USAGE (LBS.)

CASE:		NOM	I	II	III	IV	V	ALL CASES	
TPI:	fore	43.6	46.1	47.5	45.9	38.9	45.0	44.6	
	aft	0.0	0.0	0.0	0.0	0.0	0.0	[illegible]	
	up	0.0	2.6	0.6	1.7	0.0	0.0	0.8	
	down	0.0	0.0	1.4	0.0	0.0	1.7	0.6	
M/C 1:	fore	1.3	4.0	1.2	0.5	1.6	0.5	1.5	
	aft	1.1	0.0	2.2	0.9	0.0	5.0	1.7	
	up	2.0	4.7	1.3	2.5	0.0	0.1	1.6	
	down	0.0	0.0	0.3	0.0	0.3	1.2	0.3	
M/C 2:	fore	2.9	7.6	0.3	2.5	3.7	0.8	2.9	
	aft	0.0	0.0	5.3	1.9	1.0	3.6	2.1	
	up	1.4	8.5	1.9	0.6	2.3	0.1	2.5	
	down	0.0	0.0	0.5	0.6	1.1	1.3	0.6	
BRAKING:		42.3	34.6	34.3	41.9	37.2	23.9	35.3	
LOS	up	NA	NA	NA	NA	NA	NA	NA	
CONTROL:	down	NA	NA	NA	NA	NA	NA	NA	
	left	NA	NA	NA	NA	NA	NA	NA	
	right	NA	NA	NA	NA	NA	NA	NA	
ATTITUDE:		25.0	23.8	23.4	17.0	23.4	24.6	22.7	
TOTAL FUEL:		119.1	150.3	131.6	122.6	112.1	122.6	126.8	
THEORETICAL MINIMUM:		[illegible]	96.0	13.3	89.3	82.6	72.0	10.2	
DIFFERENCE:		31.1	54.3	38.3	33.3	29.5	30.6	36.6	
FACTOR:*		1.4	[illegible]	1.4	1.4	[illegible]	[illegible]	[illegible]	
TRANSFER TIME:		[illegible]	47:16	43:07	40:15	40:52	46:02	43:22	

*/ FACTOR = TOTAL FUEL/THEORETICAL MINIMUM

FIGURE 3


TOTAL PROPELLANT (LBS.)
CASE
0
50
100
150
MEAN
NOM
NOM
NOM
NOM
I
I
I
I
I
II
II
II
II
II
II
III
III
III
III
III
IV
IV
IV
IV
IV
V
V
V
V
V
MEAN
0
50
100
150
FIGURE 4

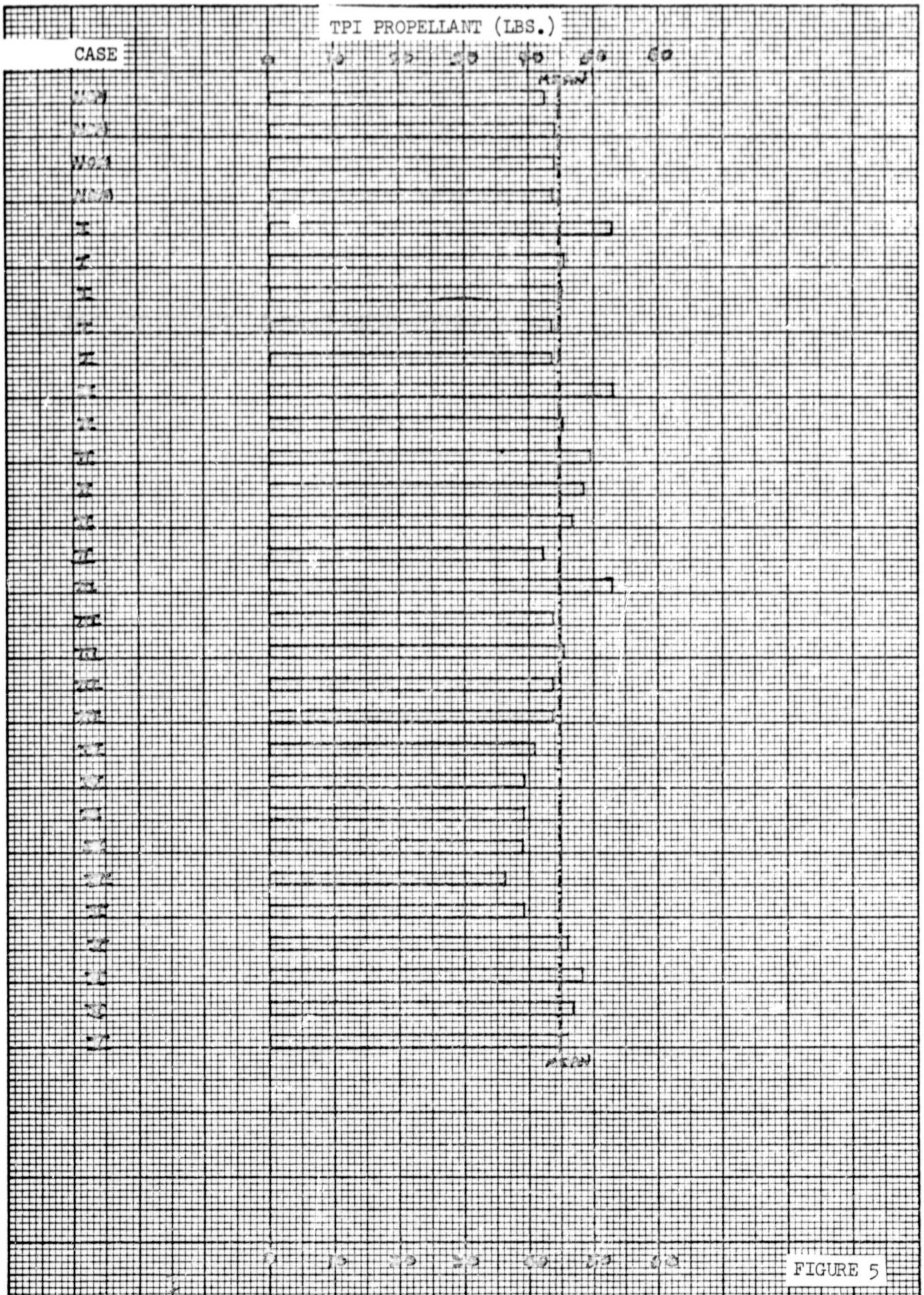


FIGURE 5

(1.8, 10.0)

1st M/C PROPELLANT (LBS.)

