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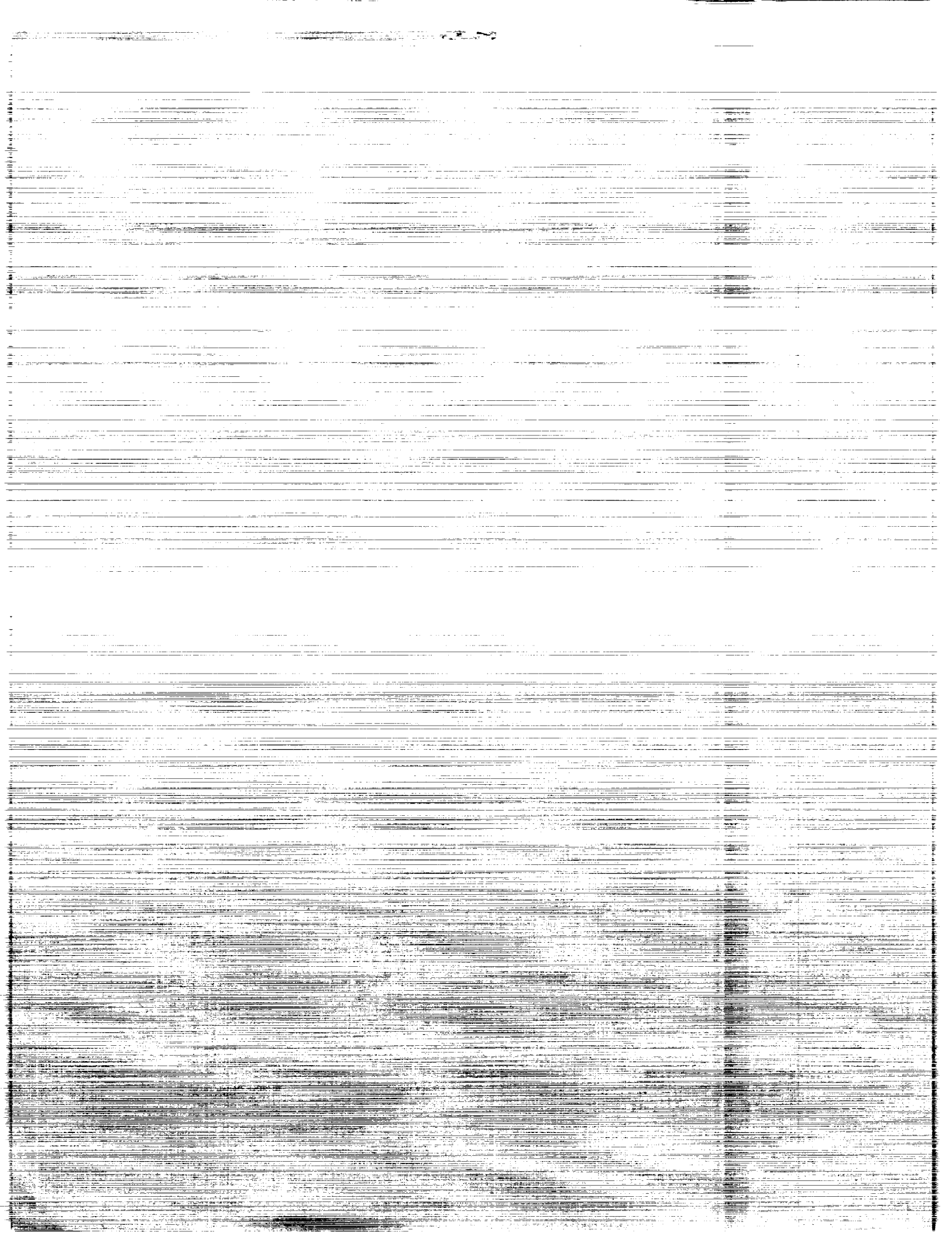

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SOYUZ Escape Trajectory Analysis From Space Station *Freedom*

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Space Administration

Office of Management

Scientific and Technical
Information Program

1993

SOYUZ Escape Trajectory Analysis from Space Station *Freedom*

Introduction

An Assured Crew Return Vehicle (ACRV) is required for *Freedom* before the station can become permanently inhabited. The Russian built SOYUZ vehicle has been proposed to be utilized in this capacity. Because SOYUZ can only accommodate 3 crew members, at least 2 vehicles are required for the permanently manned configuration in which 4 crew members reside onboard.

Although several candidate locations are under consideration based on a variety of accommodation issues, the *orientation* of the SOYUZ from an escape trajectory point of view reduces down to 3 options: +Z body (primarily nadir), -Z body (primarily zenith), and -X body (primarily minus velocity).

The trajectory path followed by the escaping SOYUZ is influenced by the following 6 factors: a)ΔV magnitude, b) departure direction, c) configuration dependent ballistic coefficient effects, d) atmospheric density, e) *Freedom* attitude control, and f) the *size* of the docking adapter which connects the SOYUZ to the station.

Objective

The purpose of this report is to compare and contrast the candidate attached SOYUZ locations from an escape departure point of view. Since no clearance specifications have been specified, parametric studies were performed to determine when interference occurred during departure. Each of the 6 parameters listed above were examined as to their effect on the trajectory path.

Assumptions

All analyses were performed assuming the Stage 17 permanently manned configuration (PMC). Unless otherwise noted, a 220 Nm, 28-1/2 deg circular orbit was assumed. Initial PMC attitude was -13 degrees in pitch, corresponding to the TEA. The departing SOYUZ was assumed to translate with respect to *Freedom* independent of the station attitude rate. The docking adapter modelled measured 2.2 meter high, 2.1 meters in diameter. Plots showing the computed SOYUZ escape trajectories superimposed over the PMC configuration had selected elements transparent in order to show SOYUZ element components and critical clearances.

To isolate the effects of atmospheric density, 2 density profiles were simulated: 1) *design* atmosphere (density = 1.45E-11 Kg/m^3), representing a maximum density at 220 Nm altitude and, 2) a -2σ minimum solar cycle (density = 3.88E-13 kg/met^3),

representing a minimum density.

Two SOYUZ configuration dependent ballistic coefficients (BC) were modelled. A max value of 203.1 kg/m^2 was used to simulate a SOYUZ with "feathered" PV arrays, while the value of 125.5 kg/m^2 was used assuming SOYUZ PV arrays were "full" into the velocity vector. *Freedom's* ballistic coefficient varied from 47.5 to 94.5 kg/m^2 twice an orbit as the solar arrays articulate to track the sun. The minimum initial *Freedom* BC was paired with the maximum SOYUZ BC, and vice-versa, to ascertain the effects of configuration dependent ballistic coefficient on the escape path. Note that any "blockage" effects of *Freedom* on SOYUZ aerodynamics was neglected in this analysis.

As stated earlier, 3 departures directions were considered: +Z body, -Z body, and -X body, which corresponds to a nadir, zenith, and minus velocity direction, respectively, offset by the -13 degree initial pitch attitude. "Canted" docking adapters, limited to ± 20 degrees, were also considered.

Three *Freedom* attitude control modes were simulated: 1) nominal CMG control 2) contingency pitch rate ≤ 0.65 deg/sec, and 3) contingency roll rate ≤ 0.4 deg/sec.

Figures 1 through 13 illustrate SOYUZ escape departure paths under a variety of conditions. All results are plotted in a coordinate frame attached to the station. The vertical axis represents the body Z location, measured in meters, while the horizontal axis represents the body X axis (except for the contingency roll rate illustrated in Figure 11, where the horizontal axis is body Y).

Results

Figure 1 (Case 1) illustrates the effects of different ΔV escape velocities for a -Z body (zenith) departure. The "high" atmospheric density model, coupled with the maximum ballistic coefficient difference obtained by simulating the feathered SOYUZ and an initially full-array *Freedom,* have been modeled to yield maximum aerodynamic effects on the escape trajectory. The general trend shows that as the SOYUZ is ejected into a higher, slower orbit, it gradually falls behind *Freedom*. No interference problems for this departure location occur as there is nothing above or behind the SOYUZ. Thus, even a 0.2 cm/sec ΔV results in a clear escape. (However, for a 0.0 ΔV, SOYUZ initially moves "forward" relative to *Freedom* because of *Freedom's* larger aerodynamic drag.) As can be seen in Figure 1, with such small ΔV escape velocities, the SOYUZ remains in the vicinity of *Freedom* for quite some time.

Figure 2 (Case 2) repeats the assumptions of Case 1 with the exception that a +Z body escape trajectory is simulated. The SOYUZ is initially ejected "downward" into a lower orbit, where it begins to move forward relative to *Freedom* as it approaches it's perigee. After a while, however, *Freedom* slows down relative to SOYUZ due to the smaller BC, hence dropping into a lower, shorter period orbit.

Thus, the SOYUZ eventually appears to bend back upward (-Z) and backward (-X) relative to *Freedom*. As with the -Z body departure, relatively small values of ΔV are required, as the main blockage concern is the forward extending lab and hab modules. As can be seen for Figure 2, a ΔV value of 0.8 cm/sec is sufficient to clear the front of Space Station.

Figure 3 (Case 3) again repeats Case 1 except the SOYUZ is attached to a third (lower) node and departs in -X body direction. The trajectory initially goes back, and drops into a lower orbit, which causes the SOYUZ to move forward relative to *Freedom*. But eventually the larger drag deceleration acting on *Freedom* causes it to drop relative to the SOYUZ. Thus, the only clearance problem occurs as the SOYUZ passes the pressurized modules extending along +X. A $\Delta V > 0.8$ cm/sec appears to assure adequate clearance.

Figures 4a and 4b (Case 4) repeat Case 2 with the exception that a *minimum* atmosphere, coupled with a minimum SOYUZ/*Freedom* BC difference is modelled, in order to simulate minimum aerodynamic effects in contrast to Case 2. The trend shown is similar to Figure 2, except that the upward and backward bending of the trajectory path relative to *Freedom* is delayed due to the reduced aerodynamic differences. A ΔV value of 0.6 cm/sec assures clearance with respect to the forward end of *Freedom*. Case 4 indicates that the aerodynamic/ballistic coefficient effects play an insignificant role in distinguishing candidate departure locations.

Cases 5, 6, and 7 repeat the -Z body, +Z body, and -X body departure trajectories of Cases 1, 2, and 3, respectively. However, a *Freedom* contingency pitch rate of 0.65 deg/sec is simulated to determine the effect on the ΔV required to achieve clear departure. All other parameters (altitude, ballistic coefficient, atmospheric density, etc.) remain as before with Cases 1-3.

Case 5 (Figure 5) simulated a +0.65 deg/sec pitch rate, whereby the upper, forward portion of *Freedom*, including the cryo tanks, rotate *toward* the -Z body departing SOYUZ. Compared to Case 1, a considerably larger ΔV, on the order of 0.15 to 0.2 met/sec, is required to clear the station quickly enough before the station pitch rate rotates into the departure path. The departure paths are all characterized by the forward bending due to viewing from the body frame rotating at a 0.65 deg/sec pitch rate.

