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AEROBRAKING

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ABSTRACT

This paper presents a discussion of the basic principles of aerobraking. Typical results are given for the application of aerobraking to orbital capture at Mars, descent to the Mars surface and orbital capture on return to Earth.

AEROBRAKING

Introduction

Aerobraking is the use of a planet's atmosphere to dissipate an entry vehicle's orbital energy to achieve a new orbital state or to descend to the planet's surface.

Numerous planetary descents have been successfully executed; however, aerobraking to a new orbit has not been attempted. A reason for this lack of attempts is that is was believed to be extremely difficult, if not impossible. With recent technology advances, aerobraking is still considered difficult, but it is more promising as a useful technology for space missions.

Many parameters with complex interactions must be considered with design of aerobraking systems and it is difficult to say which are the more important. An iterated approach is used in defining complex algorithms to achieve aerobraking trajectories.

Entry State

The entry state is one of the more important factors. The range of acceptable entry states leading to a successful braking is very limited and is nominally set after a study of the factors shown in Figure 1.1.

The basic parameters of entry state are time, latitude, longitude, altitude, velocity azimuth and flight path angle, the entry vehicle's aerodynamic characteristics and physical constraints (atmospheric structure).

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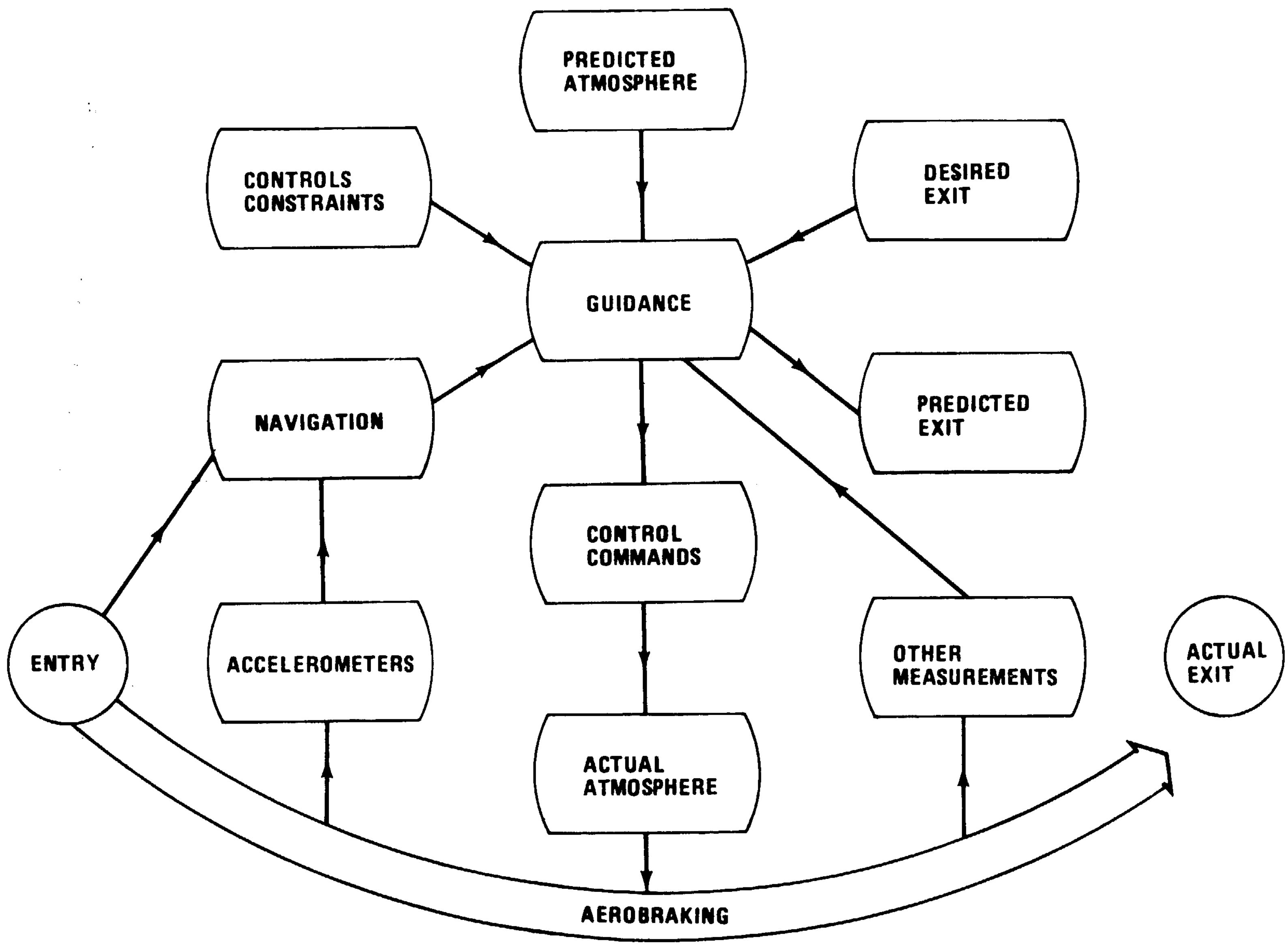