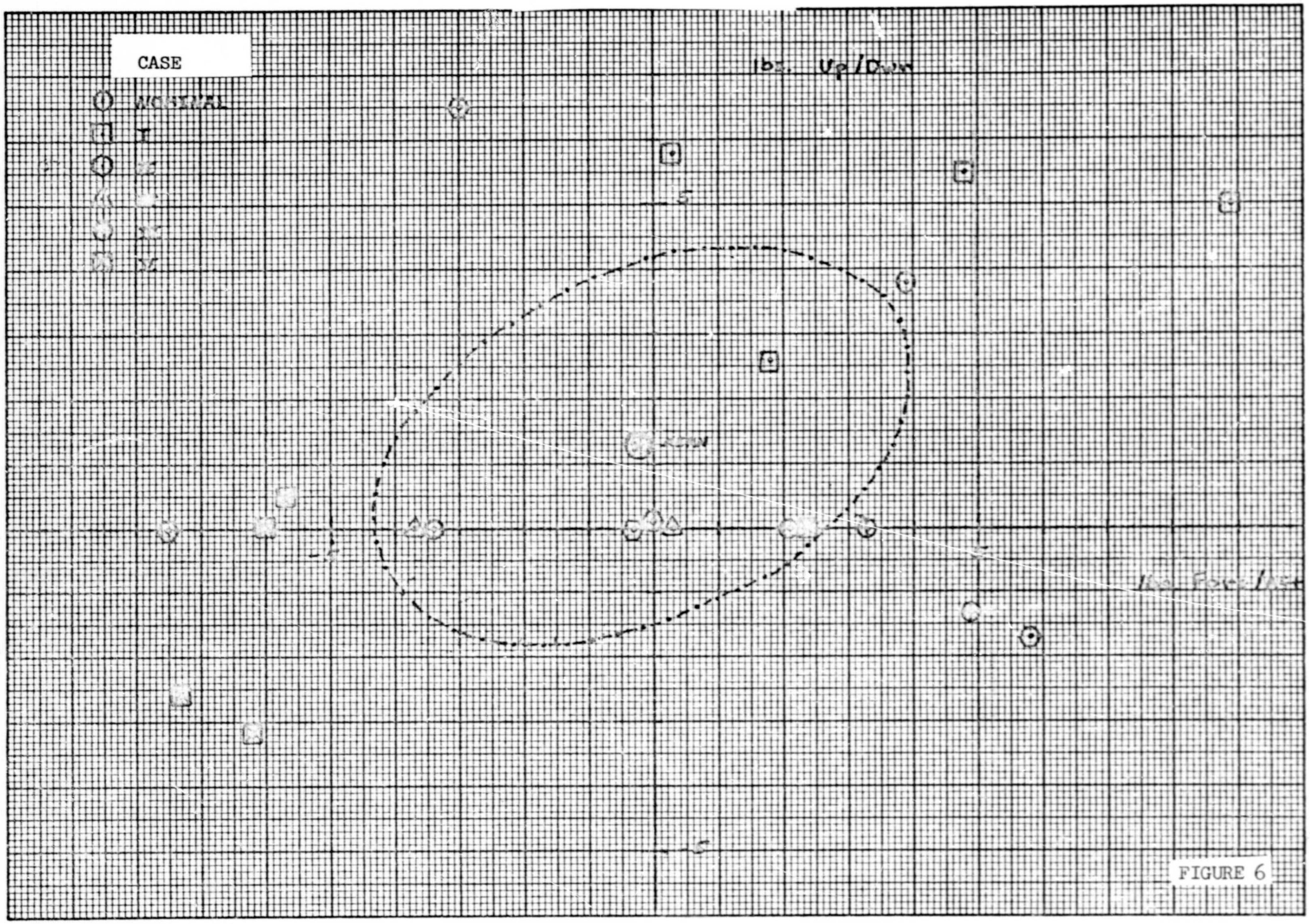


FIGURE 6

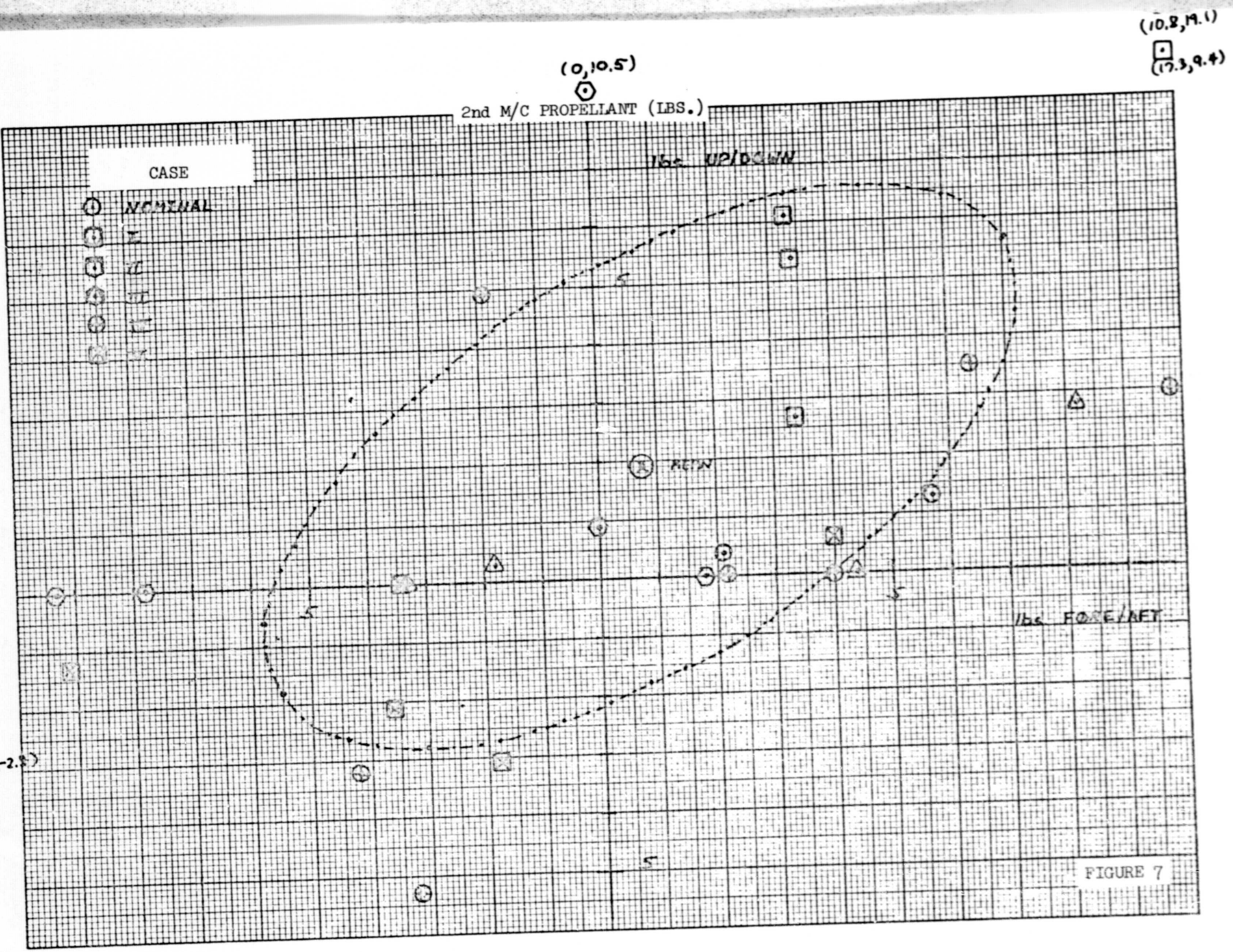

(0,10.5)
2nd M/C PROPELLANT (LBS.)
(10.8,19.1)
(17.3,9.4)
CASE
NOMINAL
I
II
lbs. UP/DOWN
lbs. FORE/AFT
REIN
5
5
5
5
-2.8)

