MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-3-13

NOMINAL PROFILE REFINEMENTS REPORT: TARGETS IN 150 AND 190 NAUTICAL MILE CIRCULAR ORBITS

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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1.0 SUMMARY

The capability to accommodate any phase angle for an in-plane launch opportunity for low orbit operations is attained by either spending time in the nominal 100 nautical mile (n.mi.) circular phasing orbit, or by applying impulsive velocity to achieve more effective phasing orbits. An investigation of rendezvous with targets in 150 and 190 n.mi. circular orbits has revealed that relatively high parking times (up to 1 ½ days) are required even when moderately large impulsive velocities are assumed.

2.0 INTRODUCTION

Refinements to the nominal sequence required to rendezvous with a target in a 120 n.mi. circular orbit were dealt with in Reference 1. Follow-on activity was recommended to determine corresponding refinements for 150 and 190 n.mi. circular target orbits. This note addresses the latter problem, and in addition cites the potential advantages of ground-hold as a means of reducing the phasing times associated with low orbit rendezvous.

3.0 DISCUSSION

The assumptions and guidelines presented in Reference 1 were used in the present study. Briefly, they are: the total impulsive velocity requirement (ΔV) will be similar to that of baseline reference mission 2 (BRM 2); anytime launch is desired; 5, 12, 24, and 36 complete revolutions of phasing will be considered; elliptical phasing orbits will be used; a 50 x 100 n.mi. insertion orbit will be assumed (one half rev); the nominal sequence will be preserved from NSR1 to TPF; only in-plane launches will be considered; and phasing orbit perigee altitude must equal or exceed 70 n.mi. The equation used to determine insertion phase angle was:

$$\Theta_i = \Theta_c - \sum_{n=1}^{3} K_n\left(n_T \frac{P_n}{2} - 180\right)$$

where Θ_c is the phase angle at NSR1 (assumed to be a constant viz., 6.5°), n_T is the mean orbital motion of the target, K_n is half revolutions and P_n is the period of the n^{th} orbital segment. These parameters will be defined in more detail on a later figure.

The following equations were used herein to determine the change in phase angle, $\Delta\Theta$, between consecutive launch opportunities:

A) Earth Rotation Rate, $\dot{\Omega}_E$: From Reference 2,

$$\dot{\Omega}_E \left(\frac{deg}{min}\right) = \frac{360°}{86{,}164.09892 + .00164T} \times 60 = .25068445$$

Where T is the number of Julian Centuries of 365.25 days per year from 1900 January 0.5 days Universal Time (T = .9 assumed).

B) Nodal Regression Rate of Orbit, $\dot{\Omega}_R$: From Reference 3,

$$\dot{\Omega}_R = \frac{-\sqrt{GM_E}\ JR_E^{\,2}}{(1-e^2)^2}\ a^{\frac{-7}{2}} \cos i$$

Where a = semi major axis; e = orbit eccentricity (0 for circular target orbits); i = orbit inclination; and, according to Reference 2, $GM_E = 3.986032 \times 10^5$ Km^3/sec^2, $J = 1.62345 \times 10^{-3}$, and $R_E = 6378.165$ Km. Orbit altitude may be converted to km as follows:

$$h(Km) = h(n.mi.) \times 1.852$$

and

$$a = R_E + h \quad (\text{for } e = 0)$$

C) <u>Time between successive in-plane passings, TBSP:</u>

$$TBSP(min) = \frac{360°}{\dot{\Omega}_E(\frac{deg}{min}) - \dot{\Omega}_R(\frac{deg}{min})}$$

D) <u>Time for m integral orbits, TM.</u>

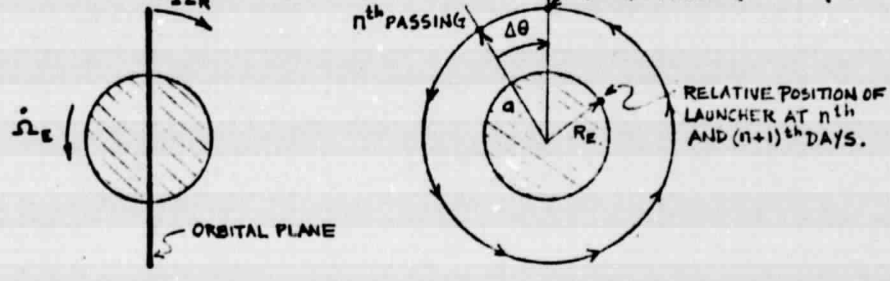
$$TM(min) = m \times Period = m2\Pi\sqrt{\frac{a^3}{GM_E}} \div 60$$

where m is an integral number of revolutions (nominally assumed to be 16).

E) <u>Decrement in phase angle between consecutive in-plane passings, Δθ:</u>

$$\Delta\theta = 360° \times \frac{TM - TBSP}{Period}$$

The foregoing parameters are defined in Sketch A.



SKETCH A - PHASE ANGLE VARIATION, Δθ, BETWEEN CONSECUTIVE IN-PLANE PASSINGS

For certain orbital inclinations there could be two acceptable launch opportunities per day from Kennedy Space Center which are compatible with the operational launch azimuths. More refined analyses should be performed in the future to explore the possibilities of utilizing both opportunities to alleviate phasing problems. In the present study one opportunity per day was assumed and therefore the results tend to be conservative.

Data presented in this note were obtained by using two body conic equations. Although insertion phase angle is represented as a continuous function, it is in reality a step function because integral numbers of half revolutions were assumed in generating the data. The total impulsive velocity requirements apply to phasing through docking maneuvers inclusively, and the corresponding BRM 2 ΔV for these maneuvers is about 748 feet per second (fps). The itemized list of BRM 2 ΔV's appearing below was taken from Reference 4.

Table 1 - BRM 2 ΔV Requirements

MANEUVER	ΔV, FPS
Phasing (NC)	86.9
Height (NH)	263.5
First Coelliptic (NSR1)	267.2
Corrective Combination (NCC)	23.3
Second Coelliptic (NSR2)	21.6
Terminal Phase Initiation (TPI)	20.4
Terminal Phase Finalization (TPF)	55.0
Docking	10.0
TOTAL	747.9

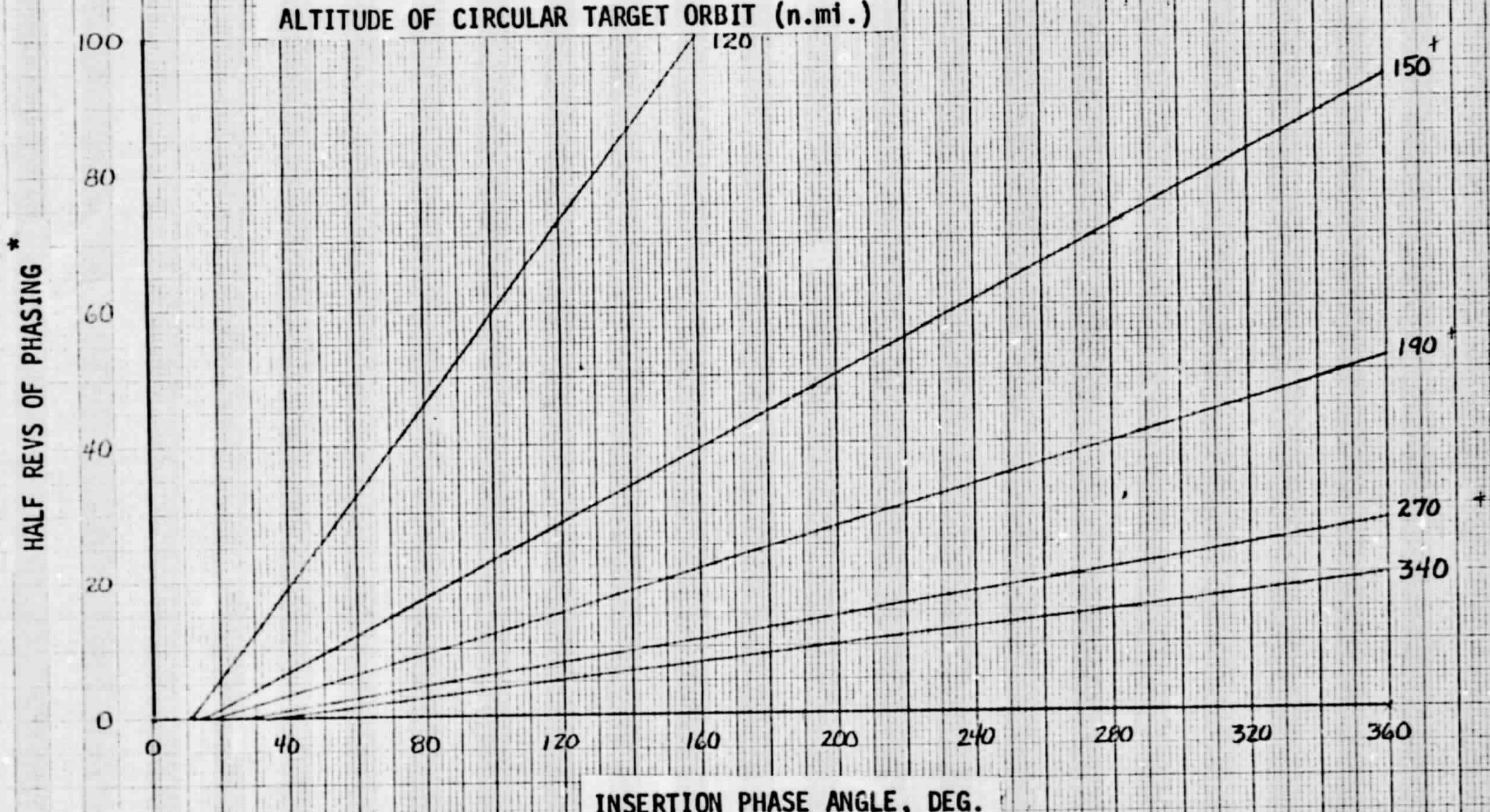
In this analysis ΔV's within about 10% of the BRM 2 value were considered to be in compliance with the established guidelines. The problem of orbit maintenance and associated ΔV's are discussed briefly but details and techniques are not addressed herein.