FIGURE 1.1 AEROBRAKING SCHEMATIC

The kinetic and potential energy per unit mass (E) of a vehicle on entry to the atmosphere is expressed as:

$$E = V^2/2 - \mu/R$$

where V is the entry velocity, and R is the radius with respect to the planet's center, and μ is the gravitational constant.

Keplerian equations can be used to calculate the entry orbit apogee, perigee, and mean motion. A time of passage from entry to exit (without an atmosphere) can be calculated. This is a lower bound on the actual passage time. In a similar manner, an upper bound can be calculated from the exit state.

Perigee altitude is a major parameter. The actual perigee, in the atmosphere, will be very near this prediction; usually within two nautical miles. Most of the aerobraking will occur in this region. Atmosphere perturbations in this altitude range can have a very large effect on the trajectory.

Exit State

The exit state conditions are usually specified as an altitude leaving the atmosphere, a desired apogee, and in most cases, a desired flight plane. The other orbit parameters can be approximated if the semimajor axis is known. The actual trajectory perigee will be near the entry perigee, and a crude approximation for the exit orbit perigee will also be near the entry perigee. Then the exit apogee and perigee will define an eccentricity, a semimajor axis, the orbit's angular momentum, and energy level. From the energy equation, an approximate exit velocity can be determined.

Aerobraking Time Limits

Once the entry orbit is known and the exit orbit has been approximated, a lower and upper limit for the aerobraking passage time can be estimated. For aerobraking at Earth, the time in general will be between 3 to 12 minutes.

The aerodynamic characteristics of this vehicle, the vehicle's controls, the predicted atmosphere, the physical constraints and the desired exit conditions are used to design the nominal entry state, and therefore, the aerobraking time. The range of the controls limit the allowable perturbation about this nominal trajectory.

Aerobraking

The aerodynamic forces are the forces that accomplish aerobraking. These are derived from the atmosphere density the velocity with respect to the atmosphere, the angle of attack, the angle and direction of bank, the lift and drag coefficients, and the vehicle's aerodynamics area and weight. It must be emphasized that once an entry has commenced, the actual passage through the atmosphere is within a narrow corridor and a slight deviation up or down in altitude can change the exit apogee drastically. See Figure 1.2 for a graph and table of density changes with altitude.

TRAJECTORY DESIGN

Goals and Physical Constraints

The goals of aerobraking are mission dependent. In both the aero-braking at Mars and at Earth, the desired exit state is an orbit around the planet, with a specified apogee. Typically, the desired orbit must be compatible with that of a transfer vehicle to return to a space station or planetary surface. During the aerobraking phase, physical constraints of aerodynamic heating, aerodynamic pressure and deceleration must be observed.

The deceleration profile is generally bell shaped and follows the atmosphere density profile encountered in the trajectory down and back up through the atmosphere. An approximation for the average acceleration (a) can be obtained from:

$$\Delta V = V\ exit - V\ entry$$

$$a = \Delta V/(\text{time of passage})$$

The maximum is about two and one-half times the average. The dynamic pressure and heating rate profiles are also similar to the density profile. The dynamic pressure (P) is estimated by:

$$P = \rho V^2/2$$

where ρ , and V are the values near perigee.