FIGURE 7

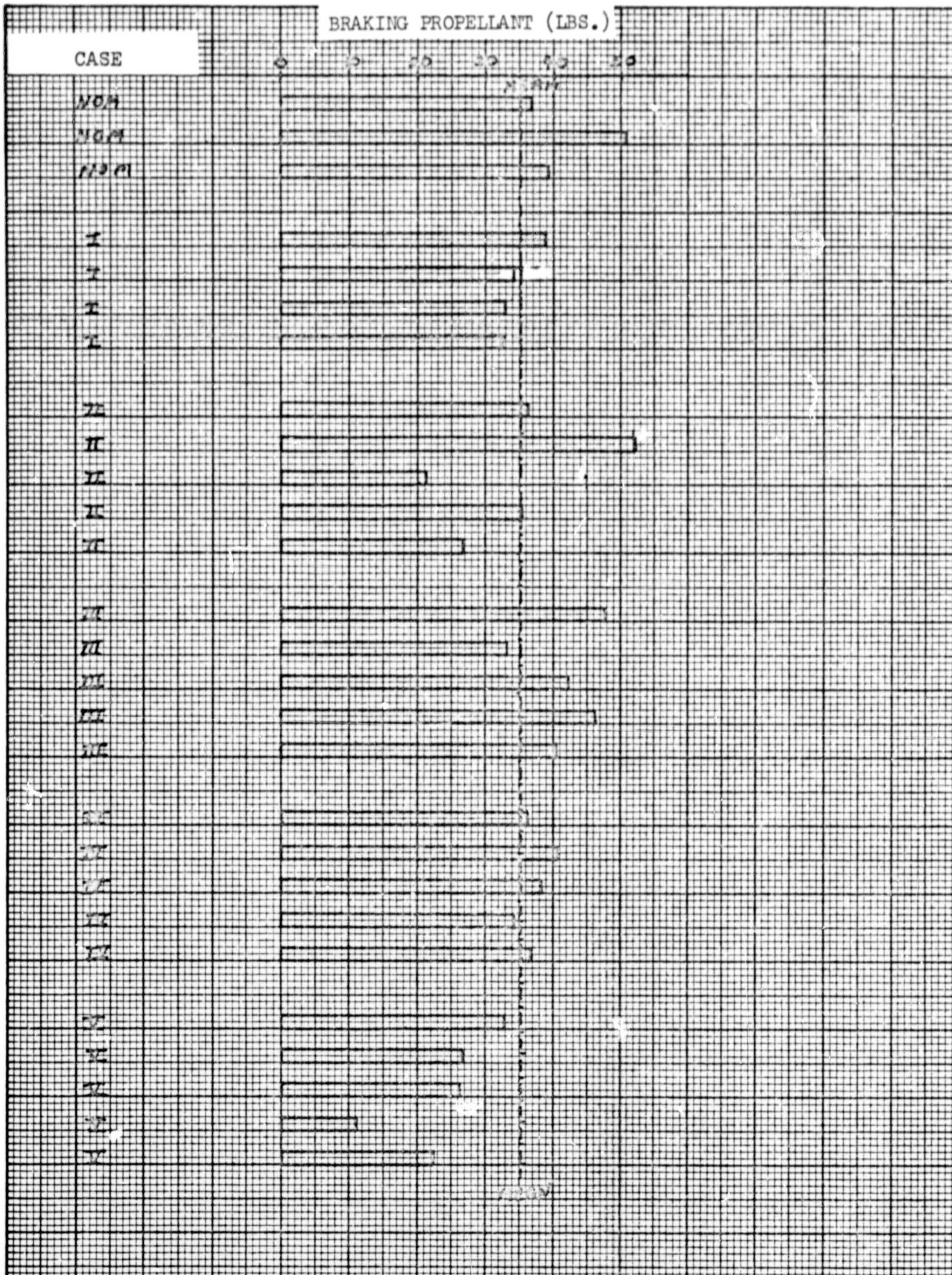


FIGURE 8

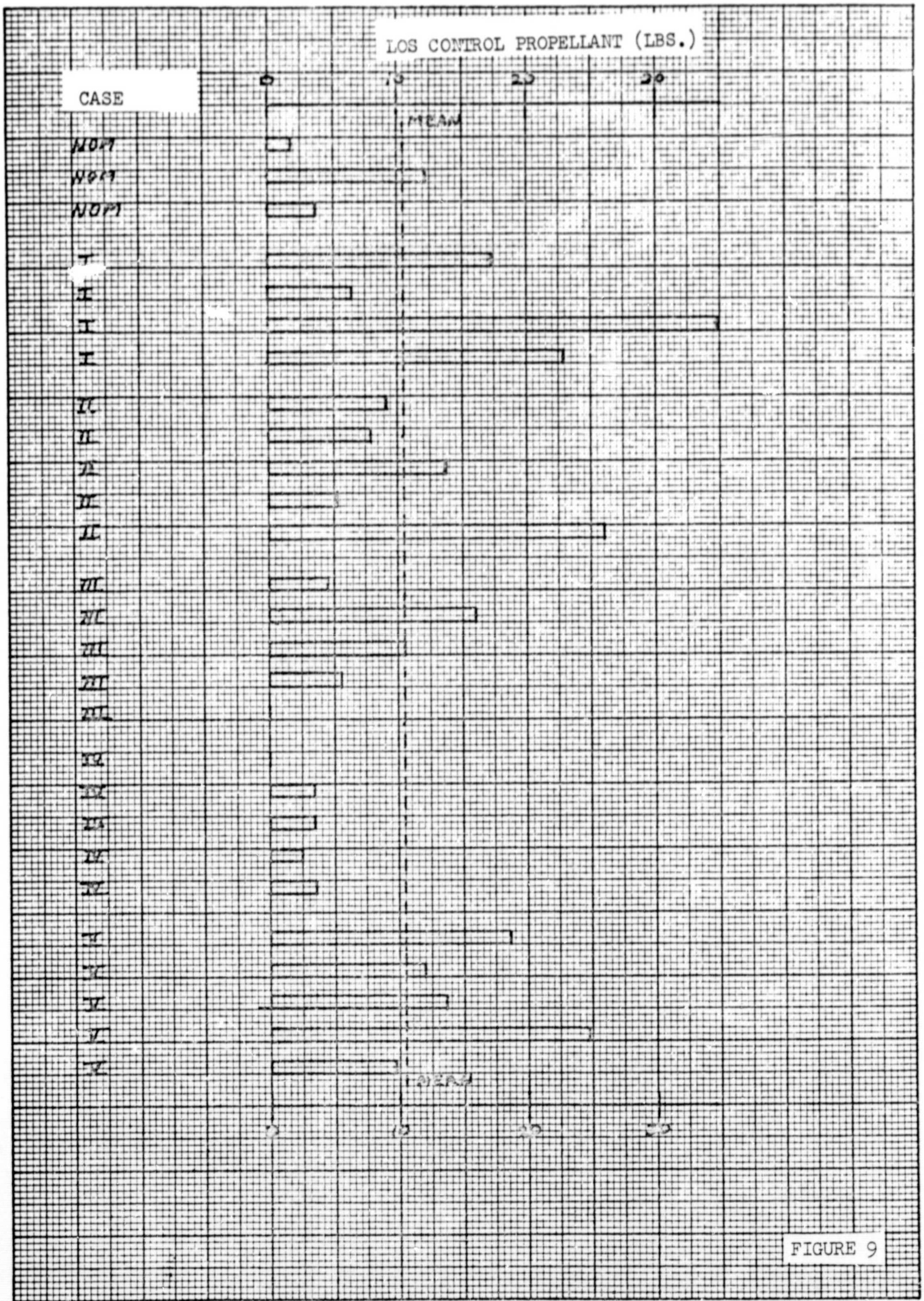


FIGURE 9

APPENDIX

ATT CONT - PULSE (3)
RATE/ERRMON - RNDZ RADAR
X-TRANSL - 2 JETS
MAN THROT - CDR
THR CONT - MAN
BAL CPL - ON
THROTTLE/JET - JET

Enter 407:+00000, 407:10000, 410:50000
(External ΔV)
Enter 450:; 451:, 452: = +00000
Readout 307: (θ)

Set E.T. to -8:00 to Count Down
When 307: 18.5 Deg, Boresight With
Precision - Reticle or Error Needles

-8:00 When 307: = 19.36 Deg, Give CP Mark, Start
E.T. Down, Copy

-5:00 Give Pilot Mark Read 307: (θ), R and $\dot{R}$
From T.M., Copy

-0:30 ATT CONT - MODE CONT (3)
MODE CONTROL - ATT HOLD
Readout 502: (Δ VZ)

0:00 Start FWD Thrust AT = 0:00
Start E.T. Counting Up
Give CP Mark When ΔV_z Attained

Readout 500:
Thrust Up/Down
Give CP Mark When ΔV_X Attained
ATT CONT - PULSE (3)