Case 6 (Figure 6) shows the results for the +Z body (nadir) departure in the presence of a -0.65 deg/sec pitch rate. The negative sign rotates *Freedom* so that potential contact with the forward pressurized modules is accelerated. A $\Delta V \geq 0.15$ met/sec is required to assure clearance.

Case 7 (Figure 7) rotates the station at +0.65 deg/sec pitch for the -X departing SOYUZ. This rotates the international elements downward and into the path of the escaping SOYUZ. A considerable ΔV on the order of 4 met/sec, is required to quickly escape the vicinity of *Freedom* without a collision. Such a contingency pitch

rate rules out a -X departure without modification to the orientation of the SOYUZ docking adapter.

Cases 8, 9, and 10 repeat the contingency pitch rate Cases 5 through 7, except the docking adopter is allowed to be canted 20 degrees with respect to the station body axis in order to reduce the ΔV requirement in the presence of the contingency pitch rate. The results are presented in Figures 8, 9, and 10. The -Z body departure is canted 20 degrees back. The +Z body departure is also canted 20 degrees back, while the -X departure is canted 20 degrees downward. The -Z body ΔV requirement is reduced to 0.1 met/sec, while the -X body departure ΔV requirement is reduced from 4.0 to 0.6 met/sec, still large, but much improved. The +Z body ΔV requirement showed the smallest improvement, from 0.15 met/sec to about 0.12 met/sec.

Case 11 simulates a contingency *roll* rate of -0.4 deg/sec. Figure 11 shows a family of SOYUZ escape trajectories for values of ΔV from 0.2 to 1.0 met/sec along the body -Z direction. Figure 11 assumes that the PV arrays are in a vertical position, which is a worse case with respects to a departing SOYUZ in the presence of a contingency roll rate. As can be seen, a ΔV of approximately 0.6 met/sec is required to clear the PV arrays during departure.

Since the *nominal* SOYUZ departure ΔV impulse has been advertised as 12 cm/sec, the -Z body departure simulations were repeated to determine the largest acceptable pitch and roll rates allowable that still assured clearance with the 12 cm/sec ΔV. These results are illustrated in Cases 12 and 13. Figure 12a shows that a station pitch rate no greater than 0.5 deg/sec is required to assure an adequate SOYUZ clearance when departing along the -Z body axis direction. Figure 12b zooms in for a close-up view of the same case. Figure 12c shows the escaping SOYUZ 1 minute after departure. Figure 13 shows that the station cannot have a roll rate in excess of 0.09 deg/sec in order to assure that a 12 cm/sec ΔV (-Z body) departing SOYUZ will not collide with a PC array.

Figure 14 depicts the docking adaptor modelled for this analysis. Table 1 summarizes the results of the studies performed.

Conclusions

The effects of variations in aerodynamic density and relative ballistic coefficients between the SOYUZ and space station *Freedom* were not significant in distinguishing among the three departure directions studied, namely, -Z body (primarily zenith), +Z body (primarily nadir), and -X body (primarily minus velocity). All three cases had ΔV requirements of less than 1 cm/sec.

However, the effect of *Freedom* contingency attitude rates was quite significants. The minus X body direction was virtually ruled out, while ΔV requirements of 0.2 and 0.15 met/sec were required for the -Z and +Z body departures,

respectively, for a contingency pitch rate of 0.65 deg/sec. For the contingency roll rate of 0.4 deg/sec, a 0.6 met/sec ΔV was required for the -Z body departure path. The introduction of canted docking adapters reduced the $\pm Z$ ΔV requirements somewhat. Finally, limiting the ΔV impulse to 12 cm/sec indicated that the *Freedom* pitch rate could not exceed 0.5 deg/sec, or the roll rate 0.09 deg/sec, in order to assure a clear departure.

In conclusion, the $\pm Z$ body departure directions were approximately equally desirable from a clear departure path point of view, while the -X body departure suffered significantly in the presence of contingency *Freedom* pitch rates.

Figure 1.

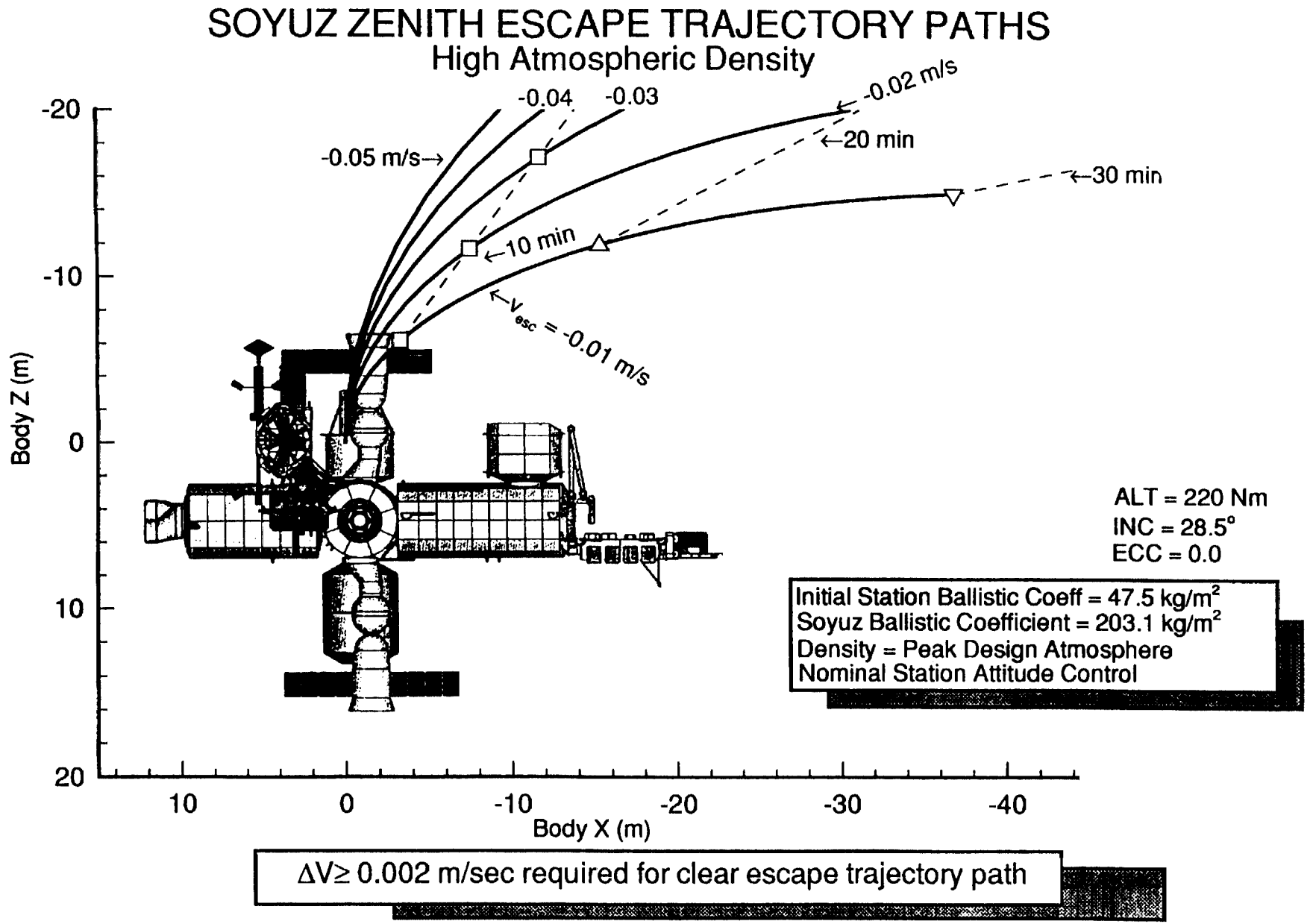
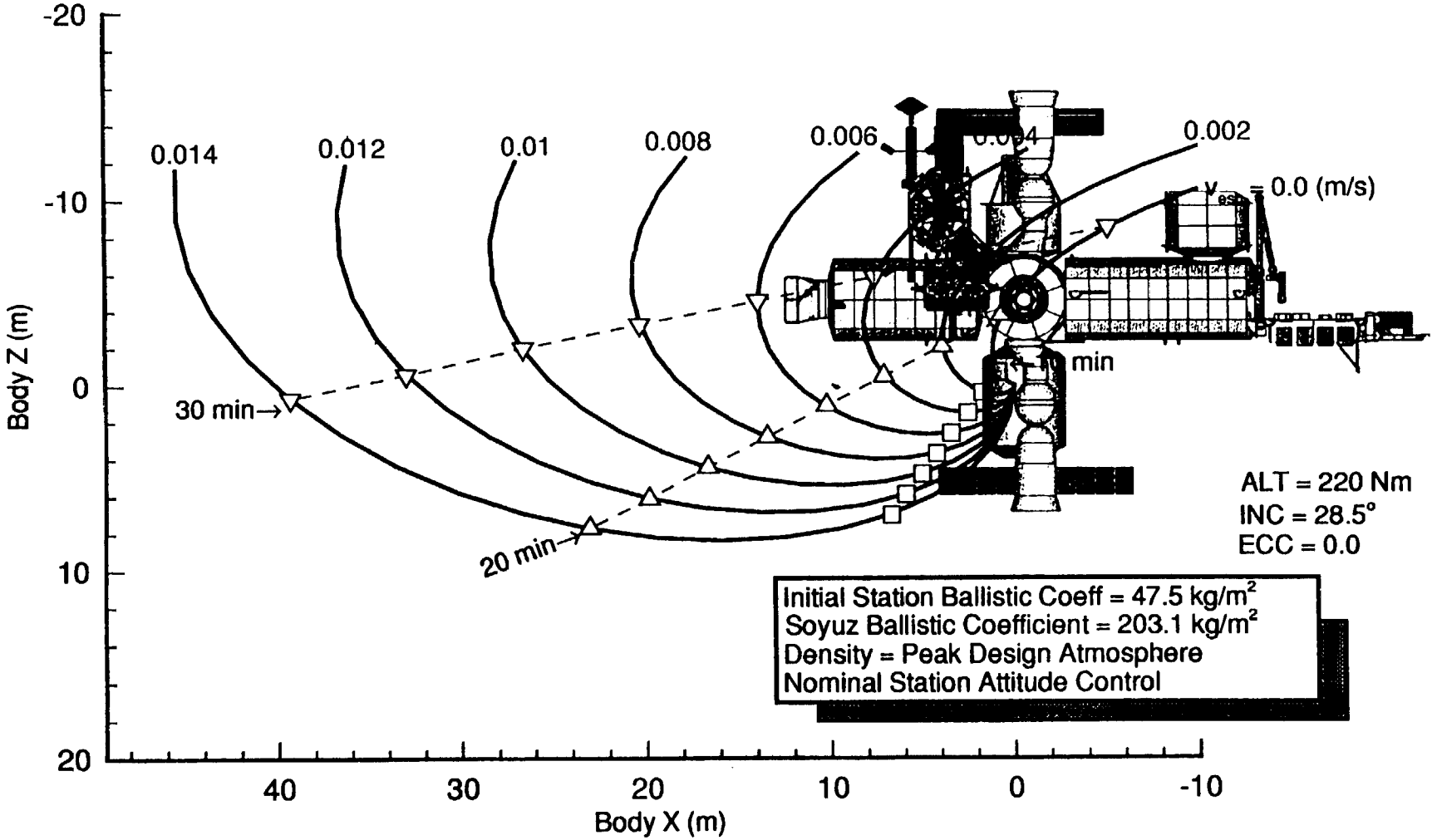

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS
High Atmospheric Density
-0.04
-0.03
-0.02 m/s
-0.05 m/s→
←20 min
←30 min
←10 min
←V esc = -0.01 m/s
Body Z (m)
-20
-10
0
10
20
10
0
-10
-20
-30
-40
Body X (m)
ALT = 220 Nm
INC = 28.5°
ECC = 0.0
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = Peak Design Atmosphere
Nominal Station Attitude Control
ΔV≥ 0.002 m/sec required for clear escape trajectory path

Figure 2.