The heating rate may be approximated by:

$$\dot{Q} = \frac{k}{\sqrt{R_n}} \left(\frac{\rho}{\rho_{SL}}\right)^{\frac{1}{2}} \left(\frac{V}{V_{ref}}\right)^{3.15}$$

where $\dot{Q}$ is heating rate, ρ is k, ρ_{SL} and V_{ref} are derived from those values in Reference 1, and are k = 17600., ρ_{SL} = .076474,

NEAR AEROBRAKING PERIGEE

ALTITUDE KM	DENSITY KGN/M3	RELATIVE RATIO
75	4.3×10^{-5}	2.1
80	2.0×10^{-5}	1.0
85	8.0×10^{-6}	.4

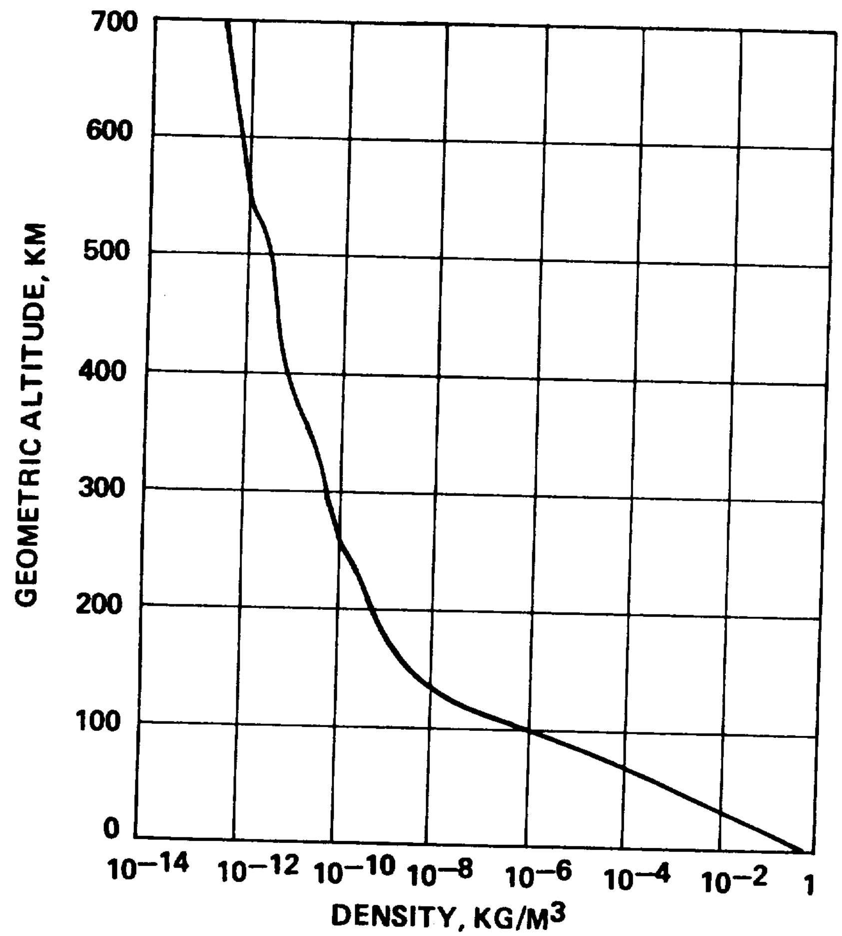

FIGURE 1.2 US62 STANDARD ATMOSPHERE

and V_{REF} = 26000 ft./sec. Limits to P and $\dot{Q}$ can be calculated from the entry orbit perigee velocity and the expected density at perigee.

Representative maximum design values are:

P 50 lbs/ft^2

and

$\dot{Q}$ 30 $BTU/ft^2/sec$ for a flexible TPS

$\dot{Q}$ 50 $BTU/ft^2/sec$ for fixed TPS

Guidance and Controls

Various guidance algorithms have been and are being investigated. See references 2 and 3. Among the algorithm's under study are: a predictor-corrector that guides to the desired apogee using a deceleration profile; a type which adds prediction of the apogee rate; types that utilize bank angle and also predict the final flight plane; types that use numerical integration of the equations of motion; and others that use closed form analytical approximations. All are designed after a consideration of the entry vehicle and it's aerodynamic characteristics and controls.