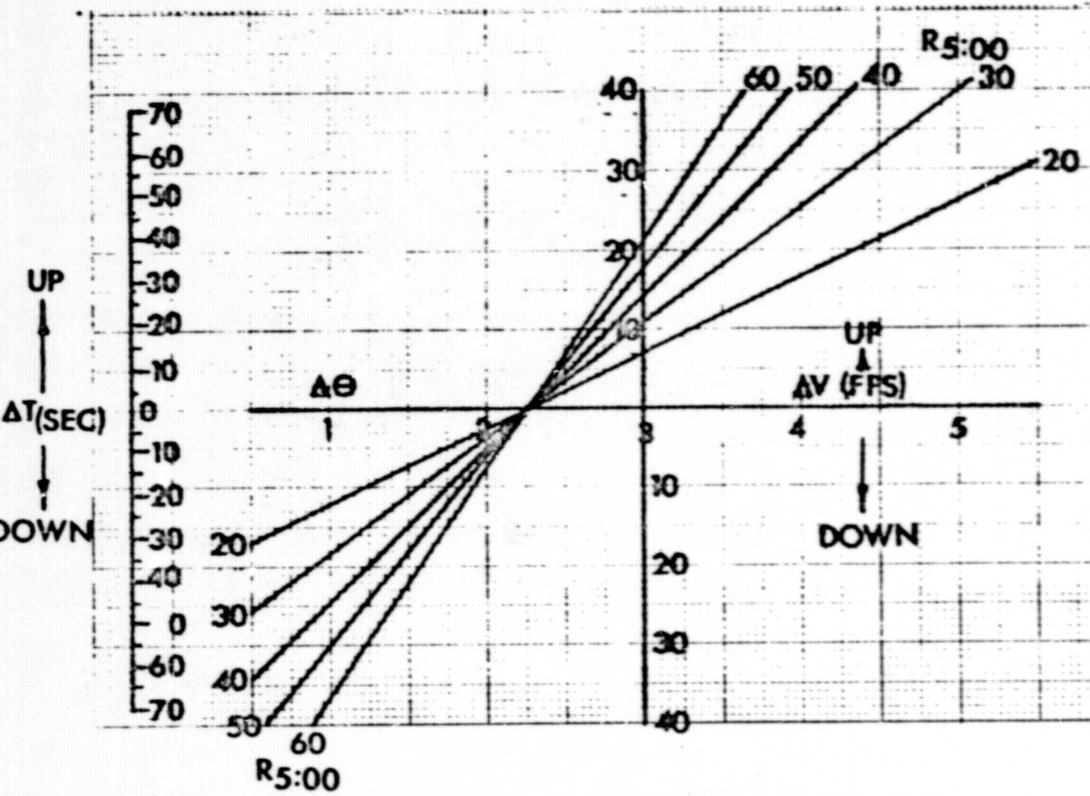
TERMINAL PHASE INITIATION

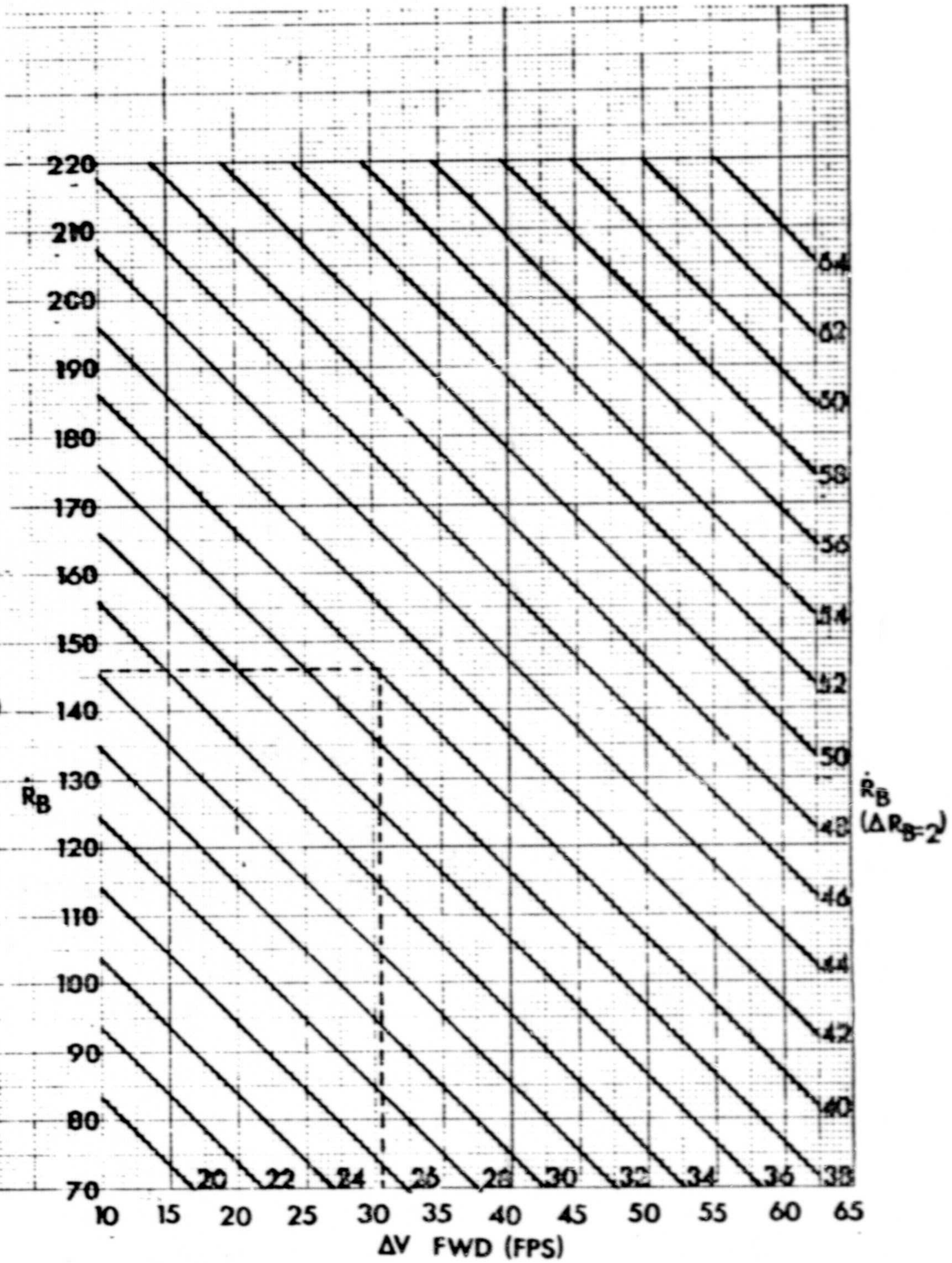
PT	TIME	θ	θ_{NOM}	R	R_{NOM}	$\dot{R}$	$\dot{R}_{NOM}$
A	-8:00	____	19.36	____	44.4	____	148.2
B	-5:00	____	-21.63	$\boxed{}$	40.1	$\boxed{}$	146.0

$-\Delta\theta$ $\boxed{}$ 2.27

TPI 0:00

AXIS	DIR	ΔV	ΔT	USED
Z	FWD	____	____	____
X	U-D	____	____	____





Boresight on Target with Reticle or Error Needles