4.0 RESULTS

Figure 1 presents phasing requirements as a function of insertion phase angle for circular target orbits of 120, 150, 190, 270 and 340 n.mi. A 100 n.mi. circular phasing orbit was assumed in Figure 1. For a target in a 270 n.mi. circular orbit, all insertion phase angles may be accommodated with nominally 30 or less half revs of phasing. According to Reference 4 the target orbit altitude for BRM 2 is 270 n.mi. and a maximum phasing requirement of 12 revolutions (24 half revs) is cited. Observe from Figure 1 that for a target in a 190 n.mi. orbit, nearly 55 half revs of phasing must be provided to guarantee an anytime liftoff capability and for a target in a 150 n.mi. orbit, this increases to nearly 100 half revs. For 120 n.mi. target orbits phasing times become even longer inasmuch as the magnitude of the semi major axis of the phasing orbit is approaching that of the target orbit.

One way to avoid long phasing times is to select a phasing orbit semi major axis significantly different from that of the target orbit. This led to the consideration of elliptical phasing orbits.

FIGURE 1 - HALF REVS OF PHASING IN A 100 n.mi. CIRCULAR PARKING ORBIT AS FUNCTION OF INSERTION PHASE ANGLE FOR CIRCULAR TARGET ORBIT ALTITUDES OF 120, 150, 190, 270 AND 340 n.mi.



* PHASING ORBIT = 100x100 n.mi.
INSERTION ORBIT = 50x100 n.mi.

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Figures 2A through 2D are plots of phasing orbit apsis altitude as a function of insertion phase angle. Phasing half revs of 10, 24, 48 and 72 are depicted. Figures 2A and 2C apply to the 150 n.mi. target orbit case. An apsis altitude of 100 n.mi. was used to generate the former figure and an apsis altitude of 130 n.mi was assumed for the latter. Figures 2B and 2D apply to the 190 n.mi. target orbit case. An apsis altitude of 100 n.mi. was assumed for the former figure and an apsis altitude of 170 n.mi. for the latter. Observe that a sketch of the trajectory profiles assumed and a brief description of sequences appear on the figures. Note that when the semi major axis of the phasing orbit exceeds that of the target orbit, a target chase situation occurs.

Figures 3A thru 3D are crossplots of Figures 2A through 2D respectively. They show half revs of phasing as a function of insertion phase angle for various phasing orbit altitudes.

The general range of apsis altitudes investigated was from 70 to 500 n.mi.; however, there are three factors which must be considered in connection with the use of low altitude phasing orbits. These are: orbit lifetime, altitude maintenance and orbiter thermal constraints. The typical natural lifetime of the orbiter with an effective drag area of 450 square feet in a 70 x 100 n.mi. orbit was found to be about 47 hours (just over 32 revolutions). Orbit termination was assumed to occur when altitude decayed to 60 n.mi. A

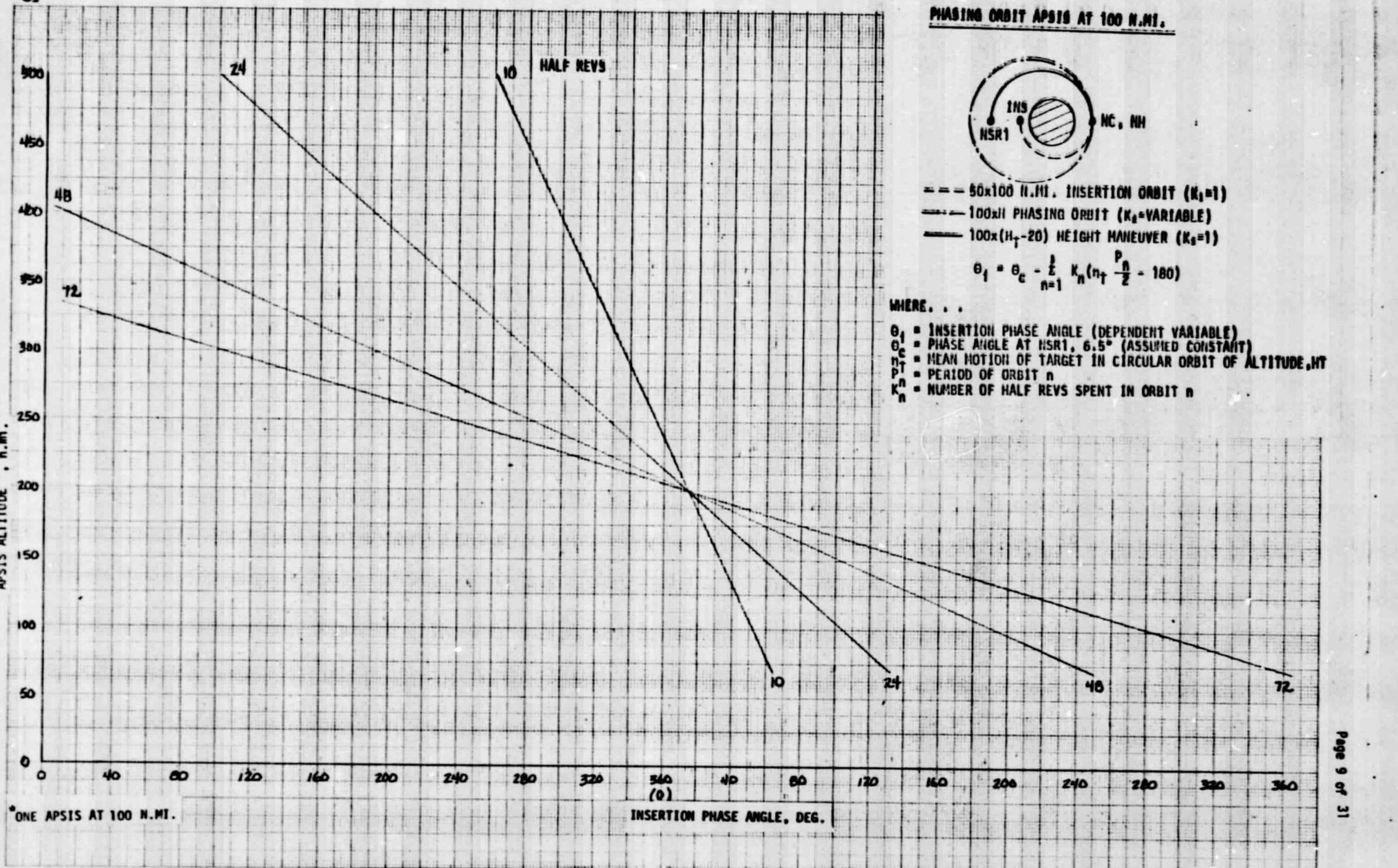

FIGURE 2A - APSIS ALTITUDE AS FUNCTION OF INSERTION PHASE ANGLE FOR 10, 24, 48 AND 72 HALF REVS OF PHASING: 150 n.mi. TARGET ORBIT

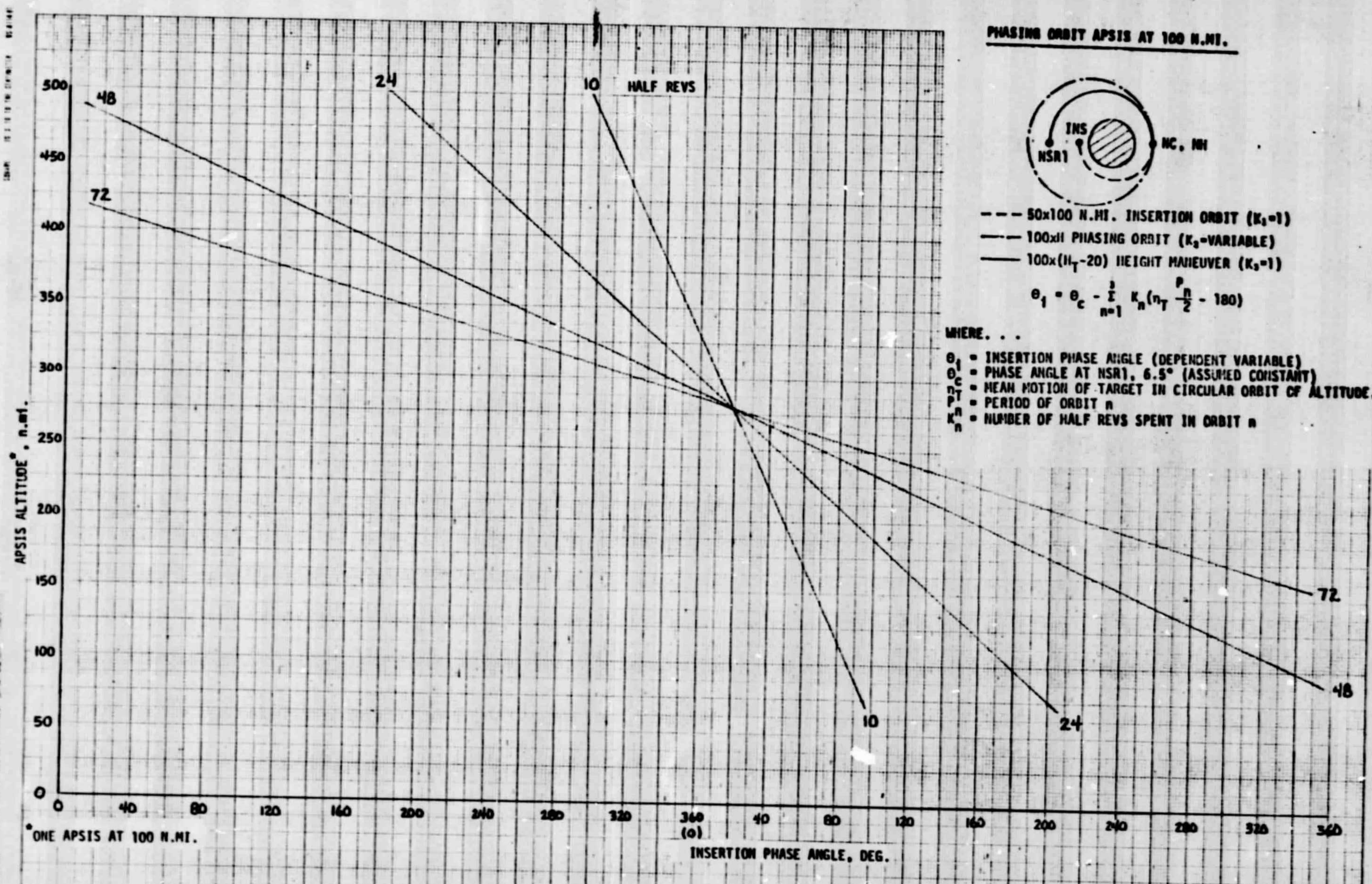

FIGURE 2B - APSIS ALTITUDE AS FUNCTION OF INSERTION PHASE ANGLE FOR 10, 24, 48 AND 72 HALF REVS OF PHASING: 190 n.mi. TARGET ORBIT