SOYUZ NADIR ESCAPE TRAJECTORY PATHS

High Atmospheric Density

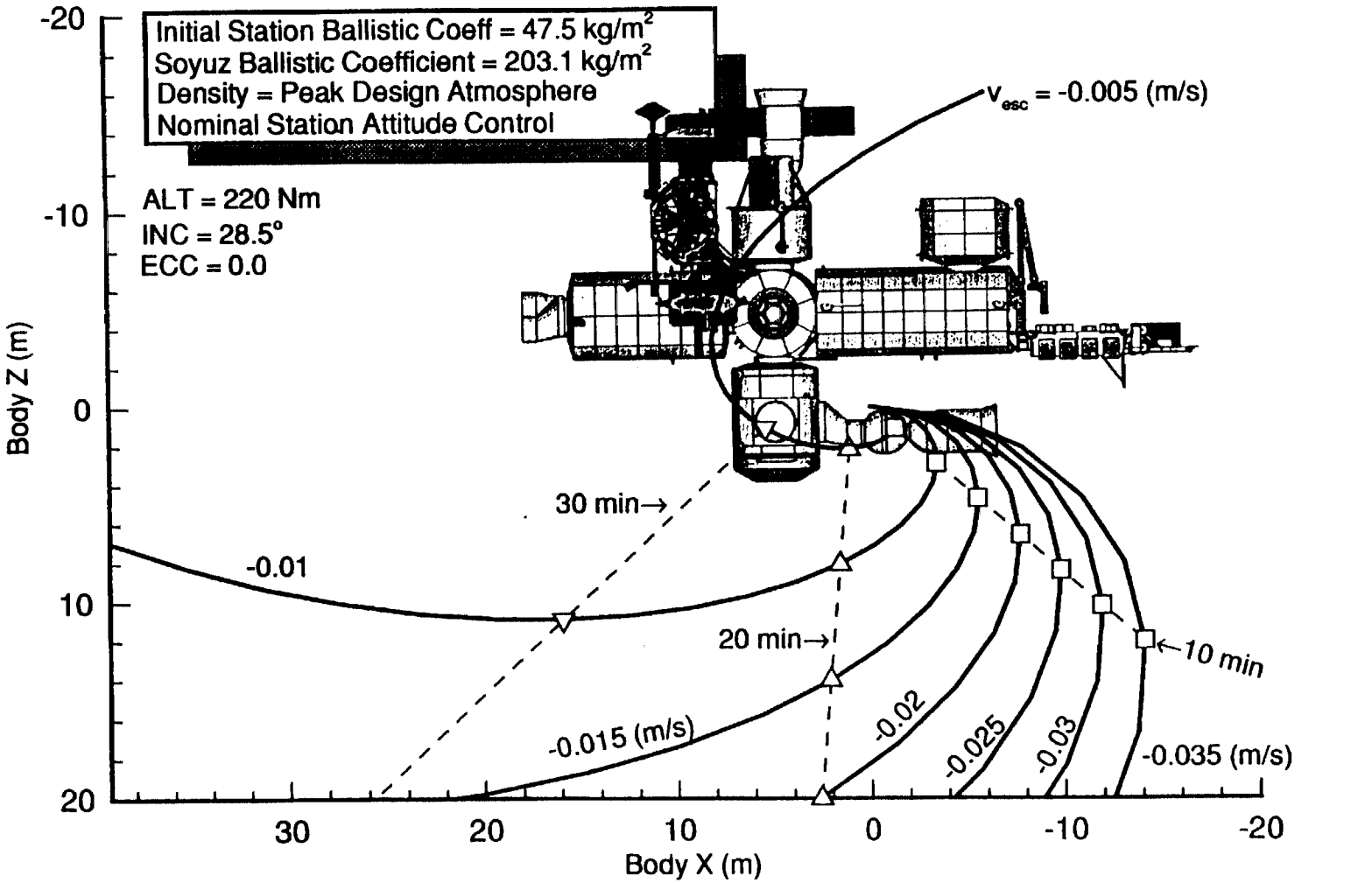


$\Delta V \geq 0.008$ m/sec required for clear escape trajectory path

Figure 3.

SOYUZ -V ESCAPE TRAJECTORY PATHS

High Atmospheric Density

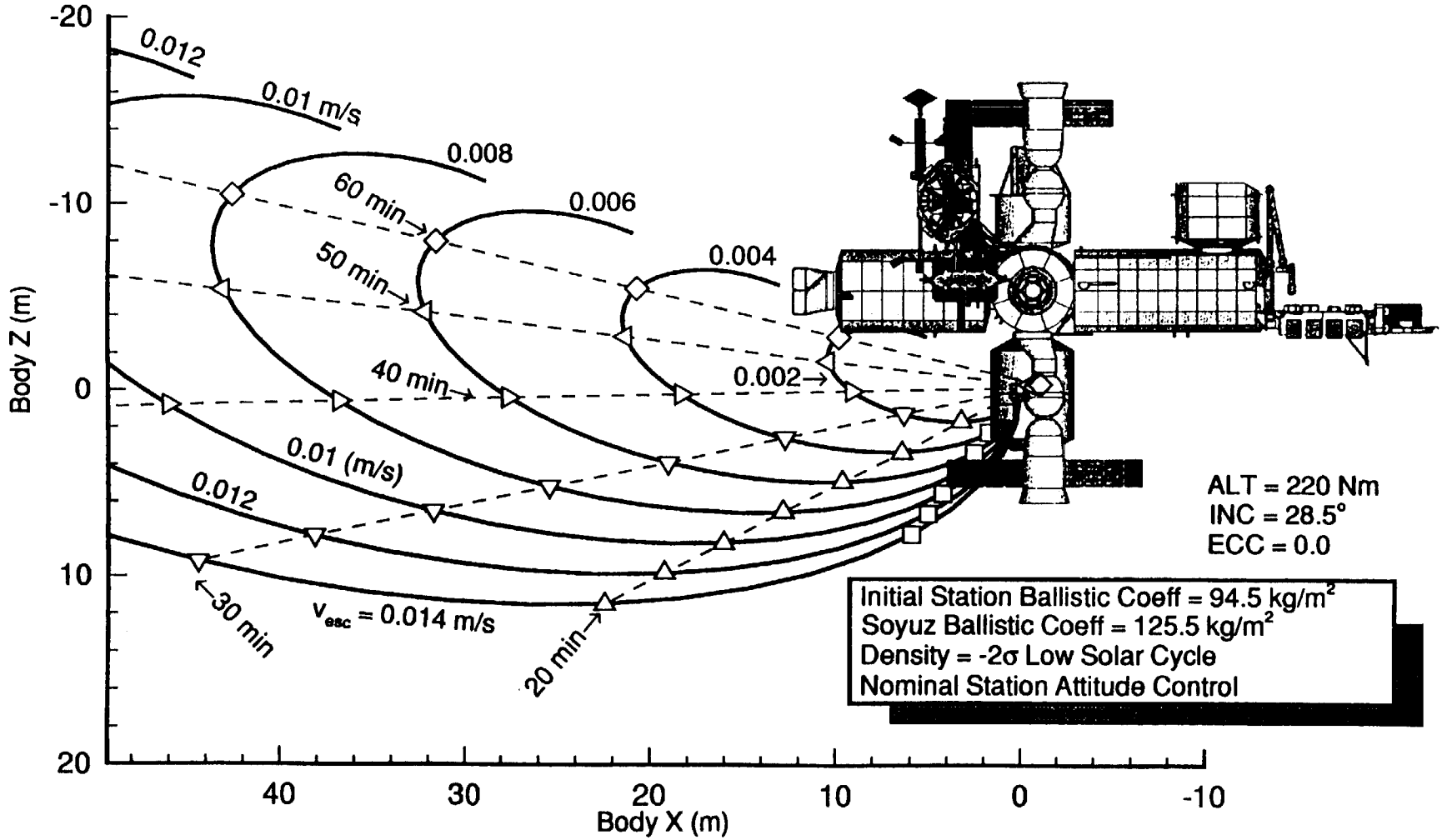


ΔV ≥ 0.008 m/sec required for clear escape trajectory path

Figure 4a.