Enter 407:+00000, 407:+10000

4:00 Readout 3C7: (θ) Copy

4:30 Readout 307: (θ) Copy, Compute $2\theta_1$

6:00 Read R and $\dot{R}$ From T.M. Copy

7:30 Readout 307: (θ) Copy

8:CO Readout 307: (θ) Copy
Compute ΔV_x, ΔV_z
Readout 502: (ΔVZ)

ATT CONT - MODE CONTROL (3)
Thrust F/A ASAP

Give CP Mark When ΔVZ Attained
Readout 500: (ΔVX)

Give CP Mark When ΔVX Attained

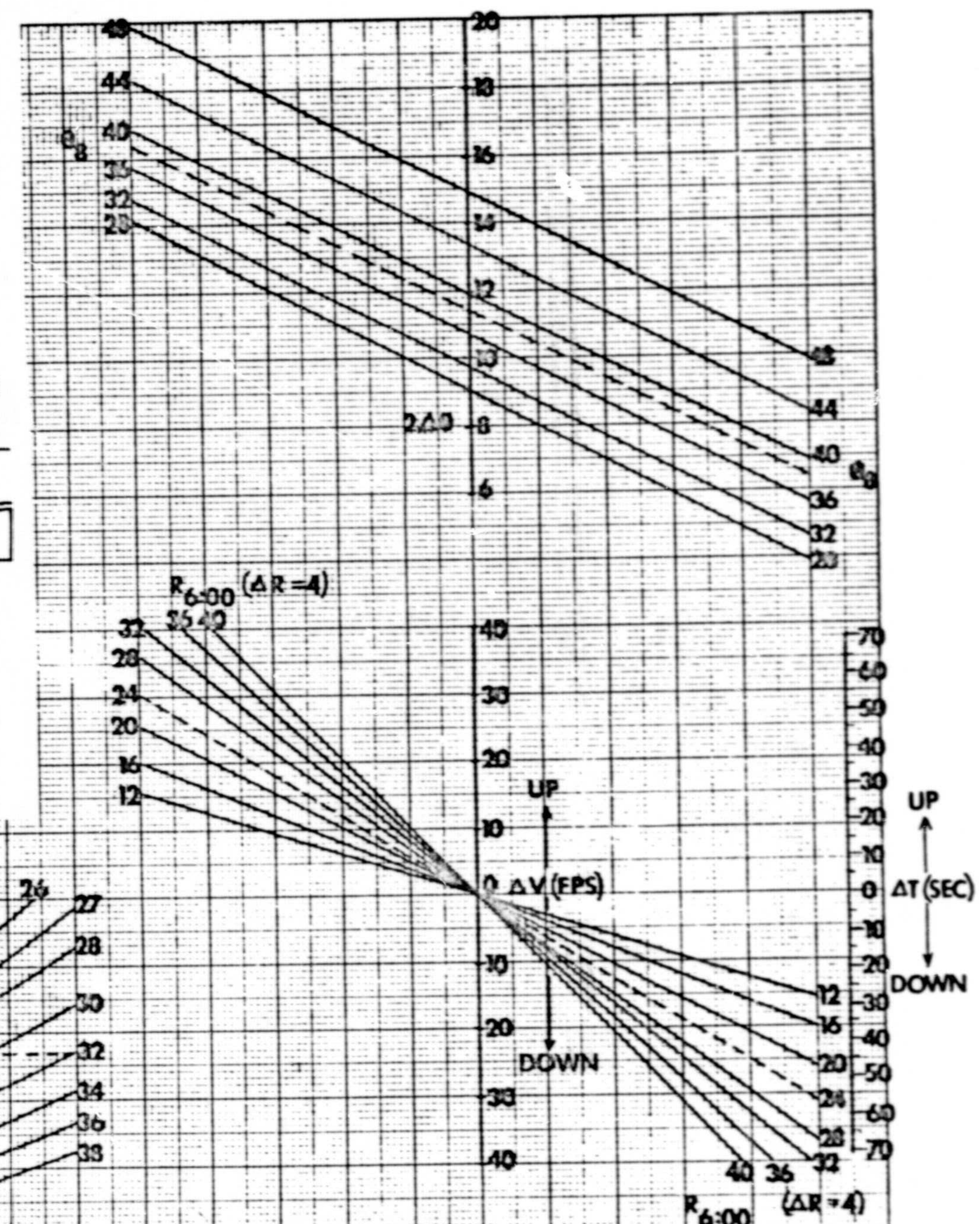
ATT CONT - PULSE (3)