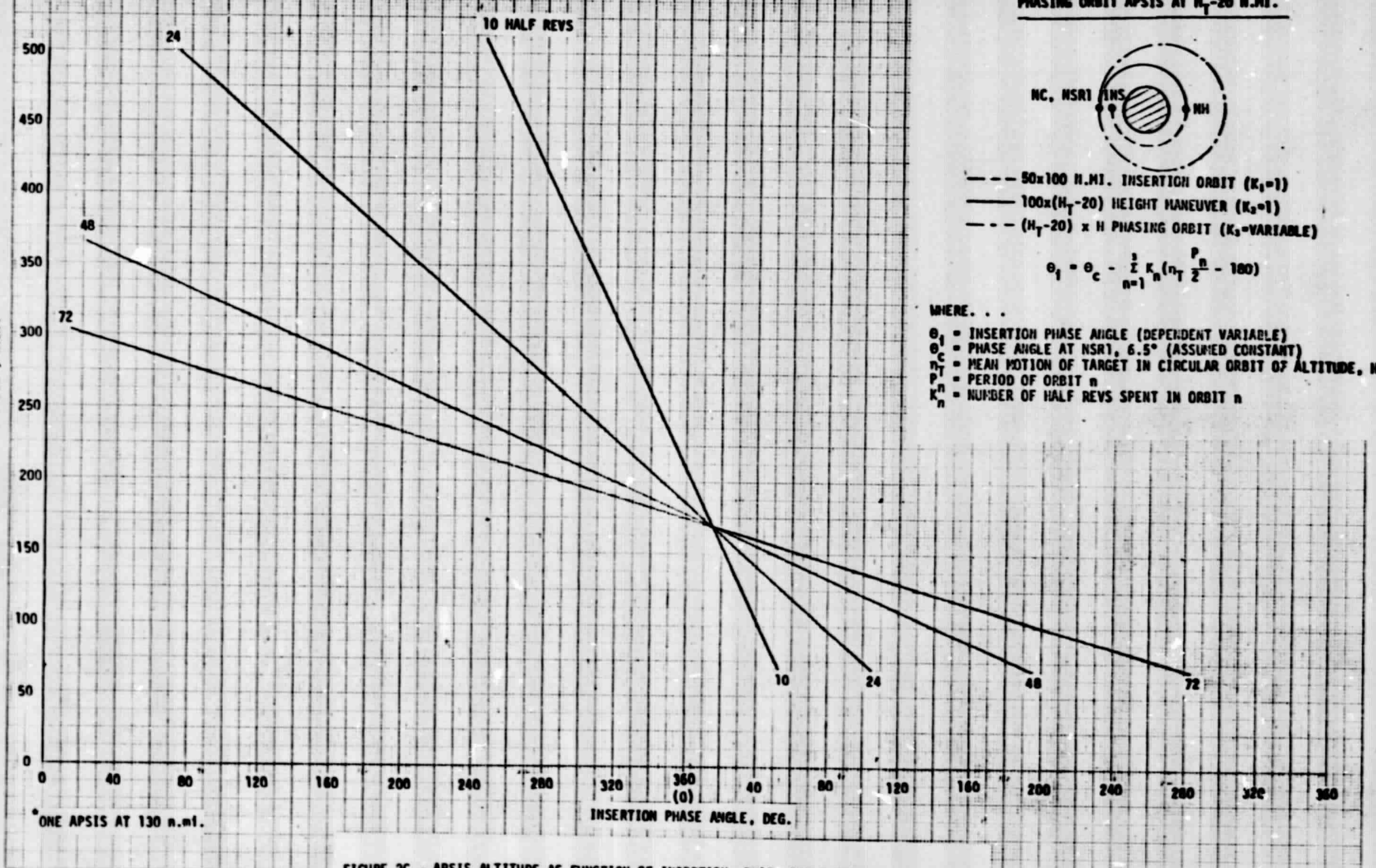

FIGURE 2C - APSIS ALTITUDE AS FUNCTION OF INSERTION PHASE ANGLE FOR 10, 24, 48 AND 72 HALF REVS OF PHASING: 150 n.mi. TARGET ORBIT

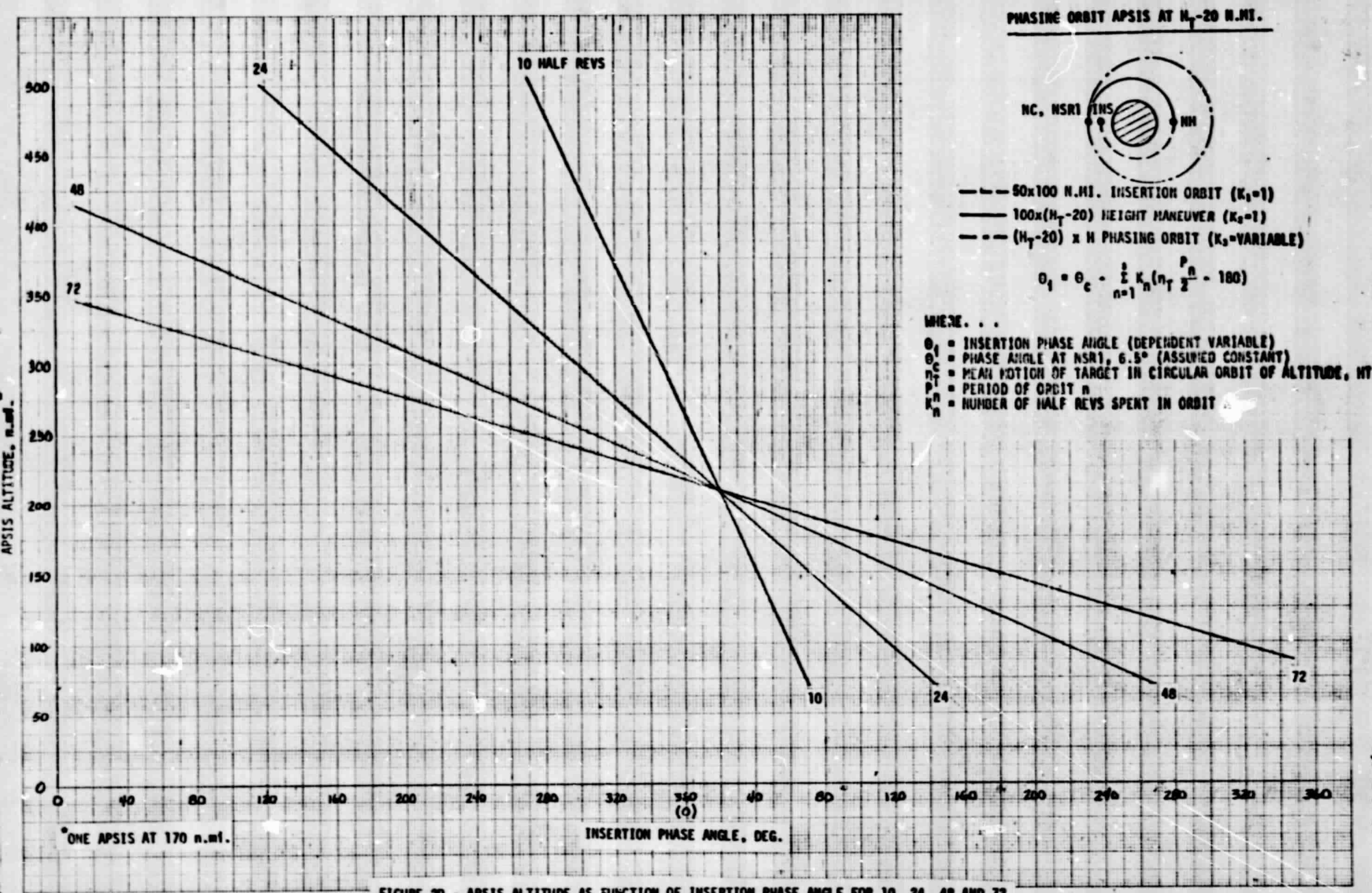

FIGURE 2D - APSIS ALTITUDE AS FUNCTION OF INSERTION PHASE ANGLE FOR 10, 24, 48 AND 72 HALF REVS OF PHASING; 190 n.mi. TARGET ORBIT