SOYUZ NADIR ESCAPE TRAJECTORY PATHS

Low Atmospheric Density

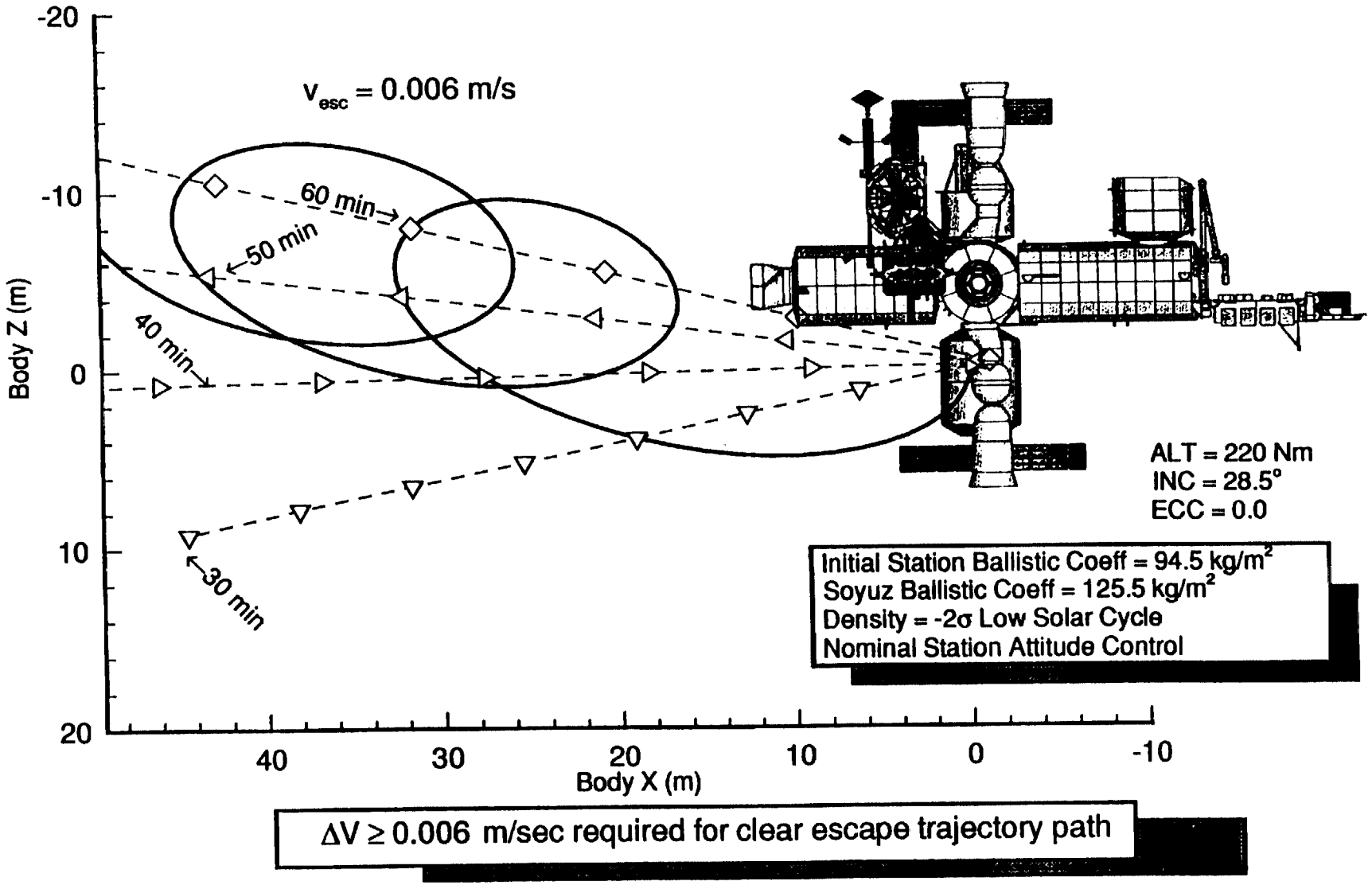


ΔV ≥ 0.006 m/sec required for clear escape trajectory path

Figure 4b.

SOYUZ NADIR ESCAPE TRAJECTORY PATHS

Low Atmospheric Density

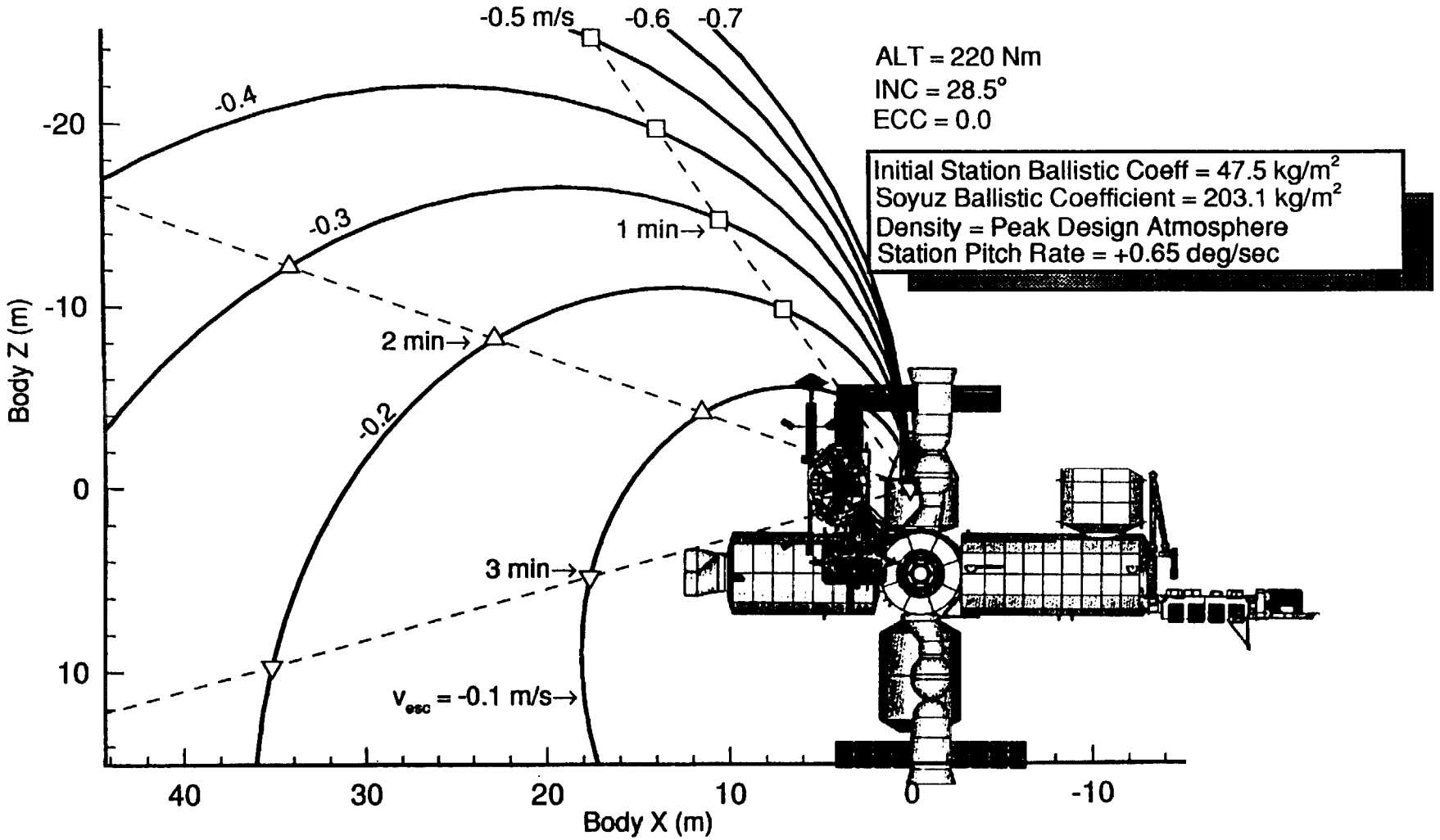


$\Delta V \geq 0.006$ m/sec required for clear escape trajectory path

Figure 5.

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS

High Atmospheric Density



ΔV ≥ 0.2 m/sec required for clear escape trajectory path

Figure 6.

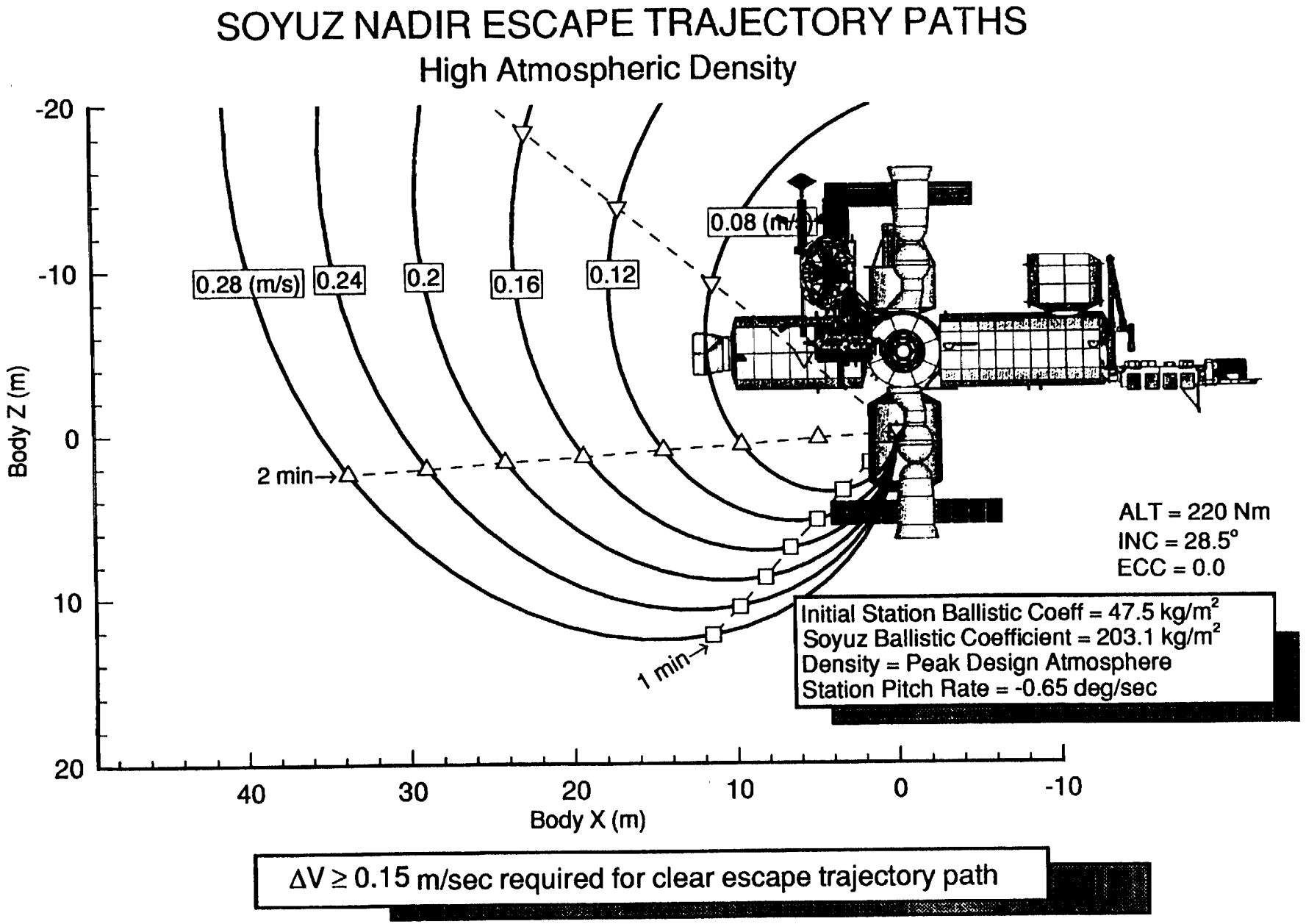
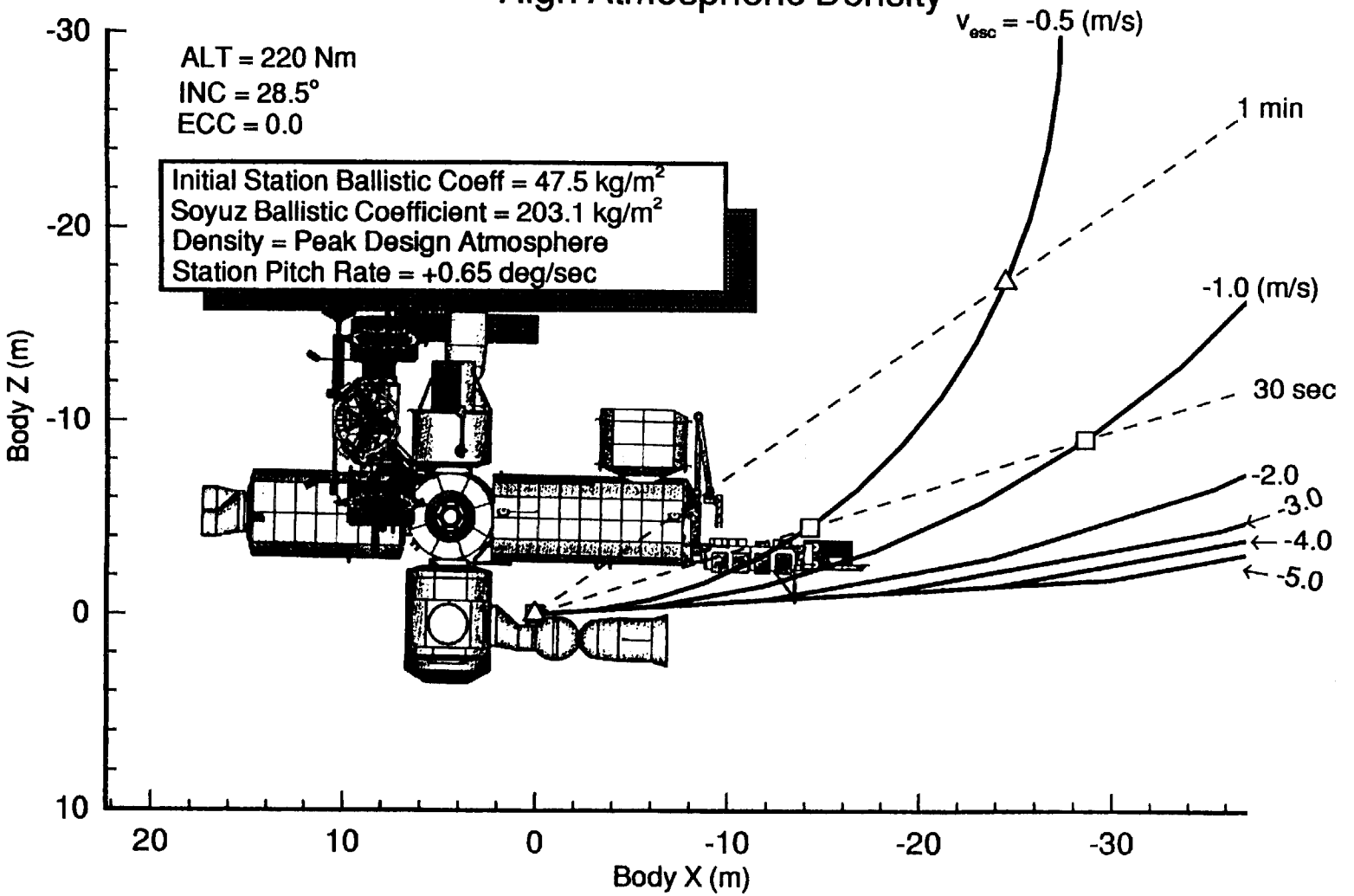