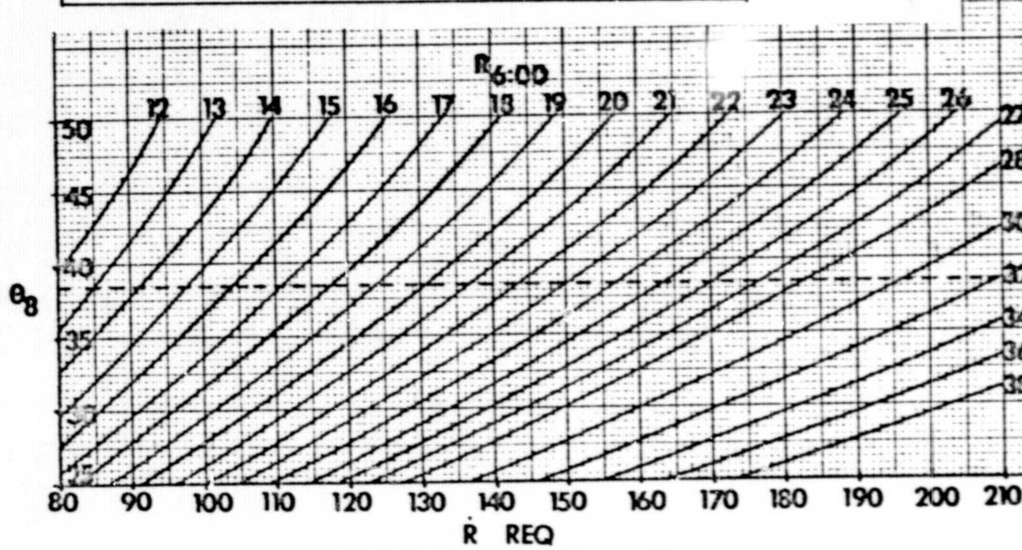
LB
9/15/66

FIRST CORRECTION

TIME	Θ	Θ_{NOM}	R	R_{NOM}	$\dot{R}$	$\dot{R}_{NOM}$
4:00	______	32.2	______	26.5	______	161.2
4:30	______	32.9	______	25.7	______	159.5
$2\Theta_1$	______	65.1				
6:00	______	35.3	☐	23.4	______	153.9
7:30	______	37.8	______	21.2	______	147.5
8:00	☐	38.7	______	20.4	______	145.2
$2\Theta_2$	______	76.5			$\dot{R}_{REQ}$	______
$2\Theta_1$	______	65.1			$\dot{R}_{6:00}$	______
$2\Delta\Theta$	☐	11.4			ΔV_Z	☐

AXIS	DIR	ΔV	ΔT	USED
Z	F−A	______	______	______
X	U−D	______	______	______





Boresight on Target With Reticle or Error Needles

Enter 407:+00000, 407:+10000

15:00 Readout 307: (θ) Copy

15:30 Readout 307: (θ) Copy, Compute $2\theta_1$

17:00 Read R and $\dot{R}$ From T.M. Copy

18:30 Readout 307: (θ) Copy

19:00 Readout 307: (θ) Copy
Compute ΔV_x, ΔV_z
Readout 502: (ΔVZ)

ATT CONT - MODE CONTROL (3)
Thrust F/A ASAP

Give CP Mark When ΔVZ Attained
Readout 500: (ΔVX)

Give CP Mark When ΔVX Attained

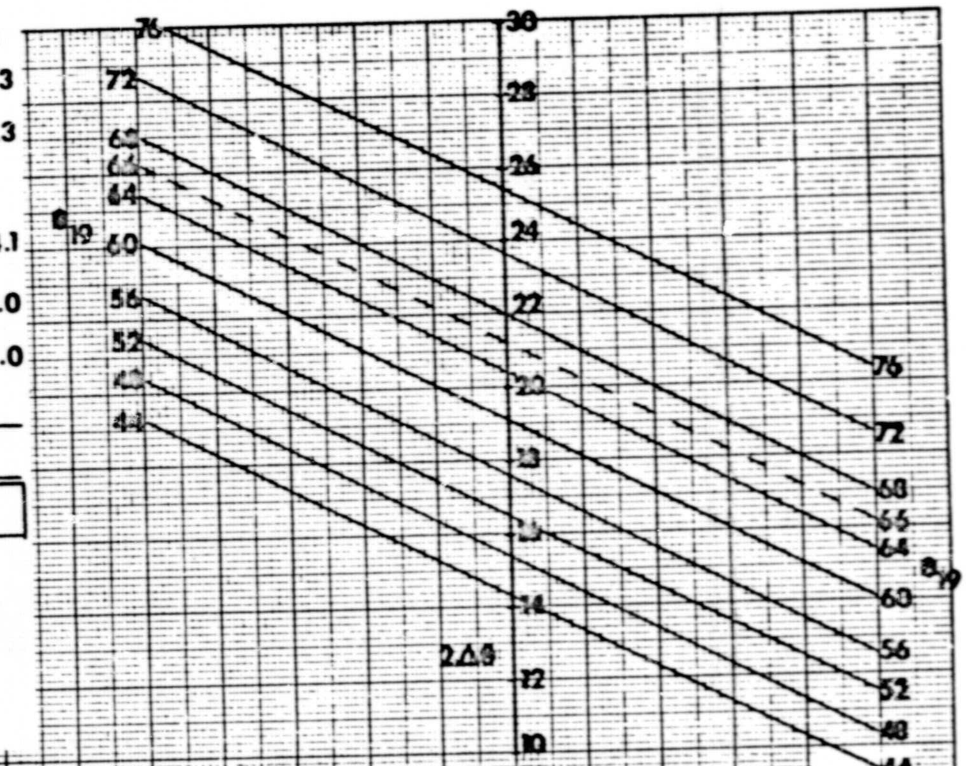
ATT CONT - PULSE (3)