With the aerodynamic parameters, the direction of bank (L-R), the reversals of bank direction, reversal rates and reversal times (RRT) can be used as control candidates for the guidance algorithm. In designing an algorithm, three types of entry craft may be considered:

I. A variable area vehicle that can fly a deceleration profile but does not have any lateral plane control. Its ability to adjust to the desired deceleration profile is limited by the physical limits of its maximum and minimum area available. Current limits are less than a ratio of 2 to 1.

II. A fixed area vehicle, but with variable angle of attack, angle of bank and RRT. A typical example of this vehicle is the Space Shuttle. It can fly a predetermined profile within its control limits and flight plane control is achieved with the angle of bank and RRT.

III. A fixed area and angle of attack vehicle, with variable angle of bank and RRT. Since $C_D = C_D(\alpha, M)$ and α is fixed, it can only indirectly fly a deceleration profile. Lift must move the craft to a lower (higher) density region to affect drag. RRT does provide a measure of flight plane control.

All of these are feasible for both Martian and Earth aerobraking. The last concept is particularly interesting and is currently being investigated by personnel at MSFC, JSC, C.S. Draper Laboratories and others.

A simple numerical integration predictor corrector algorithm is being used at MSFC to obtain representative trajectories. It iterates the angle of bank, the reversals, and reversal times to obtain the desired exit apogee and flight plane. However, it is not a flight candidate as it takes too long to converge to acceptable values.

TYPICAL RESULTS

Figure 3.1 shows some of the features of the MSFC simple "bang-bang" algorithm for entry and capture at Mars and at Earth. In figure 3.2, representative graphs of altitude, velocity, density, dynamic pressure, acceleration and heating rates are given for a 3 reversal capture profile.

Mars Aerobraking Capture

Figure 3.3 and Table 3.1 present results obtained from a 14 reversal entry into the Martian atmosphere. The initial entry is in a medium to high energy, $C_3 = 30\ km^2/sec^2$, approach orbit. The final orbit is a Molniya type orbit with a 24 hour period. Two assumed Martian atmospheres are given in Table 3.2.

Mars Descent

Results of a ballistic entry to the Martian surface are given in Table 3.3. No controls were assumed. Deboost at the apoapsis of the parking orbit described in Section 3.1 was assumed.

Earth Capture

Figure 3.4 and Table 3.4 give results from an entry into the Earth's atmosphere for capture. The initial orbit is a high energy, $C_3 = 81\ km2/sec_2$, return orbit from Mars. If aerobraking were used with this high energy orbit, the peak deceleration would be in excess of 5g for over 2 minutes. Therefore, a braking burn 1 hour before entry is used to slow the entry craft. The final orbit shown is 10 nm above the Space Station orbit for rendezvous with an orbital transfer vehicle.

SUMMARY

Aerobraking to dissipate an entry craft's energy to achieve a new orbital state is difficult but possible. Aerobraking time from entry to

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- **APOGEE CONTROL**
  - ANGLE OF ATTACK α
    - FIXED
  - ANGLE OF BANK ϕ
    - ITERATED

- **BANG–BANG PLANE GUIDE**
  - PREDICTED PLANE ERROR δ
  - DEAD BAND LOGIC
    - INSIDE – HOLD DIRECTION
    - OUTSIDE – SET DIRECTION (L/R)