SOYUZ NADIR ESCAPE TRAJECTORY PATHS
High Atmospheric Density
0.28 (m/s)
0.24
0.2
0.16
0.12
0.08 (m/s)
2 min→
1 min→
ALT = 220 Nm
INC = 28.5°
ECC = 0.0
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = Peak Design Atmosphere
Station Pitch Rate = -0.65 deg/sec
Body Z (m)
-20
-10
0
10
20
Body X (m)
40
30
20
10
0
-10
ΔV ≥ 0.15 m/sec required for clear escape trajectory path

Figure 7.

SOYUZ -V ESCAPE TRAJECTORY PATHS

High Atmospheric Density



ΔV ≥ 4 m/sec required for clear escape trajectory path

Figure 8.

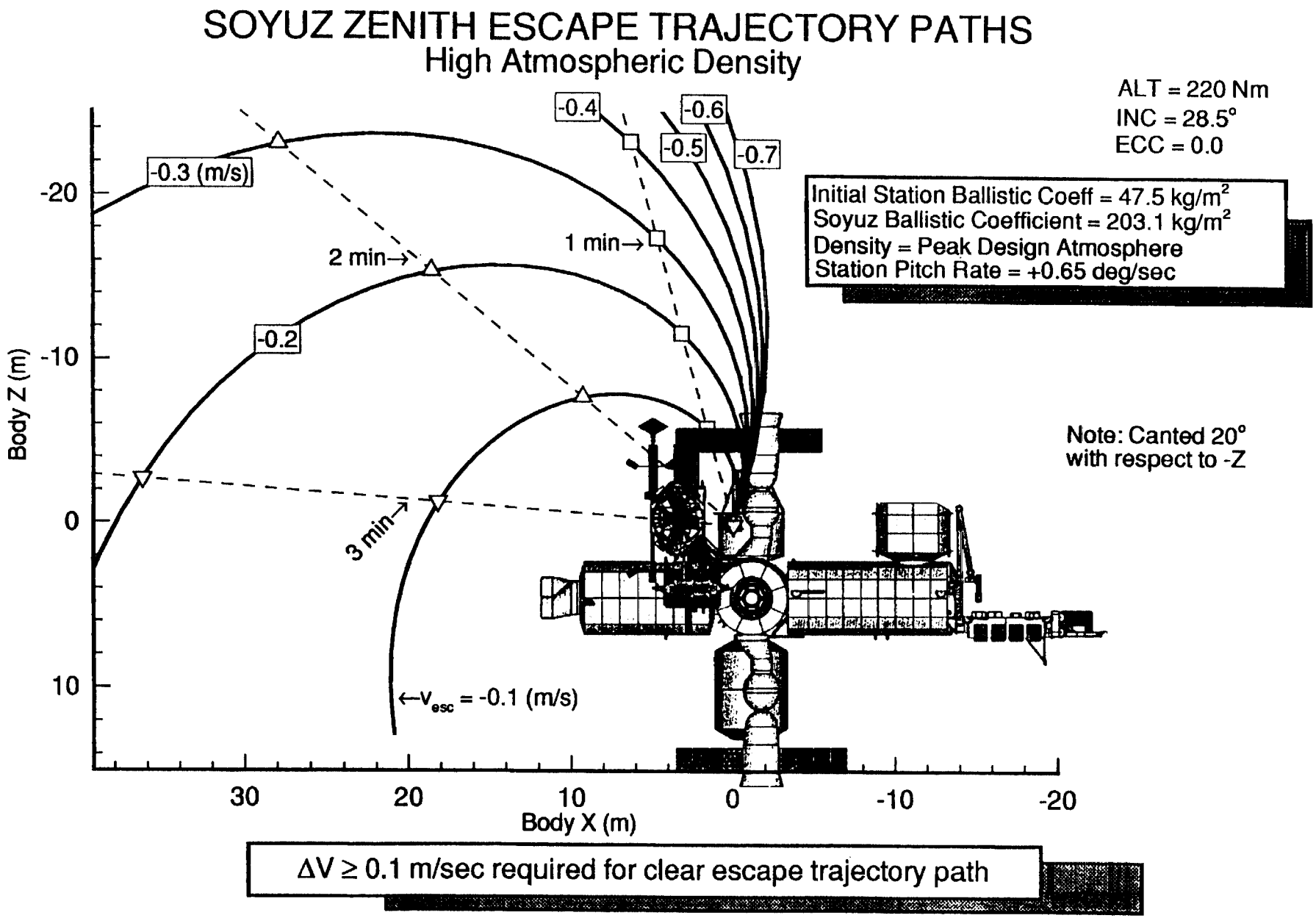

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS
High Atmospheric Density
ALT = 220 Nm
INC = 28.5°
ECC = 0.0
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = Peak Design Atmosphere
Station Pitch Rate = +0.65 deg/sec
-0.4
-0.6
-0.5
-0.7
-0.3 (m/s)
-0.2
1 min→
2 min→
3 min→
←V_{esc} = -0.1 (m/s)
Note: Canted 20° with respect to -Z
Body Z (m)
-20
-10
0
10
30
20
10
0
-10
-20
Body X (m)
ΔV ≥ 0.1 m/sec required for clear escape trajectory path

Figure 9.