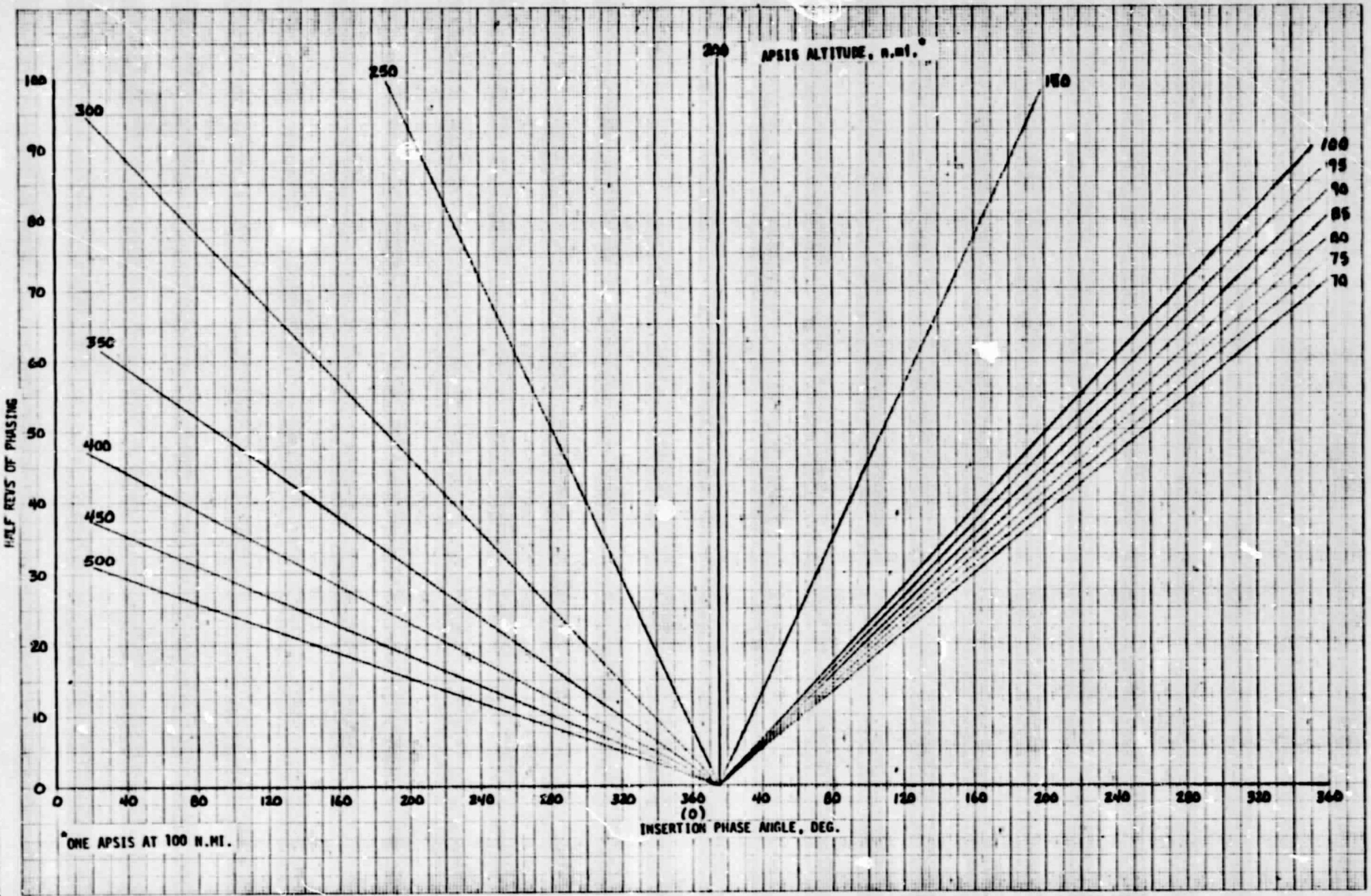

FIGURE 3A - HALF REVS OF PHASING AS FUNCTION OF INSERTION PHASE ANGLE FOR VARIOUS APSIS ALTITUDES: 150 n.mi. TARGET ORBIT

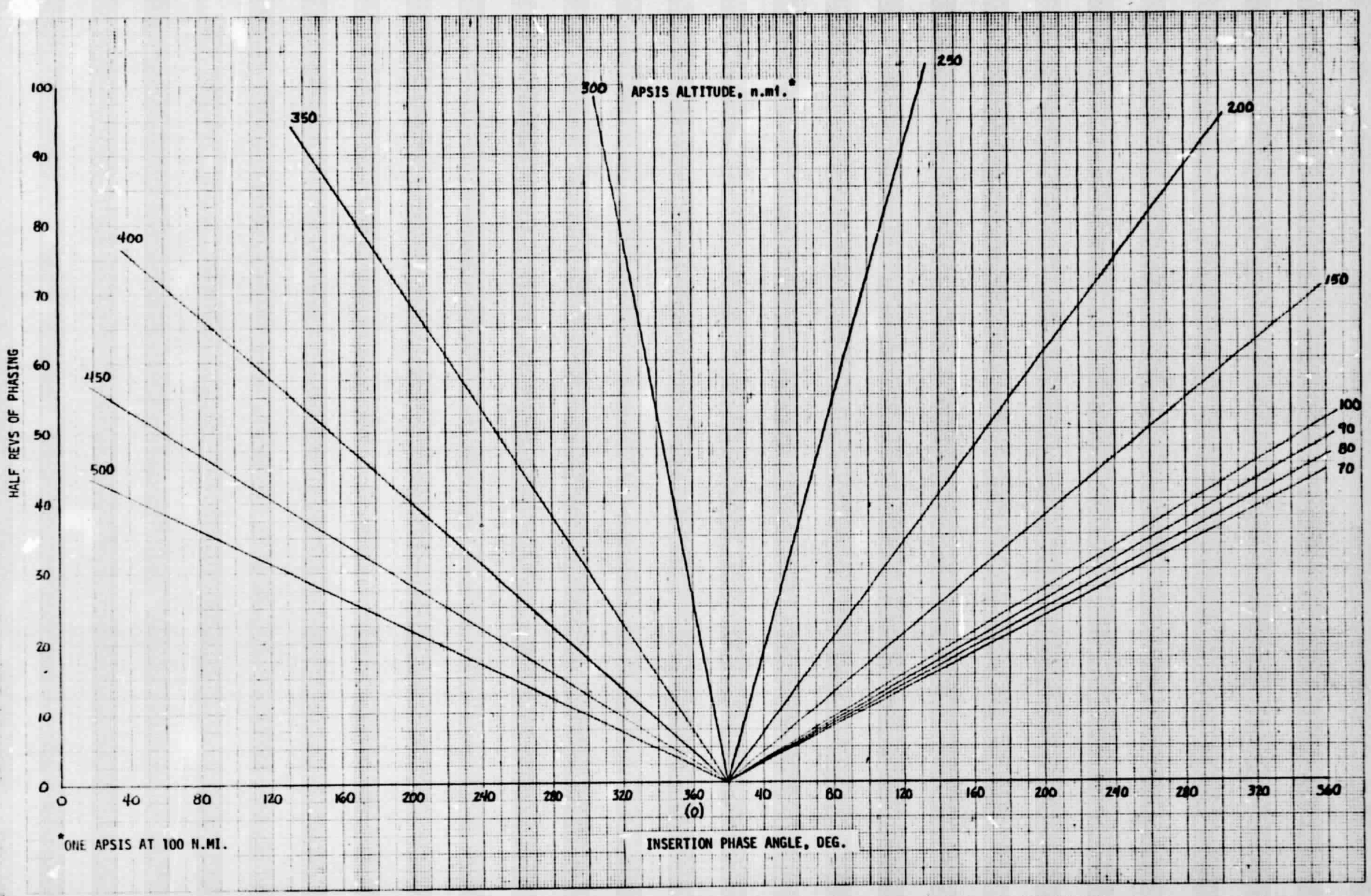

FIGURE 3B - HALF REVS OF PHASING AS FUNCTION OF INSERTION PHASE ANGLE FOR VARIOUS APSIS ALTITUDES: 190 n.mi. TARGET ORBIT

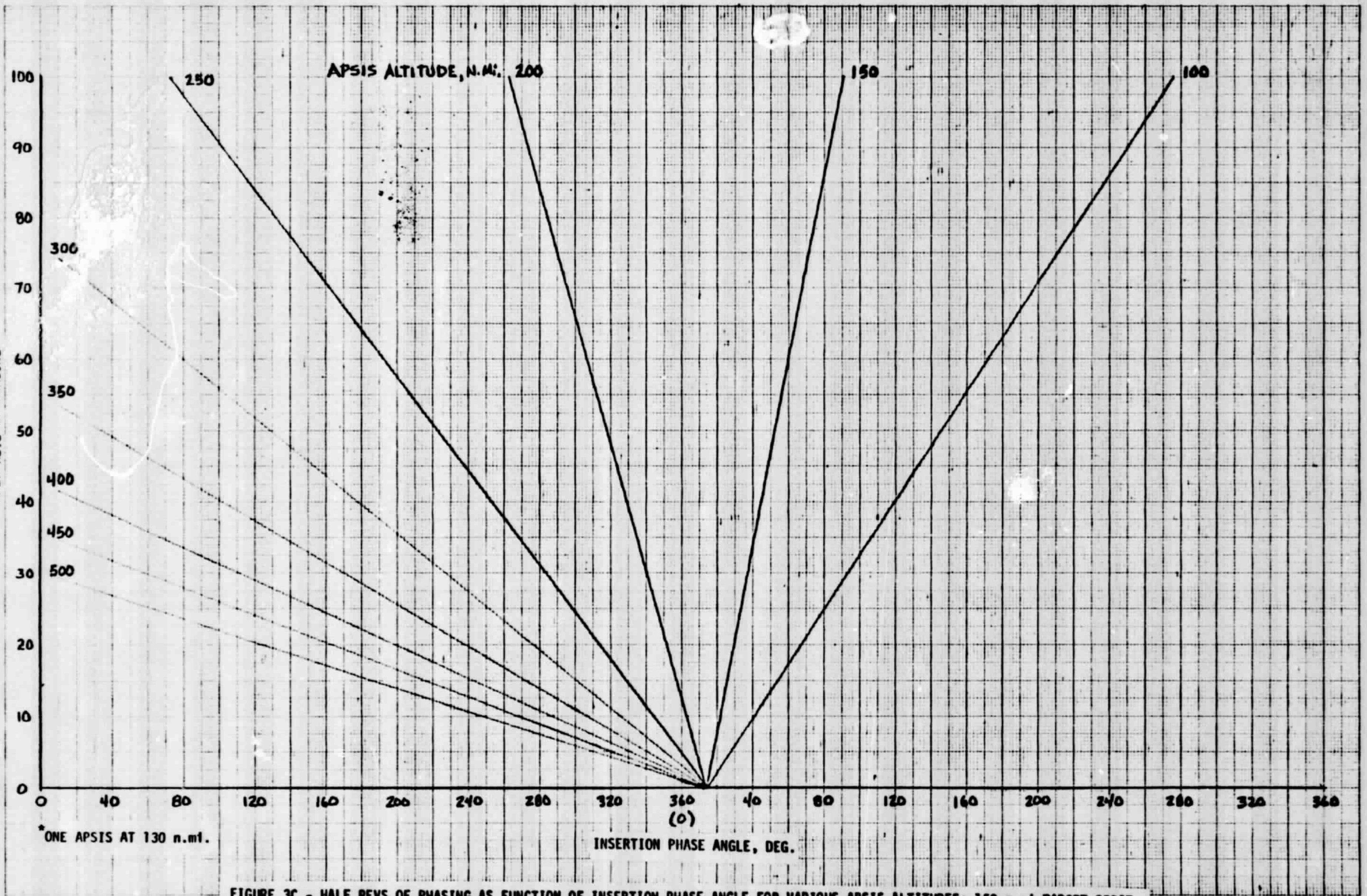

FIGURE 3C - HALF REVS OF PHASING AS FUNCTION OF INSERTION PHASE ANGLE FOR VARIOUS APSIS ALTITUDES: 150 n.mi. TARGET ORBIT