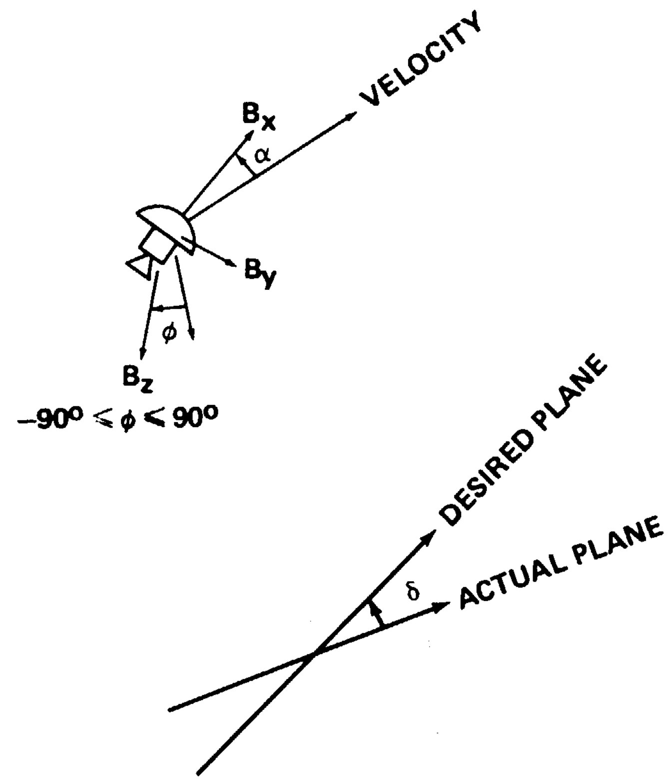

FIGURE 3.1 A SIMPLE GUIDE ALGORITHM

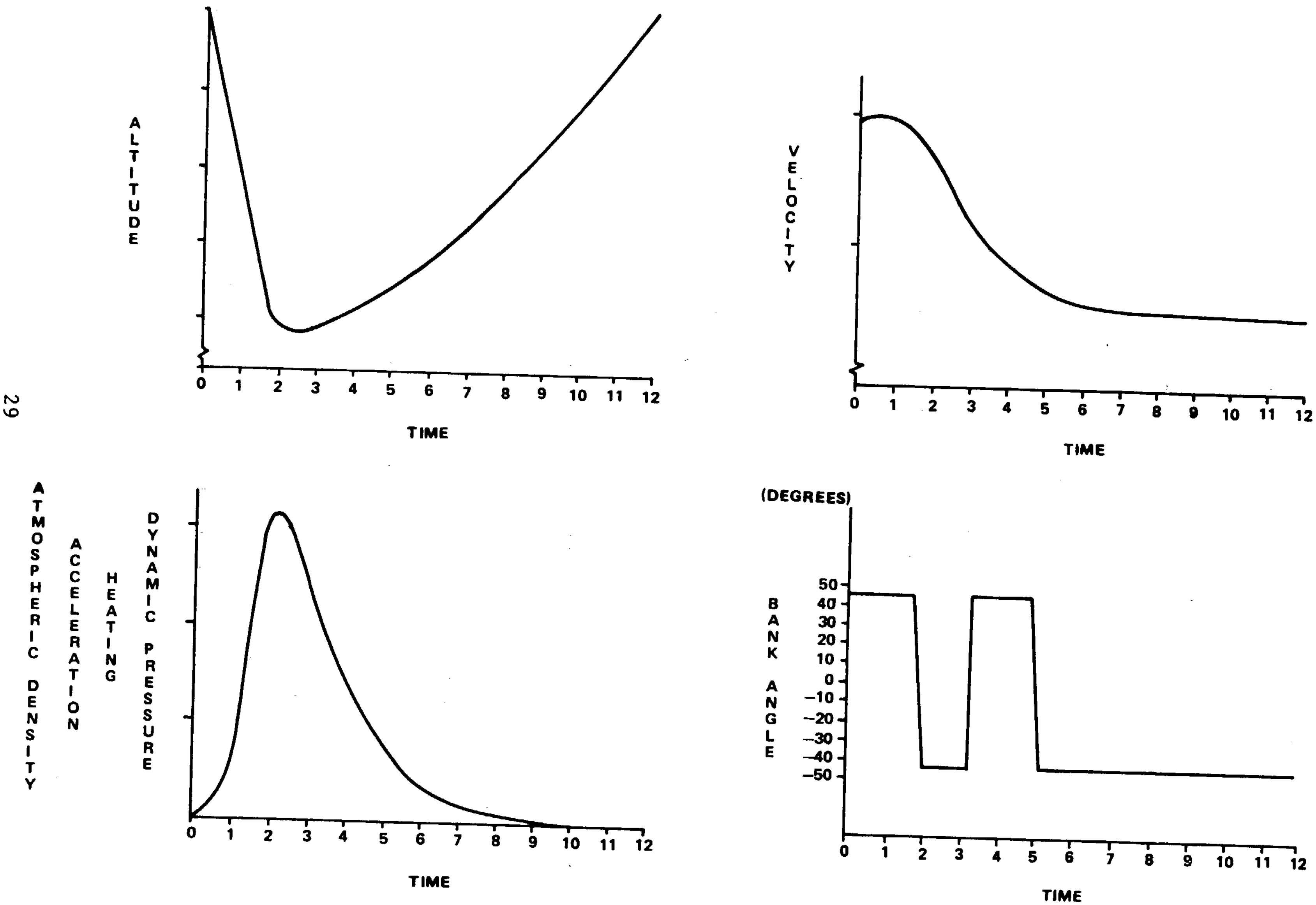