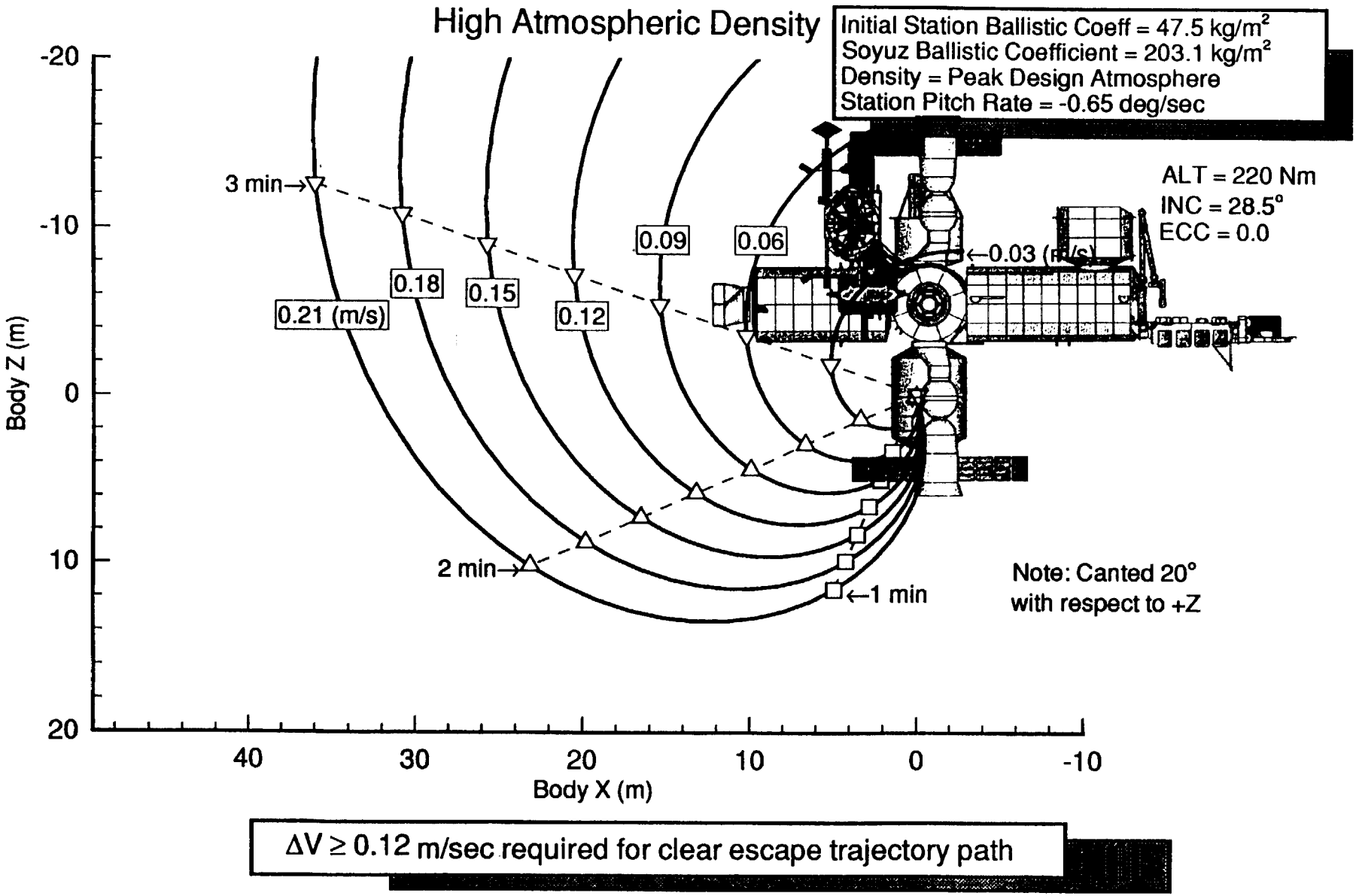
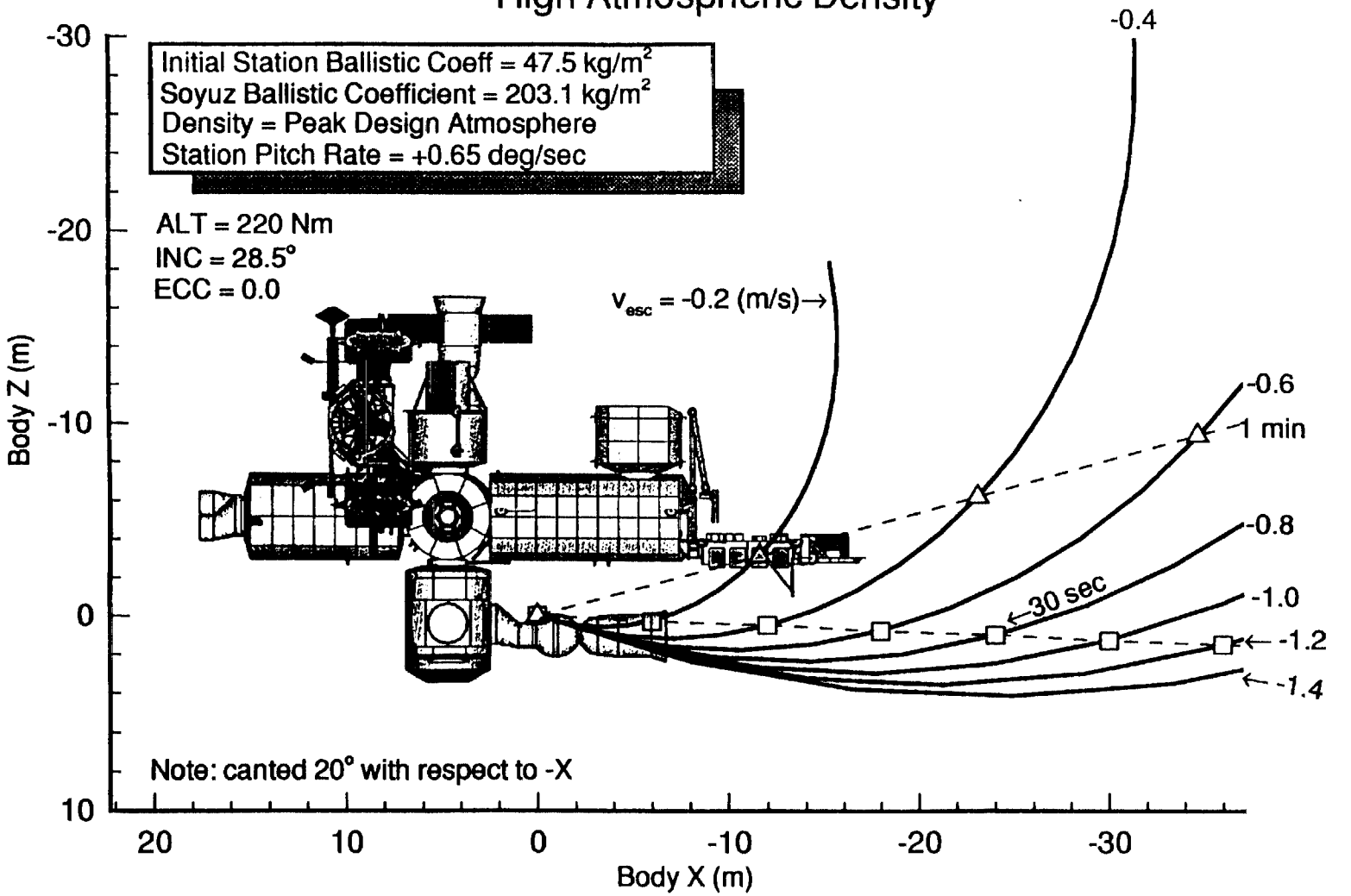

SOYUZ NADIR ESCAPE TRAJECTORY PATHS
High Atmospheric Density
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = Peak Design Atmosphere
Station Pitch Rate = -0.65 deg/sec
ALT = 220 Nm
INC = 28.5°
ECC = 0.0
3 min→
0.21 (m/s)
0.18
0.15
0.12
0.09
0.06
←0.03 (m/s)
2 min→
←1 min
Note: Canted 20°
with respect to +Z
Body Z (m)
-20
-10
0
10
20
40
30
20
10
0
-10
Body X (m)
ΔV ≥ 0.12 m/sec required for clear escape trajectory path

Figure 10.

SOYUZ -V ESCAPE TRAJECTORY PATHS

High Atmospheric Density



ΔV≥ 0.6 m/sec required for clear escape trajectory path

Figure 11.

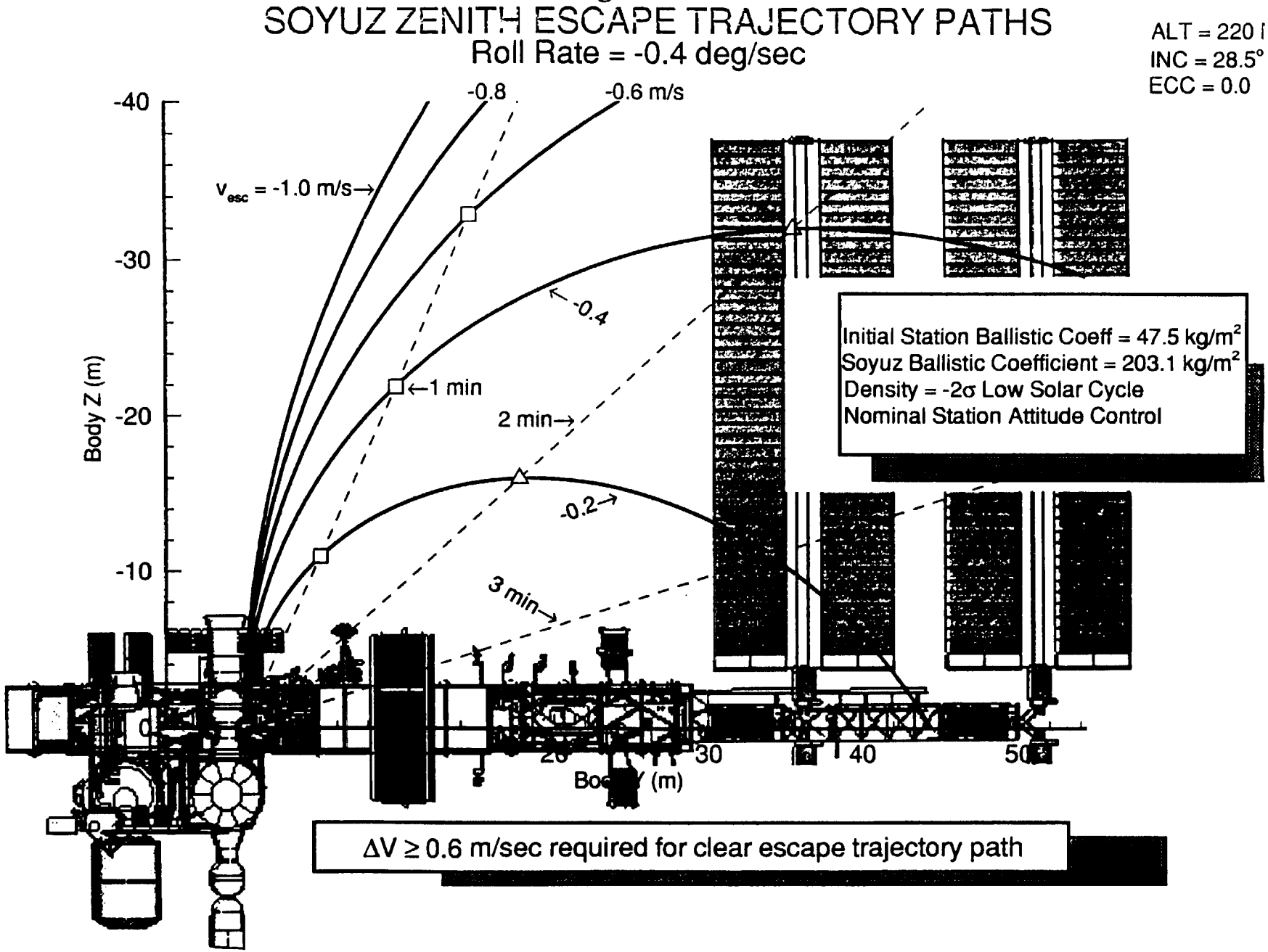

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS
Roll Rate = -0.4 deg/sec
ALT = 220 I
INC = 28.5°
ECC = 0.0
-0.8
-0.6 m/s
-40
-30
-20
-10
v_{esc} = -1.0 m/s→
-0.4
←1 min
2 min→
-0.2→
3 min→
Body Z (m)
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = -2σ Low Solar Cycle
Nominal Station Attitude Control
30
40
50
(m)
ΔV ≥ 0.6 m/sec required for clear escape trajectory path

Figure 12a.