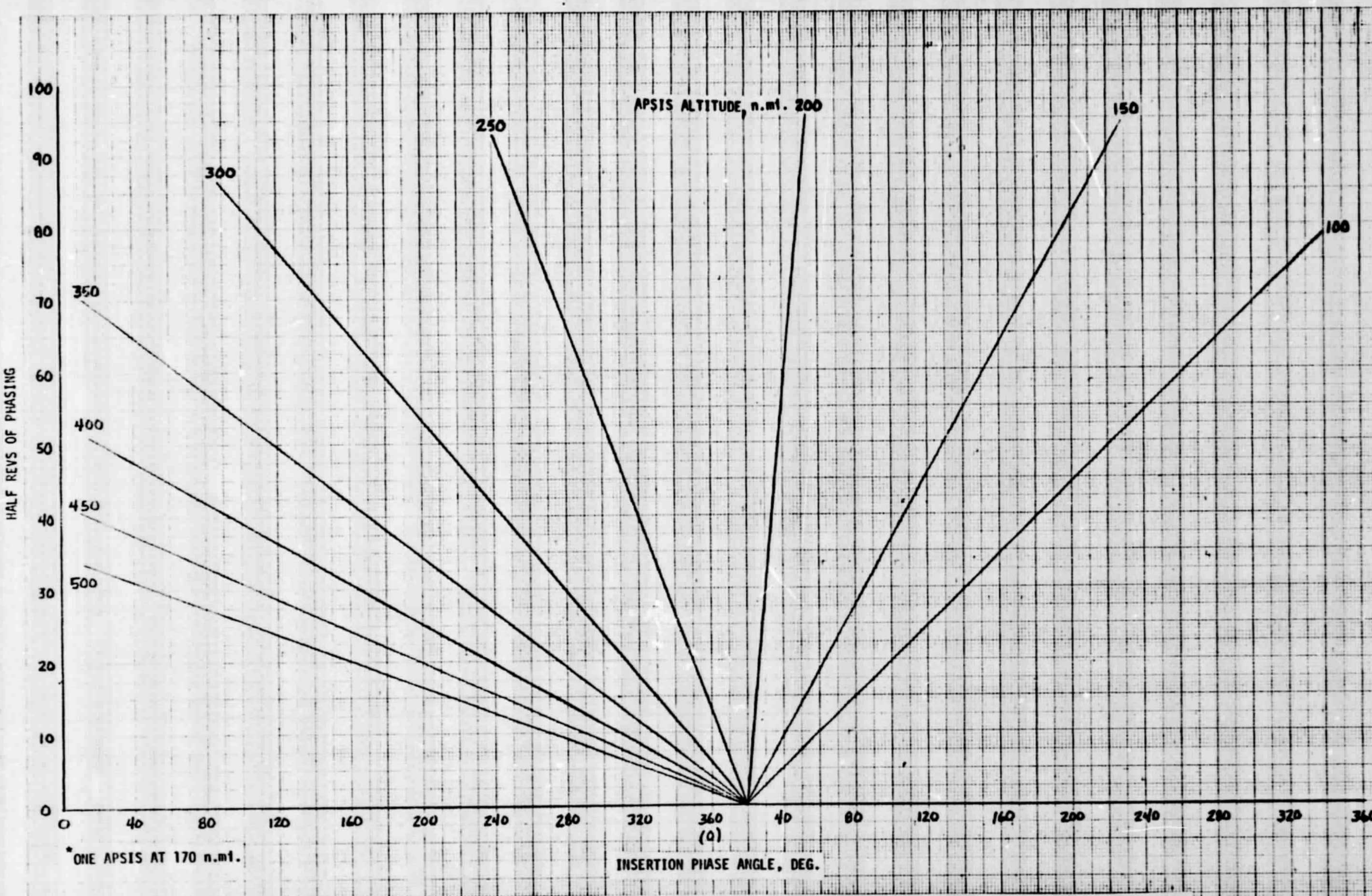

FIGURE 3D - HALF REVS OF PHASING AS FUNCTION OF INSERTION PHASE ANGLE FOR VARIOUS APSIS ALTITUDES: 190 n.mi. TARGET ORBIT graph depicting the time history for such a vehicle in a 70 x 100 n.mi. orbit is presented in Appendix A.

For the same typical case, a corrective ΔV of about .2 fps applied at apogee results in maintenance of orbit perigee at 70 n.mi. Furthermore, a corrective ΔV of about .9 fps applied at perigee results in maintenance of the of the orbit apogee at 100 n.mi. The ΔV cost for maintaining both would be approximately 1.1 fps per revolution for this typical case.

In Reference 5 a maximum allowable parking time of about 6 revolutions is cited for orbits in the vicinity of 65 n.mi. altitude, at which point atmospheric heating will have caused orbiter structure and/or thermal insulation to reach the maximum design temperature of 350°F. No detailed studies have been made of the thermal constraints for internal components and consequently six revolutions may be too optimistic. Thus the solutions herein calling for 70 x 100 n.mi. phasing orbits may not necessarily be usable in all cases.

BRM 2, which incorporates one Orbital Maneuvering System (OMS) payload bay kit, has a post insertion ΔV requirement of about 750 fps. If a phasing orbit having an apogee of 500 n.mi. were desired, an additional ΔV of about 900 fps would be required over BRM 2. Since each payload bay kit will provide about 500 fps of additional capability, the total allowable number of kits, namely 3, would be needed to attain phasing orbits having apogees in the vicinity of 500 n.mi.

Figures 4A through 4D present half revs of phasing, apsis altitude, and impulsive velocity requirements as functions of insertion phase angle. Each figure has four parts representing phasings of 10, 24, 48 and 72 half revs. An arrow identifies the BRM 2 ΔV requirement. Apsis altitudes below 70 n.mi. were not considered. Observe on Figures 4A and 4C that for apsis altitudes below 130 n.mi. ΔV requirements are identical. Also observe from Figures 4B and 4D that ΔV requirements are the same for apsis altitudes below 170 n.mi. No orbit maintenance ΔV's are included on the figures.

On Figures 5A and 5B the candidate half revs, apsis altitudes, and impulsive velocity requirements are given as functions of phase angle for 150 and 190 n.mi. circular orbits respectively. The solid lines represent the case where one apsis altitude equals 100 n.mi. and the dashed lines represent the case where one apsis altitude is 20 n.mi. below the target orbit. Observe that 48 half revs of phasing are required much of the time if the ΔV budget is to be kept at 750 fps (BRM 2). The recommended approach is to use the trajectories represented by the minimum half rev envelope. This will not necessarily minimize the ΔV requirements.

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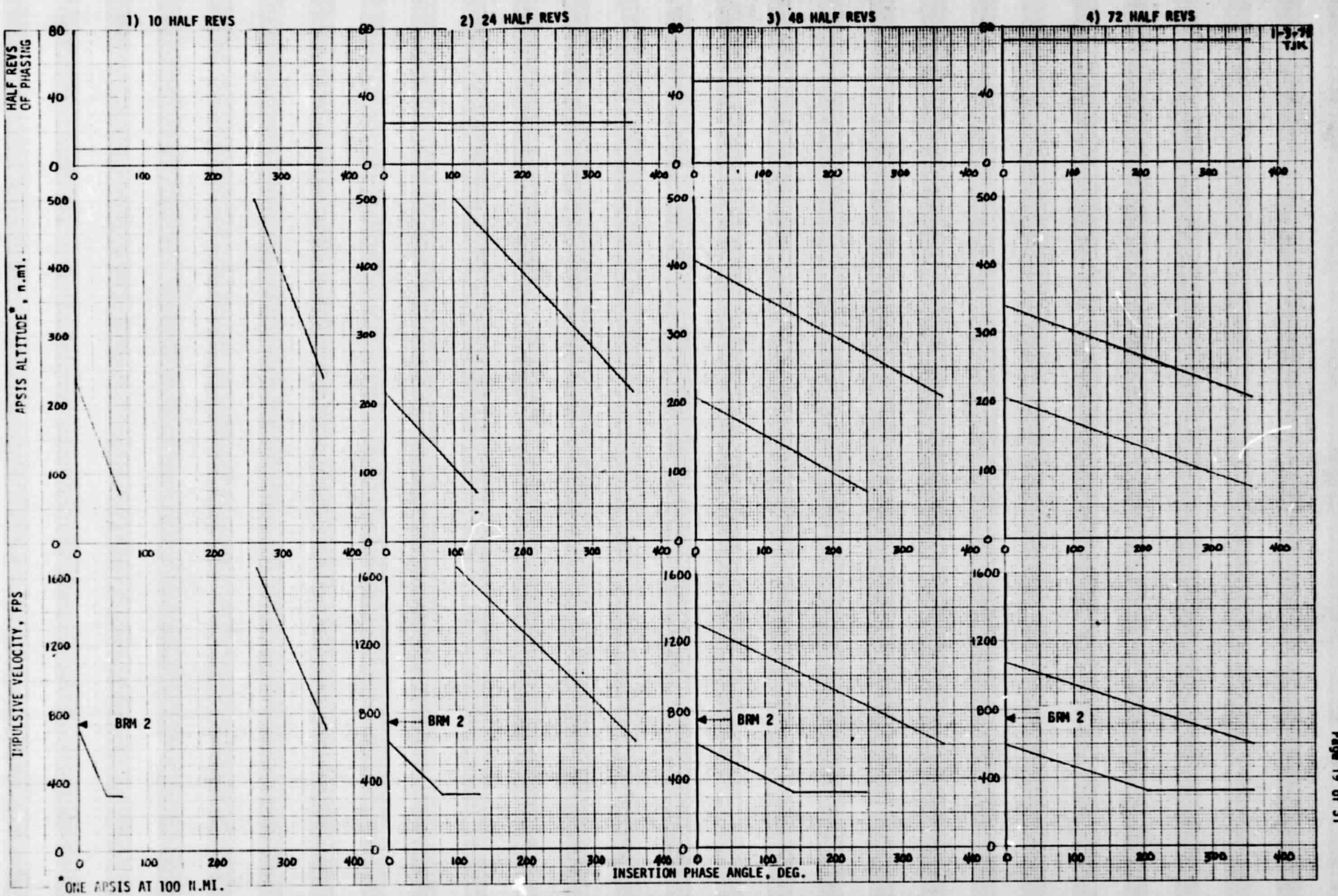