FIGURE 3.2 REPRESENTATIVE CAPTURE PROFILE

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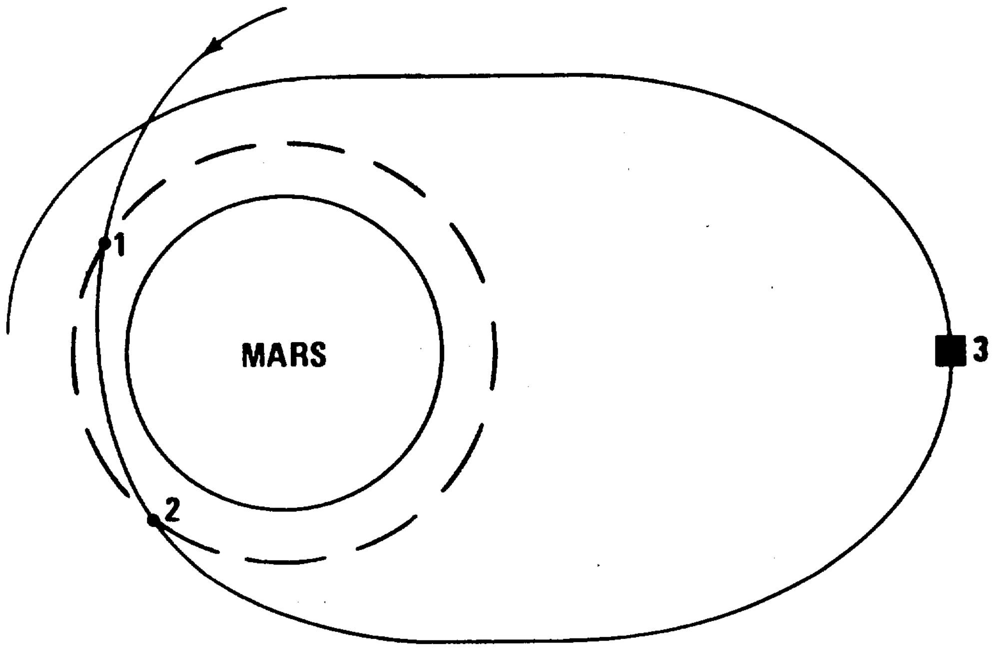