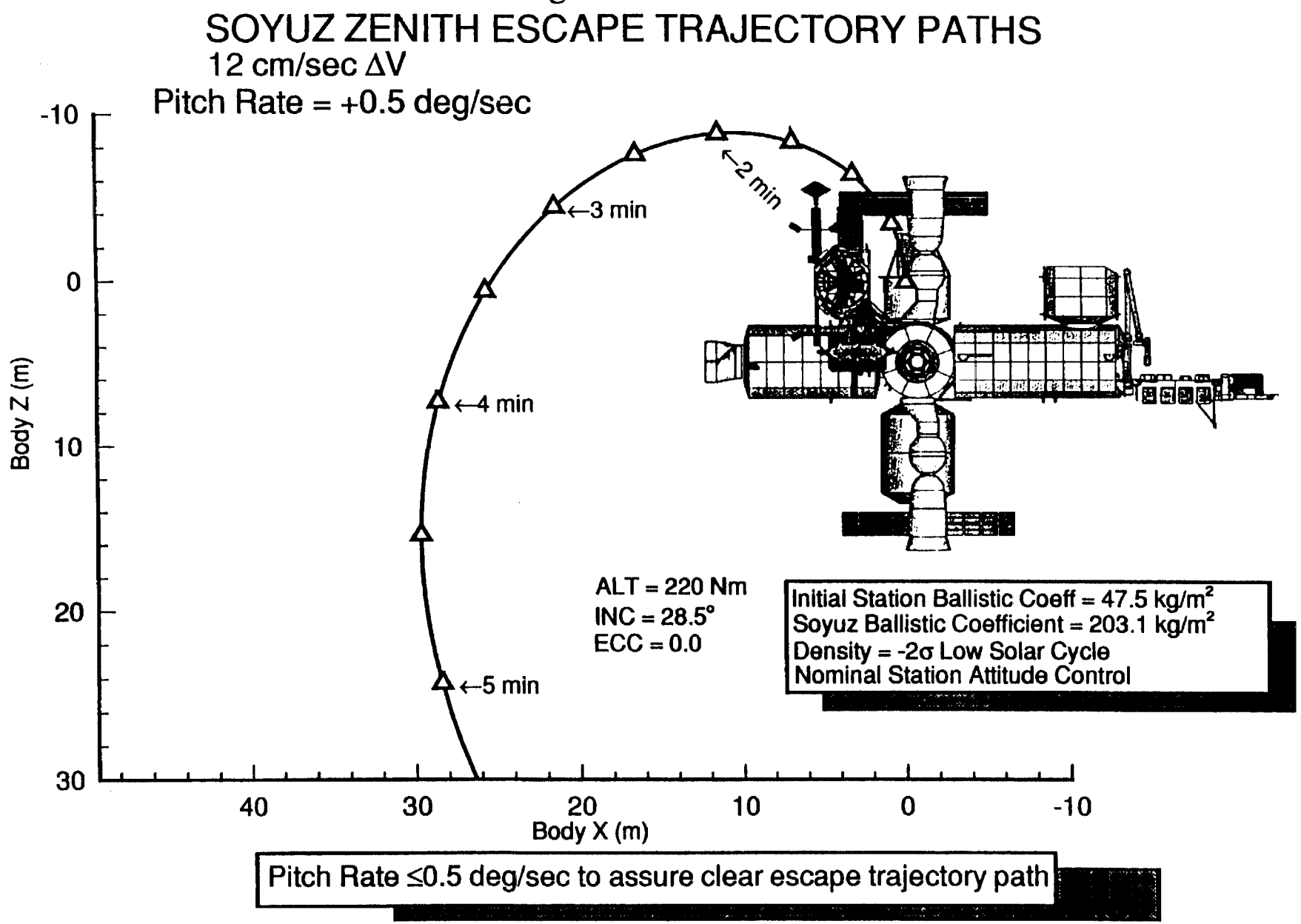

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS
12 cm/sec ΔV
Pitch Rate = +0.5 deg/sec
-10
0
10
20
30
Body Z (m)
←2 min
←3 min
←4 min
←5 min
ALT = 220 Nm
INC = 28.5°
ECC = 0.0
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = -2σ Low Solar Cycle
Nominal Station Attitude Control
40
30
20
10
0
-10
Body X (m)
Pitch Rate ≤0.5 deg/sec to assure clear escape trajectory path

Figure 12b.

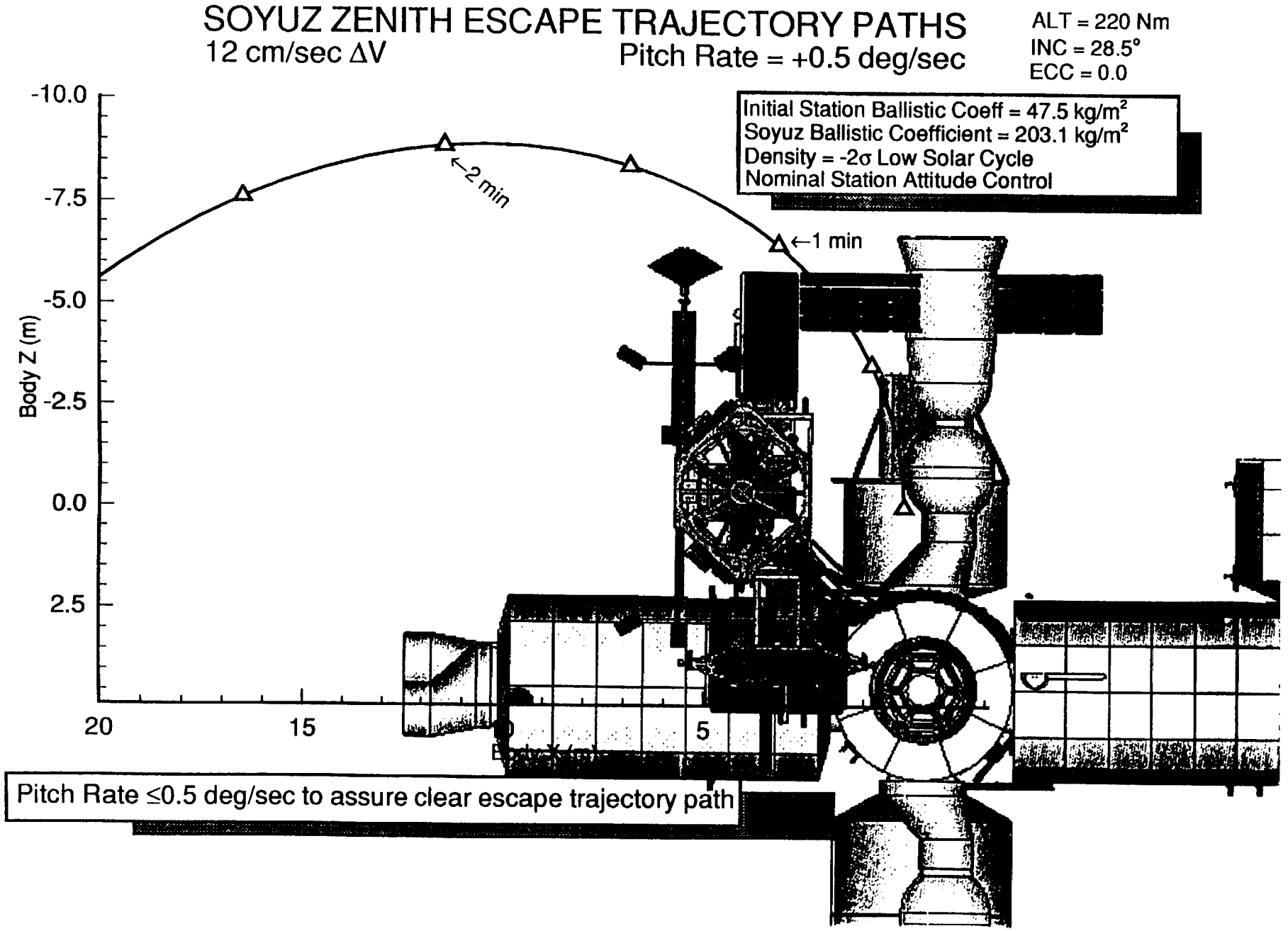

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS
12 cm/sec ΔV
Pitch Rate = +0.5 deg/sec
ALT = 220 Nm
INC = 28.5°
ECC = 0.0
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = -2σ Low Solar Cycle
Nominal Station Attitude Control
←2 min
←1 min
Body Z (m)
-10.0
-7.5
-5.0
-2.5
0.0
2.5
20
15
5
Pitch Rate ≤0.5 deg/sec to assure clear escape trajectory path

Figure 12c.