FIGURE 4A - HALF REVS, APSIS ALTITUDE, AND IMPULSIVE VELOCITY REQUIREMENTS AS FUNCTIONS OF INSERTION PHASE ANGLE: 150 n.mi. TARGET ORBIT

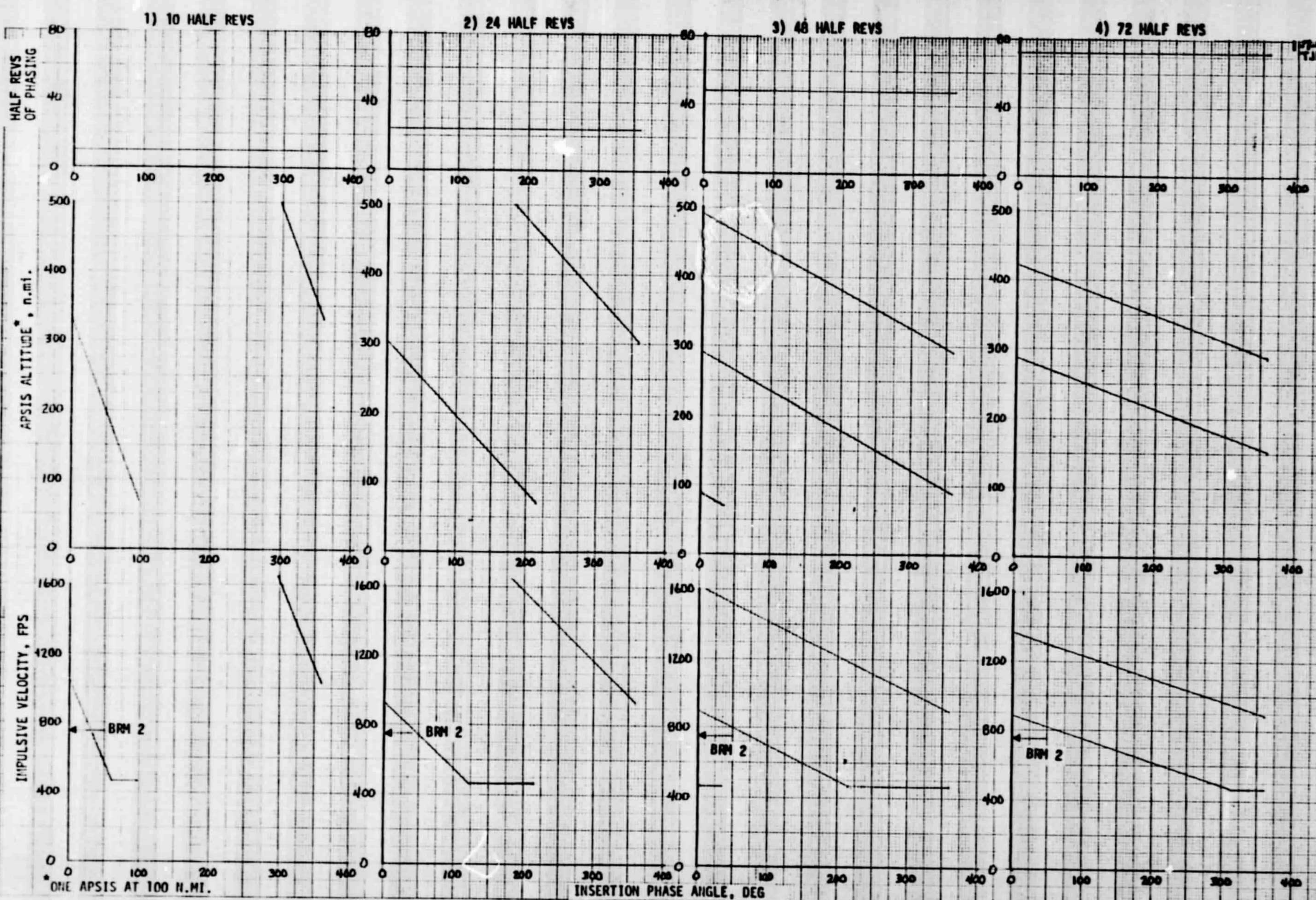


FIGURE 4B - HALF REVS, APSIS ALTITUDE, AND IMPULSIVE VELOCITY REQUIREMENTS AS FUNCTIONS OF PHASE ANGLE: 190 n.mi. TARGET ORBIT

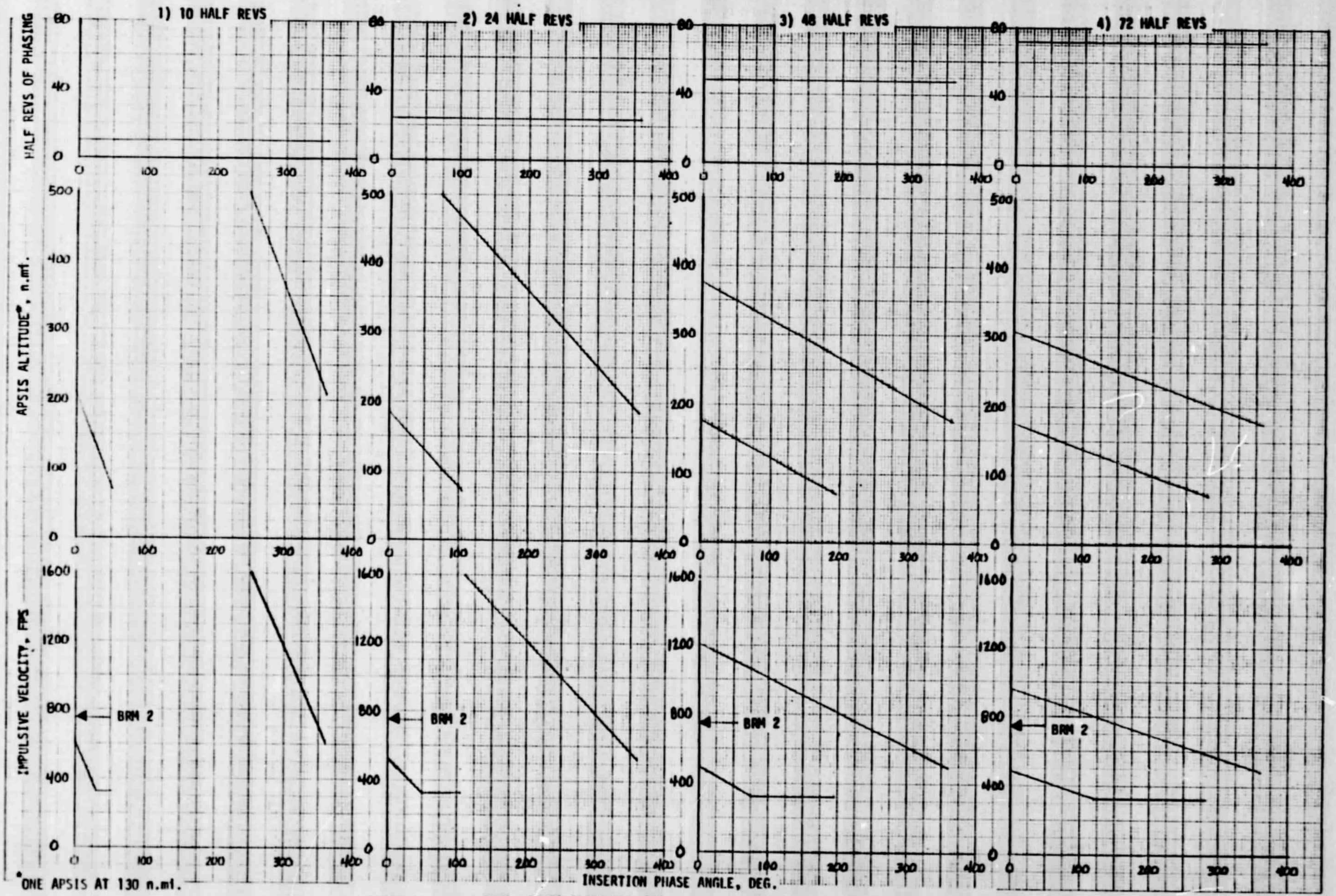
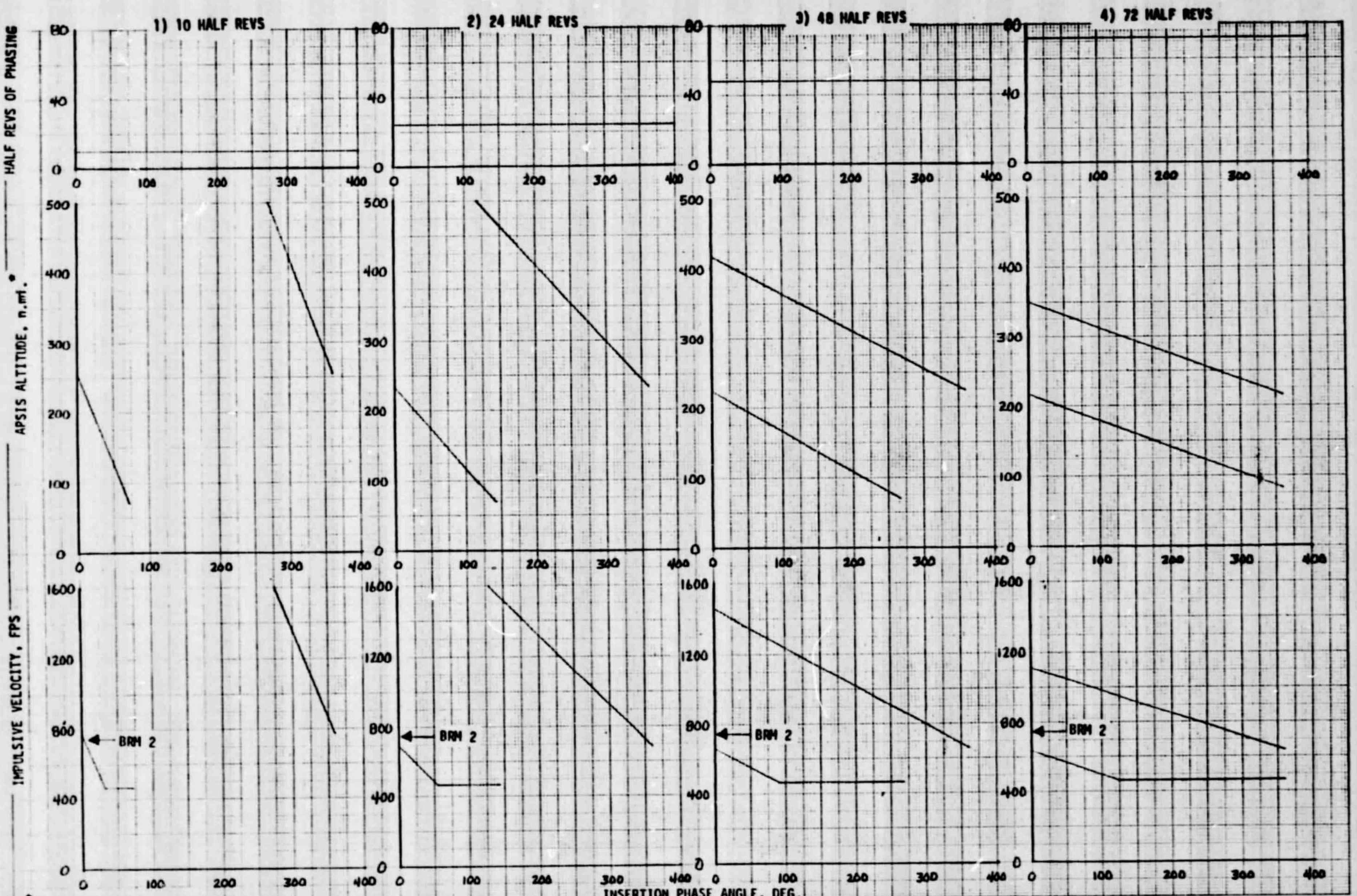