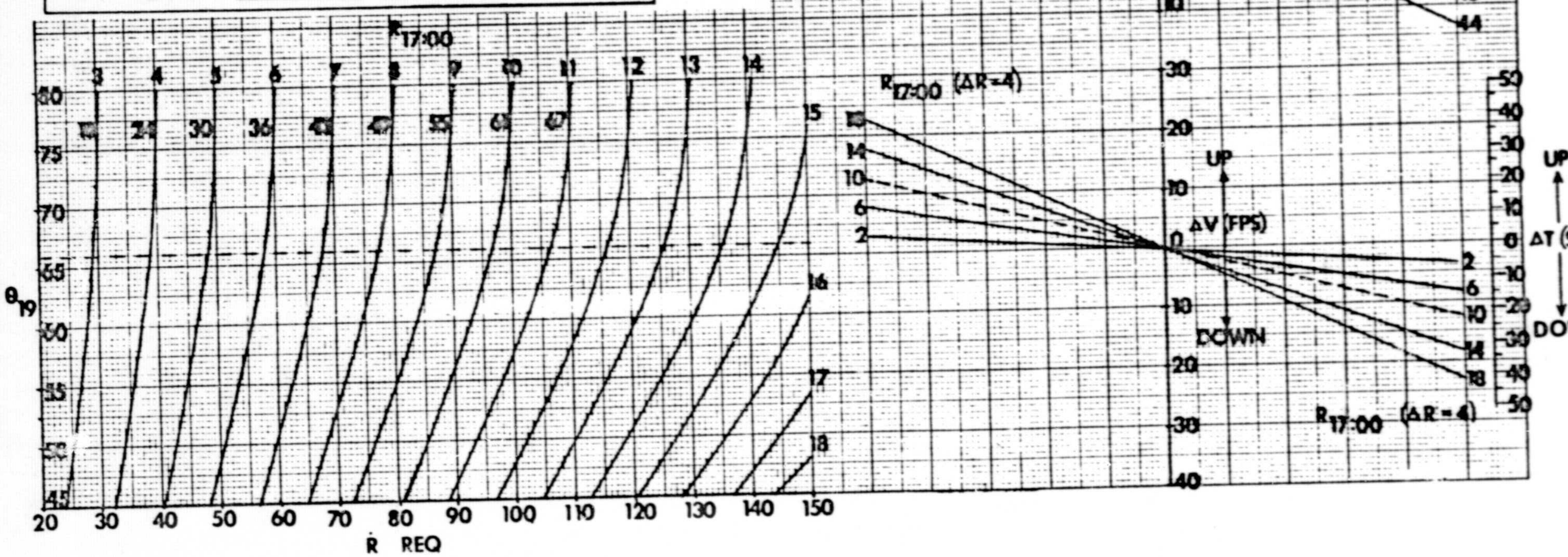
LB
/15/66

SECOND CORRECTION

TIME	Θ	Θ_{NOM}	R	R_{NOM}	$\dot{R}$	$\dot{R}_{NOM}$
15:00	______	54.3	______	11.7	______	106.3
15:30	______	55.7	______	11.2	______	103.3
$2\Theta_1$	______	110.0				
17:00	______	60.0	$\boxed{}$	58,895	______	94.1
18:30	______	64.8	______	50,837	______	85.0
19.00	$\boxed{}$	66.5	______	48,331	______	82.0
$2\Theta_2$	______	131.3			$\dot{R}_{REQ}$	______
$2\Theta_1$ =	______	110.0			$\dot{R}_{17:00}$ =	______
$2\Delta\Theta$	$\boxed{}$	21.3			ΔV_Z	$\boxed{}$

AXIS	DIR	ΔV	ΔT	USED
Z	F – A	______	______	______
X	U – D	______	______	______





SECOND CORRECTION

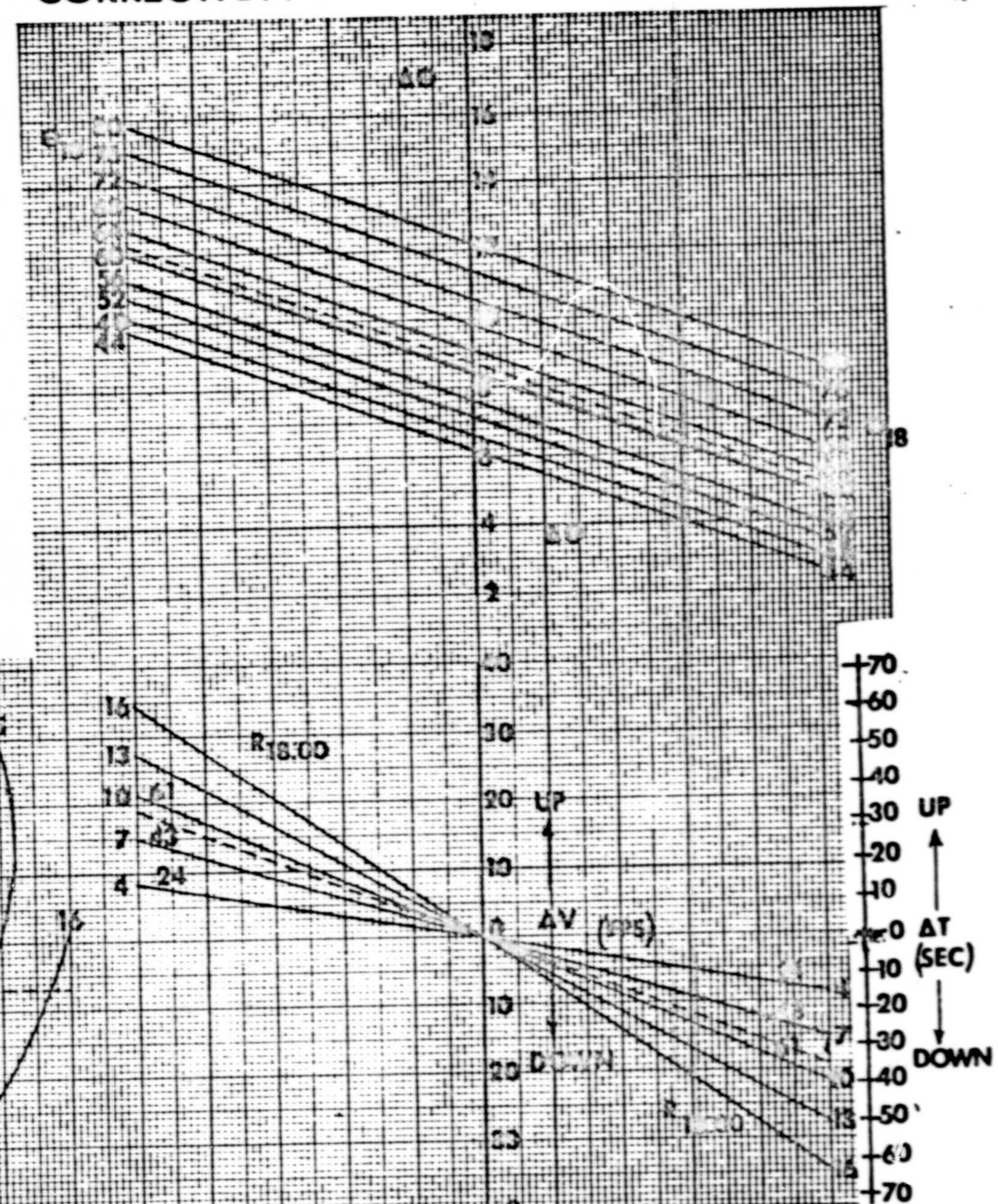
TIME	Θ	Θ_{NOM}	R	R_{NOM}	$\dot{R}$	$\dot{R}_{NOM}$
15:00		52.96		12.2		109.00
18:00		61.60		55200		90.04
$\Delta\Theta$		8.64				