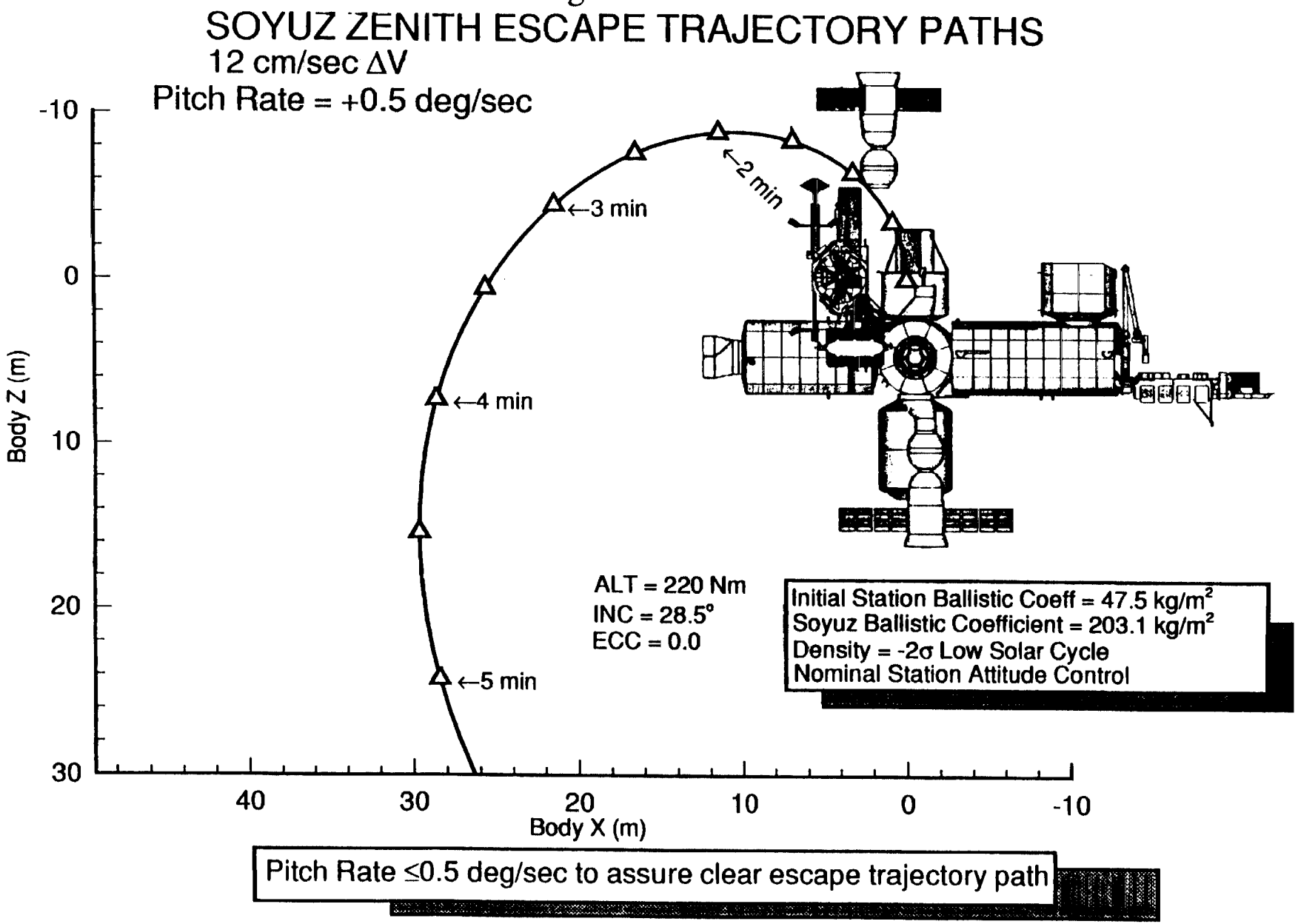

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS
12 cm/sec ΔV
Pitch Rate = +0.5 deg/sec
←2 min
←3 min
←4 min
←5 min
ALT = 220 Nm
INC = 28.5°
ECC = 0.0
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = -2σ Low Solar Cycle
Nominal Station Attitude Control
Body Z (m)
-10
0
10
20
30
40
30
20
10
0
-10
Body X (m)
Pitch Rate ≤0.5 deg/sec to assure clear escape trajectory path

Figure 13.

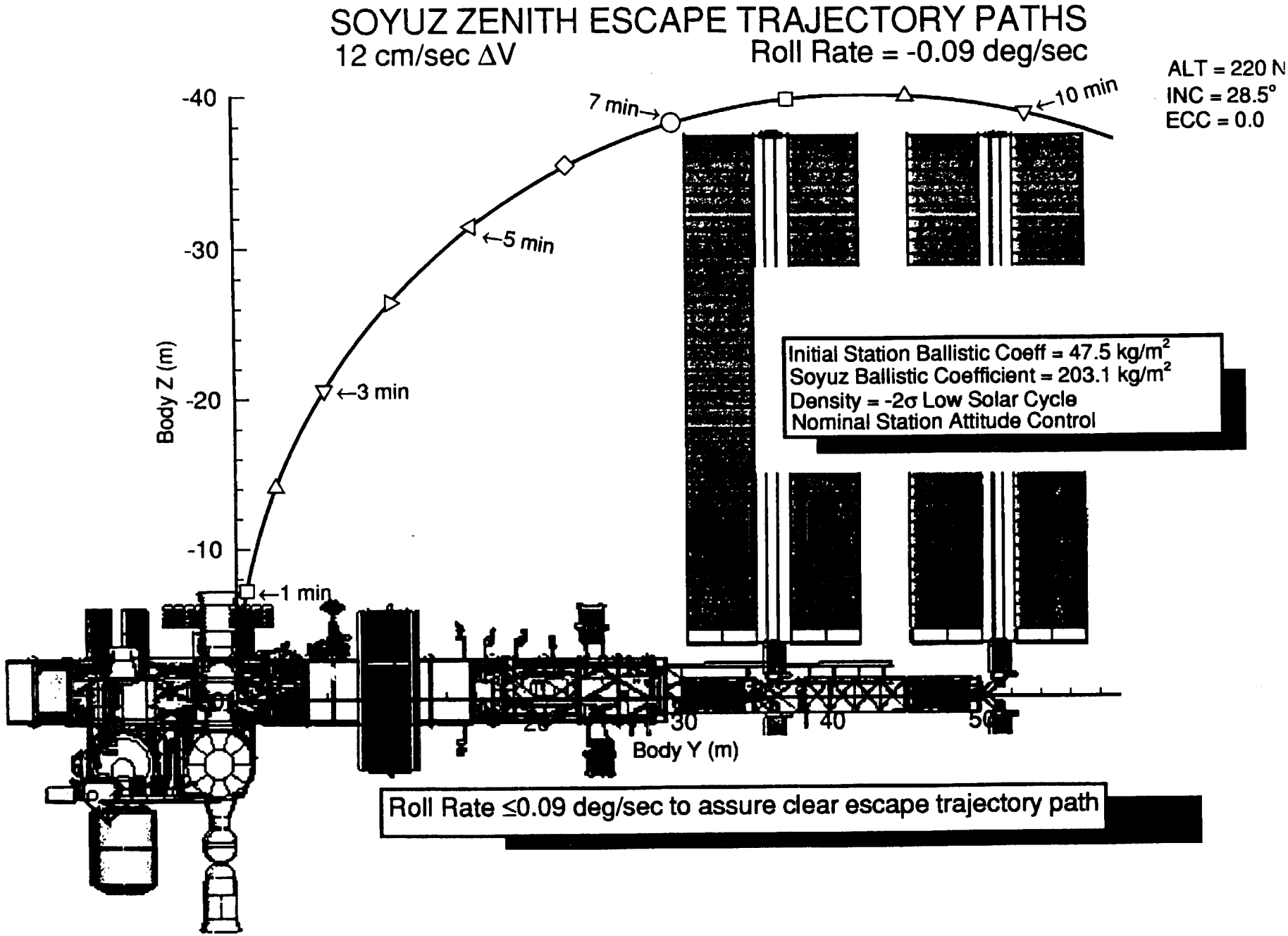
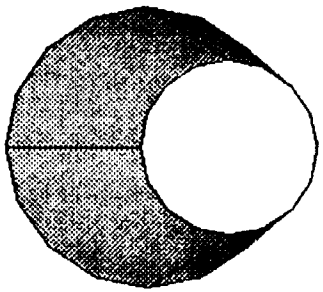
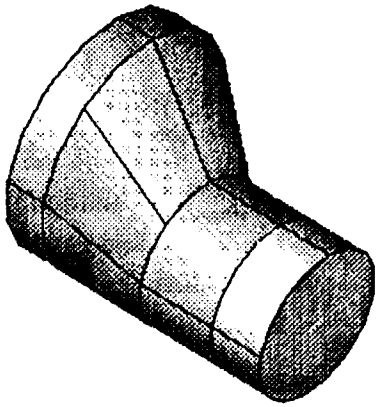

SOYUZ ZENITH ESCAPE TRAJECTORY PATHS
12 cm/sec ΔV
Roll Rate = -0.09 deg/sec
ALT = 220 N
INC = 28.5°
ECC = 0.0
-40
-30
-20
-10
Body Z (m)
7 min
10 min
5 min
3 min
1 min
Initial Station Ballistic Coeff = 47.5 kg/m²
Soyuz Ballistic Coefficient = 203.1 kg/m²
Density = -2σ Low Solar Cycle
Nominal Station Attitude Control
30
40
Body Y (m)
Roll Rate ≤0.09 deg/sec to assure clear escape trajectory path

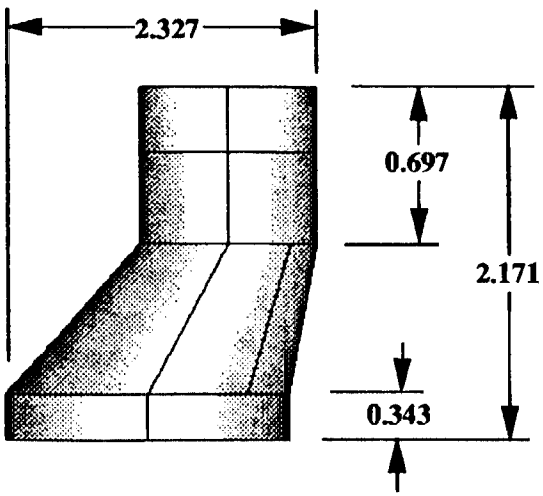
Figure 14.

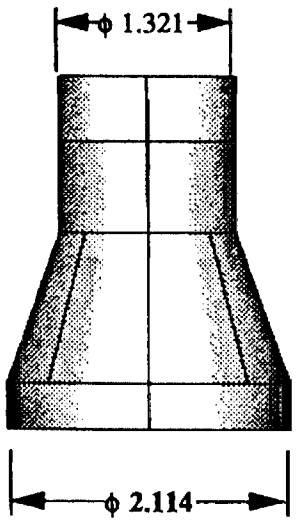
DIMENSIONS USED FOR PMA

NOTES: 1) ALL DIMENSIONS IN METERS.
2) DIMENSIONS EXTRACTED FROM MODEL RECEIVED FROM LEVEL II.









NASA FREEDOM

Table 1. SOYUZ ΔV Required for Clear Escape Trajectories

	High Atmospheric Density (Design atmosphere) 220 Nm Init Station BC = 47.5 kg/m^2 *SOYUZ* BC = 203.1 kg/m^2 (feathered)				Low Atmospheric Density (−2σ min solar cycle) Init Station BC = 94.5 kg/m^2 *SOYUZ* BC = 125.5 kg/m^2 ("full" arrays)
	Nominal Station Attitude Control	0.65 deg/sec Station pitch rate	0.65 deg/sec Station pitch rate 20 deg Cant	0.4 deg/sec Station roll rate	Nominal Station Attitude Control
−Z (Zenith)	**0.002**	**0.2**	**0.1**	**0.6**	**0.006**
+Z (Nadir)	**0.008**	**0.15**	**0.12**	**N/A**	**0.006**
−X (minus vbar)	**0.008**	**4.0**	**0.6**	**N/A**	**0.002**

Units are met/sec

LaRC SSFO

Table2

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13. ABSTRACT *(Maximum 200 words)*

It has been proposed to utilize the Russian built SOYUZ as an assured crew return vehicle (ACRV) for Space Station FREEDOM. Three departure directions (nadir, zenith, minus velocity) are evaluated to determine escape path clearances. In addition, the effects of the following parameters were also evaluated: ΔV magnitude, configuration dependent ballistic coefficients, atmospheric density, FREEDOM attitude control, and canted docking adaptors.

The primary factor influencing the escape trajectory was station contingency attitude rate. The nadir and zenith departures were preferable to minus velocity. The impact of atmospheric density and relative ballistic coefficients was minimal.

14. SUBJECT TERMS

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