FIGURE 4C - HALF REVS, APSIS ALTITUDE, AND IMPULSIVE VELOCITY REQUIREMENTS AS FUNCTIONS OF INSERTION PHASE ANGLE: 150 n.mi. TARGET ORBIT



*ONE APSIS AT 170 n.mi.

FIGURE 4D - HALF REVS, APSIS ALTITUDE, AND IMPULSIVE VELOCITY REQUIREMENTS AS FUNCTIONS OF PHASE ANGLE: 190 n.mi.TARGET ORBIT

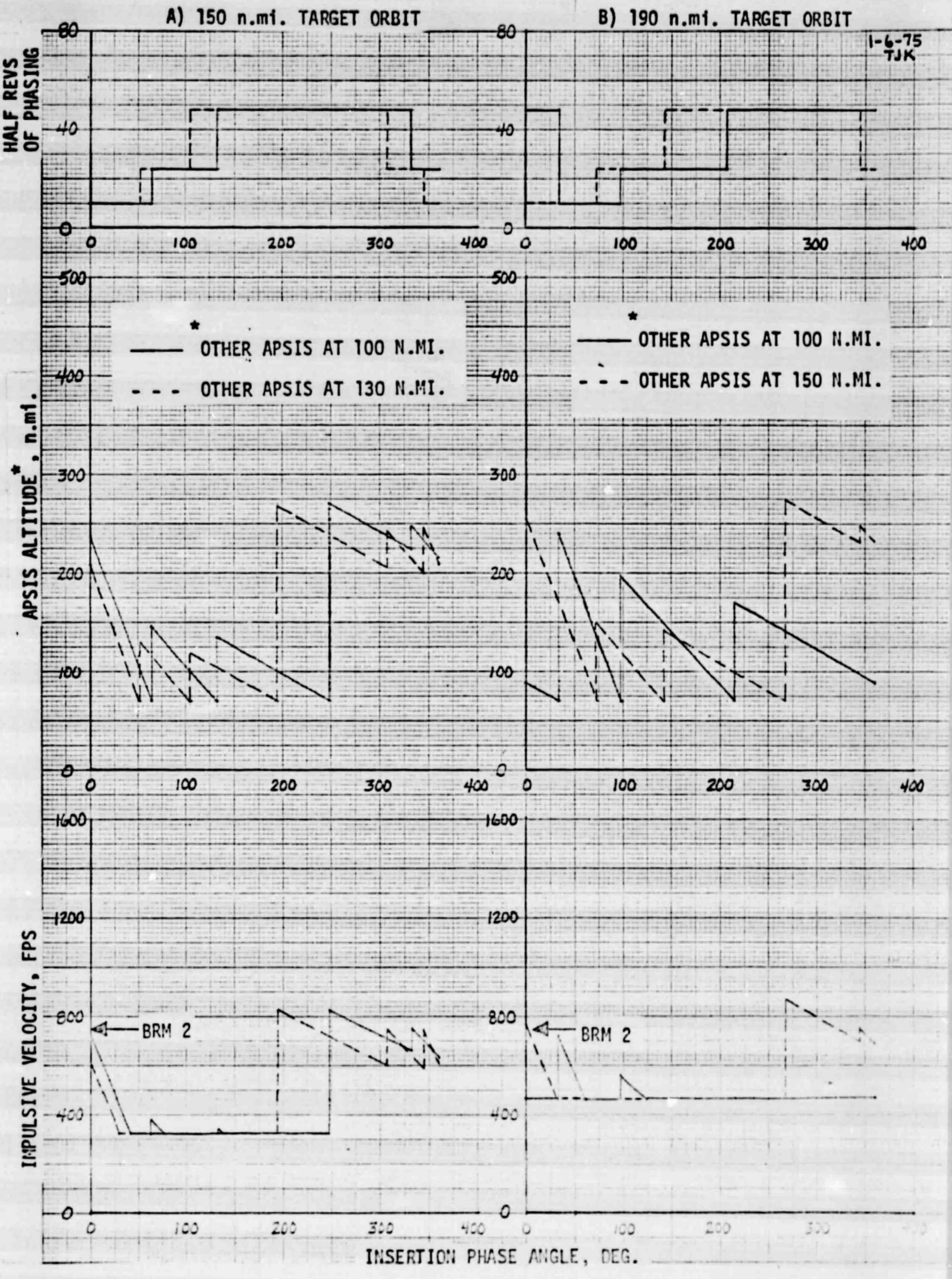


FIGURE 5 - HALF REVS, APSIS ALTITUDE, AND IMPULSIVE VELOCITY AS FUNCTIONS OF PHASE ANGL

On Table 2 the likelihoods of 48 half revs of phasing are listed for target orbit altitudes of 120, 150 and 190 n.mi. It can be seen from Table 2 that the likelihood of 48 half rev phasing decreases with increasing target orbit altitude.

The question may be asked, "Is there some way to reduce phasing time requirements?" One possible way is to alter insertion phase angle by deferring launch to the next in-plane opportunity. The net result of a ground hold is to alter the geocentric target-to-launch phase angle.

Figure 6 presents phase angle decrement for a one day hold as a function of circular target orbit altitude for orbital inclinations of 28.5°, 55° and 90°. On Table 3 the phase angle decrement via ground hold is compared to that obtained if a 100 n.mi. circular parking orbit were used. Target orbit altitudes of 120, 150, 190, 270 and 340 n.mi. are shown.

To demonstrate how a ground hold may be used to advantage, consider the following example. Suppose a rendezvous is required with a target in a 150 n.mi. circular orbit having an inclination of 28.5°. Assume that the insertion phase angle for the desired day is 195°. It can be seen from Figure 5A that about 48 half revs of phasing in a 100 n.mi. circular parking orbit would be needed to accomplish rendezvous.

TABLE 2 - LIKELIHOOD OF $1\frac{1}{2}$ DAY* PHASING FOR RENDEZVOUS WITH TARGETS IN 120, 150, AND 190 n.mi. CIRCULAR ORBITS

Target Orbit Altitude, n.mi.	Insertion Phase Angle Region Requiring 48 Half Revs of Phasing	Likelihood* of 48 Half Rev Phasing, Percent
120	76° - 256°	50.0
150	132° - 307°	48.6
190	206° - 345°	38.9

* (Assumes that any insertion phase angle has an equal likelihood of occurrence.)