1. ENTER ATMOSPHERE — V_R = 23422 FT/SEC

   C_3 = 30 KM^2/SEC^2

   PERIAPSIS = 24 NM

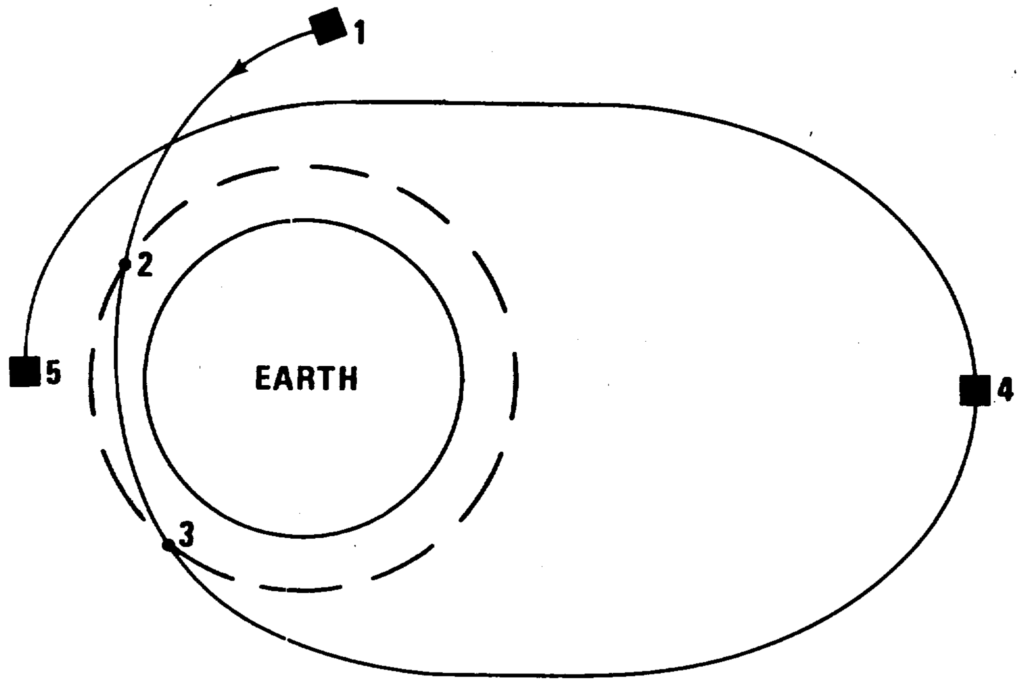
2. LEAVE ATMOSPHERE — V_R = 14708 FT/SEC

   ORBIT 24 X 17814 NM

3. BURN TO RAISE PERIAPSIS — ΔV = 85 FT/SEC

   ORBIT 268 X 17814 NM
   24 HOUR PERIOD

FIGURE 3.3 MARS AEROBRAKING CAPTURE



1. BRAKING BURN
   C_3 = 81 KM^2/SEC^2

2. ENTER ATMOSPHERE — V_R = 36297 FT/SEC
   C_3 = 9 KM^2/SEC^2
   PERIGEE = 45.2 NM

3. LEAVE ATMOSPHERE — V_R = 24802 FT/SEC
   ORBIT 44 X 350 NM

4. BURN TO RAISE PERIGEE — ΔV = 406 FT/SEC
   ORBIT 280 X 350 NM

5. BURN TO CIRCULARIZE — ΔV = 118 FT/SEC
   280 X 280 NM

FIGURE 3.4 EARTH AEROBRAKING CAPTURE

TABLE 3.1

MARS CAPTURE DATA

Entry Parameters	
Weight	415000 lbs
W/CDA	61 lbs/ft$_2$
Altitude	54 nm
Inertial Velocity	24225.7 ft/sec
Flight Path Angle	-9.1328 deg
Orbit C_3	30 km$_2$/sec$_2$
Inclination	1 deg
Periapsis	23 nm
Aerodynamic Parameters	
C_L	.405
C_D	1.35
Heat Shield	
Diameter	80 ft
Curvature	50 ft
Atmosphere	Mars Low Density
Controls - Bank Angle - Reversals - Times of Reversal	
Maxima	
Heating Rate	20.5 BTU/ft$_2$/sec
Dynamic Pressure	134 lbs/ft$_2$
Deceleration	2.4 g's
Orbit Leaving the Atmosphere	24 x 17814 nm
Time in the Atmosphere	380 sec
Apoapsis Burn to Raise Periapsis to	268 nm
ISP	482 sec
Propellant	2280 lbs
Delta - V	85.4 ft/sec
Final Orbit	268 x 17814 nm
Inclination	1 deg
Period	24 hours

TABLE 3.2

SUMMER, MID-LATITUDE, DAILY-MEAN ATMOSPHERE OF MARS
(COOL AND WARM MODELS)