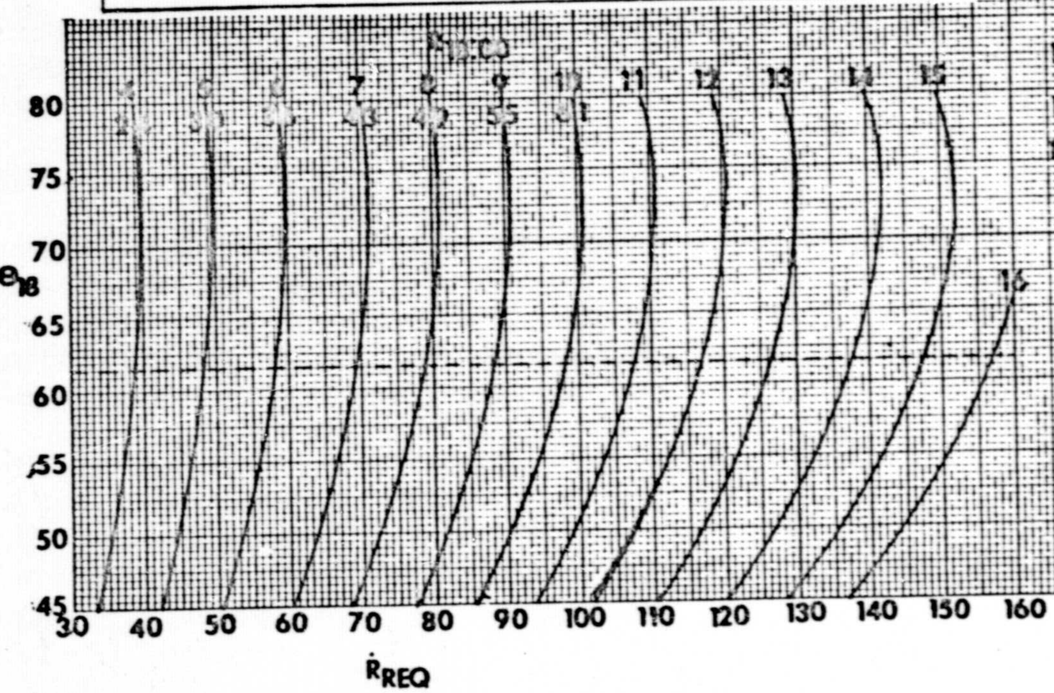
$\dot{R}_{REQ}$ ____________

$\dot{R}_{18:00}$ = ____________

ΔV_Z ____________

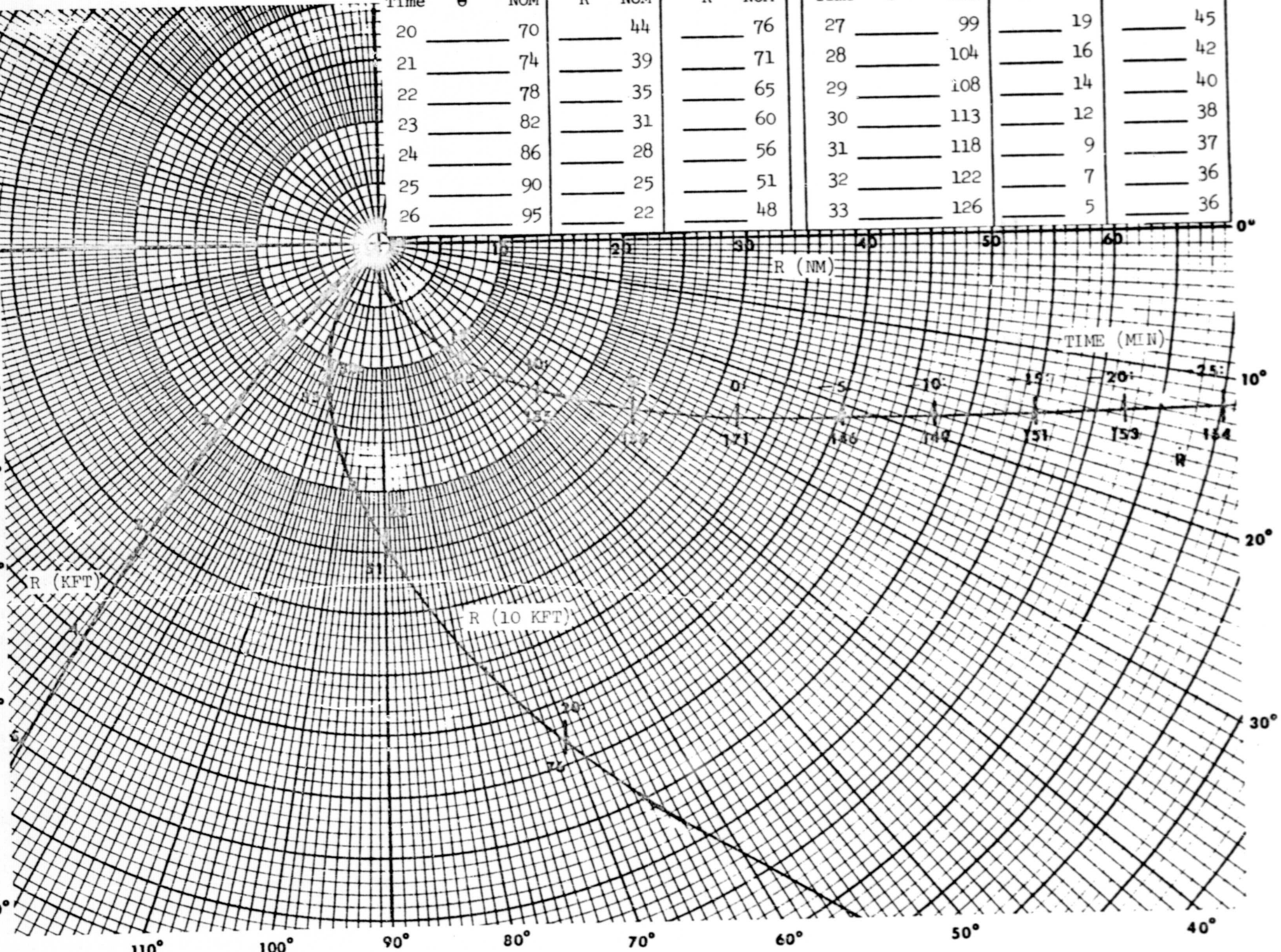
AXIS	DIR	ΔV	ΔT	USED
Z	F–A	______	______	______
X	U–D	______	______	______





LM RENDEZVOUS FROM BELOW RELATIVE REFERENCE TRAJECTORY

Time	θ	NOM	R	NOM	Ṙ	NOM	Time	θ	NOM	R	NOM	Ṙ	NOM
20		70		44		76	27		99		19		45
21		74		39		71	28		104		16		42
22		78		35		65	29		108		14		40
23		82		31		60	30		113		12		38
24		86		28		56	31		118		9		37
25		90		25		51	32		122		7		36
26		95		22		48	33		126		5		36



Boresight on Target With Reticle or Error Needles

Enter 407:+00000, 407:+10000

15:00 Readout 307: (θ) Copy

15:30 Readout 307: (θ) Copy, Compute $2\theta_1$

17:00 Read R and $\dot{R}$ From T.M. Copy

18:30 Readout 307: (θ) Copy

19:00 Readout 307: (θ) Copy
Compute ΔV_x, ΔV_z
Readout 502: (ΔVZ)

ATT CONT - MODE CONTROL (3)
Thrust F/A ASAP

Give CP Mark When ΔVZ Attained
Readout 500: (ΔVX)

Give CP Mark When ΔVX Attained

ATT CONT - PULSE (3)