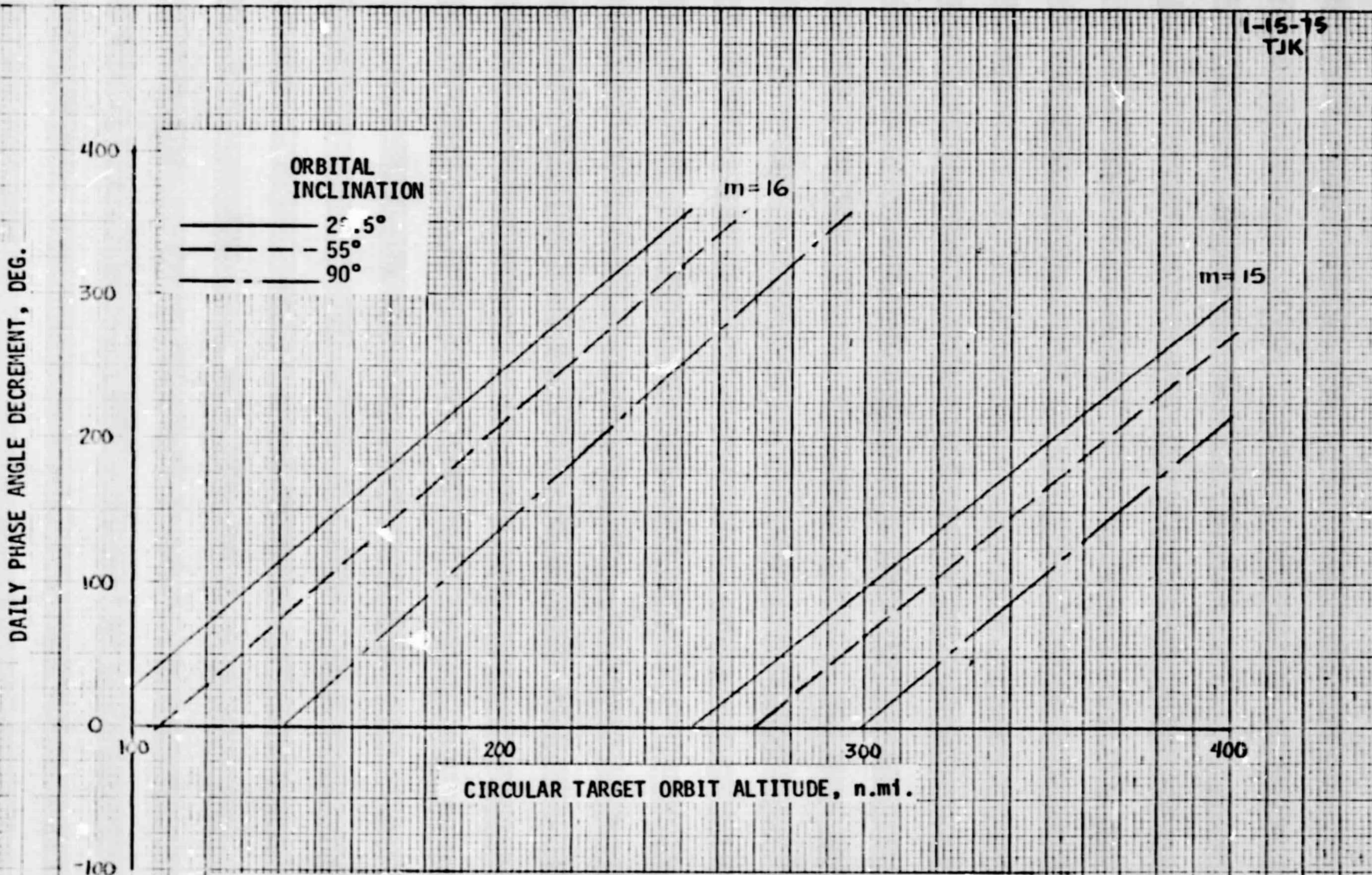


FIGURE 6 - DAILY PHASE ANGLE DECREMENT V.S. TARGET ORBIT ALTITUDE FOR ORBITAL INCLINATIONS OF 28.5, 55, AND 90 DEGREES

TABLE 3 - PARKING ORBIT AND GROUND HOLD PHASING CAPABILITIES

	Daily Decrement in Phase Angle, Deg. *			
Target Orbit Altitude, n.mi.	Via 100 n.mi. Circular Parking Orbit **	Via Ground Hold ***		
		i=28.5°	i=55°	i=90
120	48	70	28	308
150	118	137	97	21
190	210	225	188	115
270	379	36	0	296
340	516	178	147	87

* Catch-up Angle of Launcher is 360 Minus the Angle Shown

* * Assumes 16 Complete Revolutions in 100 n.mi. Circular Parking Orbit

* * * Assumes Launch is Delayed by Approximately One Day

Observe from Table 3 that by delaying launch approximately one day, the ensuing insertion phase angle becomes:

$$195° - 137° = 58°$$

For an insertion phase angle of 58°, rendezvous may be achieved by spending only 10 half revs in a 70 x 100 n.mi. parking orbit or, referring to Figure 1, by spending 13 half revs in a 100 n.mi. circular parking orbit. In the latter instance a savings of 35 half revs of phasing (25.72 Hours) was realized by simply postponing launch by one day.

It will not always be more advantageous to employ ground hold in lieu of parking orbit phasing, and individual decisions will have to be made for each flight based on such things as predicted insertion phase angle, desired duty cycle or revs of phasing, and available impulsive velocity.

Circumstances could exist wherein ground hold would be totally unacceptable. One example of this might be an emergency rescue situation. If the target vehicle were in a low orbit and if some minimum time to rendezvous were specified, a "you can't get there from here" predicament could arise for some phase angles. Consequently, certain guidelines assumed herein would have to be relaxed, removed or reestablished. A requirement for shuttle on-orbit rescue operations is cited in Reference 6; however, no specific rescue criteria, rationale, or groundrules have been established.

5.0 CONCLUSION

Four conclusions were reached during the course of this study:

A) Assuming the parking time should be no more than 1 ½ days (48 half revs) use of a 100 n.mi. circular parking orbit for low target orbits will not provide a launch capability for all phase angles.

B) Only limited use may be made of parking orbits whose altitudes are in the vicinity of 70 n.mi. because of orbiter thermal constraints. Furthermore, orbital maintenance will be required if low parking orbits are used.

C) Use of elliptical parking orbits (or circular orbits with altitudes greater than the target orbit) is necessary to achieve any phase angle for low target orbits; however, a modified rendezvous sequence would be required and parking times of the order of 1½ days are typically required assuming a ΔV budget similar to that of BRM 2.

D) The long orbital parking times associated with low orbit rendezvous may in some cases be avoided by parking on the launch pad, i.e., delaying launch.

Based on the foregoing considerations, shuttle rescue requirements, which have yet to be determined, are expected to be demanding especially for low orbit operations. The development of shuttle rescue rationale and techniques should be addressed in the future.

6.0 REFERENCES

1. SSEOS Design Note No. 1.4-3-10, "Nominal Profile Refinements Report: Target in 120 Nautical Mile Circular Orbit", McDonnell Douglas Technical Services Company, Inc., dated 24 December 1974.

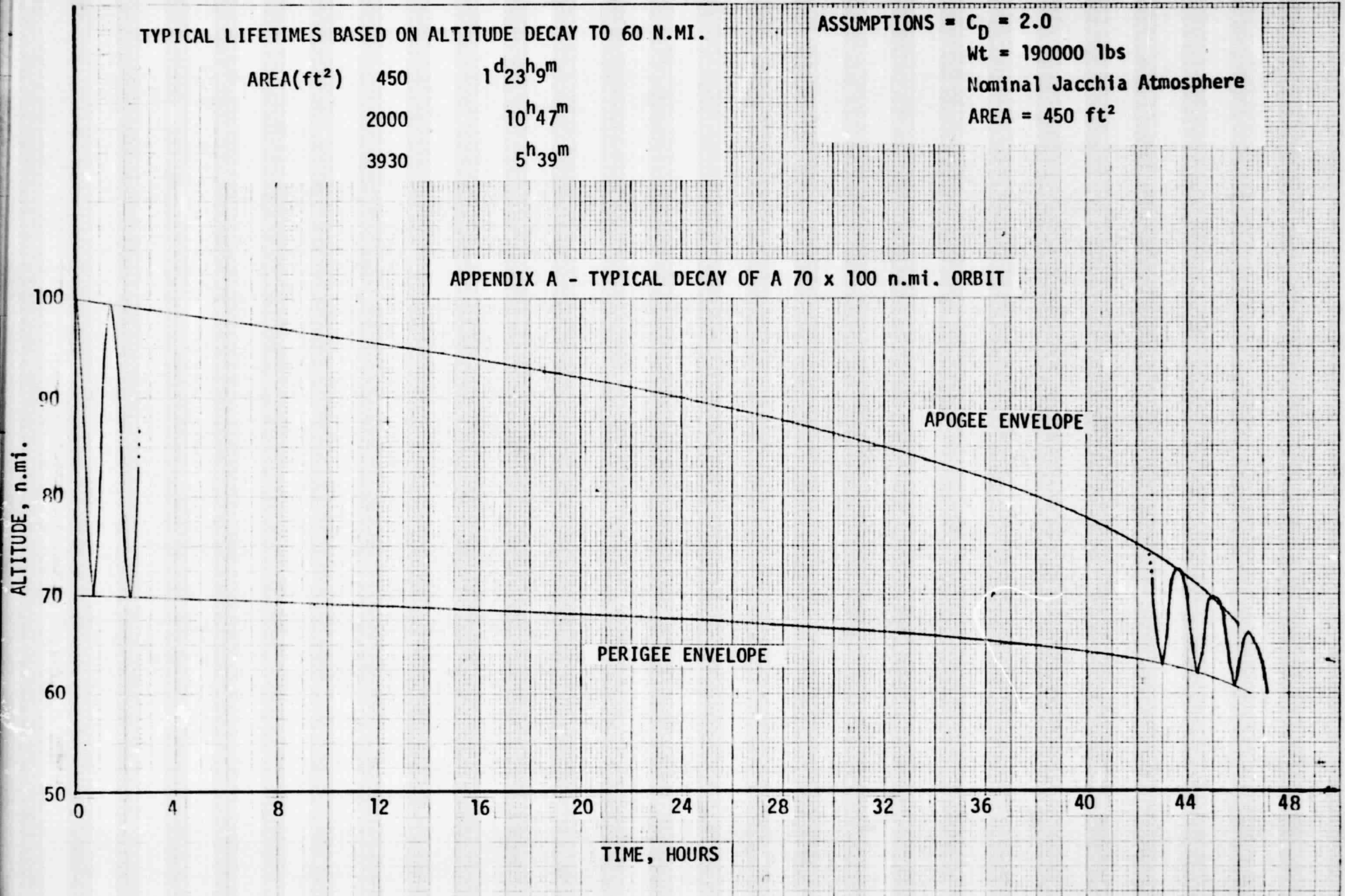
2. JPL Technical Report No. 32-604, "Constants and Related Data for Use in Trajectory Calculations" , Jet Propulsion Laboratory, dated 6 March 1964.

3. Gemini Design Note No. 58, "Effect of Catch-Up on Out of Plane Angle", McDonnell Douglas Technical Services Company, Inc., dated 7 December 1962.

4. JSC Internal Note No. 73-FM-47, " Space Shuttle Baseline Reference Missions - Volume II Mission 2 Revision 1", Johnson Space Center, dated 29 May 1974.

5. SSEOS Design Note No. 1.4-3-9, "Orbital Lifetime Studies in Support of AMPS Missions", McDonnell Douglas Technical Services Company, Inc., dated 9 December 1974.

6. JSC 07700, "Space Shuttle Program Level II Program Definition and Requirements: Volume X: Space Shuttle Flight and Ground System Specification", Section 3.2.1.1.13, Johnson Space Center, dated 20 March 1973.


TYPICAL LIFETIMES BASED ON ALTITUDE DECAY TO 60 N.MI.
AREA(ft²) 450 $1^d23^h9^m$
2000 10^h47^m
3930 5^h39^m
ASSUMPTIONS = C_D = 2.0
Wt = 190000 lbs
Nominal Jacchia Atmosphere
AREA = 450 ft²
APPENDIX A - TYPICAL DECAY OF A 70 x 100 n.mi. ORBIT
APOGEE ENVELOPE
PERIGEE ENVELOPE
ALTITUDE, n.mi.
100
90
80
70
60
50
0
4
8
12
16
20
24
28
32
36
40
44
48
TIME, HOURS