	Cool, Low Pressure Model				Warm, High Pressure Model			
z, k	T. ^oK	p. mb	p. kg/m^2	P/P_o	T. ^oK	p. mb	p. kg/m^3	p/p_o
0	204	5.9	1.51×10^{-2}	1.000	224	7.8	1.82×10^{-2}	1.000
4	204	4.03	1.03	0.683	224	5.51	1.29	0.706
8	199	2.74	7.20×10^{-3}	0.464	219	4.09	9.77×10^{-3}	0.524
12	191	1.84	5.04	0.312	211	2.85	7.07	0.366
16	185	1.22	3.45	0.207	205	1.97	5.01	0.252
20	178	7.96×10^{-1}	2.34	0.135	198	1.34	3.54	0.172
24	173	5.13	1.55	8.70×10^{-2}	193	9.03×10^{-1}	2.45	0.116
28	168	3.27	1.02	5.54	188	6.03	1.68	7.73×10^{-2}
32	163	2.06	6.60×10^{-4}	3.49	183	3.99	1.14	5.11
36	158	1.28	4.23	2.17	178	2.61	7.67×10^{-4}	3.35
40	152	7.81×10^{-2}	2.69	1.32	172	1.69	5.13	2.16
44	148	4.70	1.66	7.96×10^{-3}	168	1.08	3.36	1.38
48	144	2.79	1.01	4.73	164	6.83×10^{-2}	2.18	8.75×10^{-3}
52	140	1.64	6.12×10^{-5}	2.78	160	4.28	1.40	5.48
56	137	9.49×10^{-3}	3.62	1.61	157	2.65	8.84×10^{-5}	3.40
60	134	5.44	2.12	9.22×10^{-4}	154	1.63	5.55	2.09
64	132	3.09	1.22	5.23	152	9.99×10^{-3}	3.44	1.28
68	130	1.74	7.01×10^{-6}	2.95	150	6.08	2.12	7.79×10^{-4}
72	129	9.76×10^{-4}	3.96	1.65	149	3.68	1.29	4.72
76	129	5.47	2.22	9.27×10^{-5}	149	2.23	7.83×10^{-6}	2.86
80	129	3.07	1.24	5.20	149	1.35	4.75	1.73
84	129	1.72	6.99×10^{-7}	2.92	149	8.21×10^{-4}	2.88	1.05
88	129	9.70×10^{-5}	3.93	1.64	149	4.99	1.75	6.39×10^{-5}
92	129	5.46	2.22	9.26×10^{-6}	149	3.03	1.07	3.89
96	129	3.08	1.25	5.22	149	1.85	6.49×10^{-7}	2.37
100	129	1.74	7.00×10^{-8}	2.95	149	1.13	3.96	1.44

TABLE 3.3

MARS DESCENT DATA

Deboost at Apoapsis (From Capture Orbit)	
Weight	135000 lbs
ISP	293 sec
Propellant	1228 lbs
Delta-V	85.4 ft/sec
Entry Parameters	
Weight	133770 lbs
W/CDA	45 lbs/ft_2
Altitude	54 nm
Inertial Velocity	15515.16 ft/sec
Flight Path Angle	-7.1518 deg
Orbit	22 x 17814 nm
Inclination	1.0 deg
Aerodynamic Parameters	
C_L	0
C_D	1.0
Heat Sheild Area	
Diameter	50 ft
Curvature	50 ft
Atmosphere	Mars Low Density
Controls - None - Ballistic Entry	
Maxima	
Heating Rate	4.4 $BTU/ft_2/sec$
Dynamic Pressure	64 lbs/ft_2
Deceleration	1.4 g's
Time to an altitude of 1 nm	593 sec
Velocity at 1 nm	1980 ft/sec

EARTH CAPTURE DATA
TABLE 3.4

Initial State	
Weight	40795 lbs
Altitude	17580.8 nm
Inertial Velocity	33049 ft/sec
Flight Path Angle	-76.3196 deg
Orbit C_3	81 km^2/sec^2
Inclination	28.5 deg
Perigee	65.8 nm
Braking Burn	(C_3 = 78 km^2/sec^2)
ISP	482 sec
Propellant	25795 lbs
Entry	
Weight	15000 lbs
W/C_DA	8.84 lb/ft^2
Altitude	65.8 nm
Inertial Velocity	37652 ft/sec
Flight Path Angle	-4.5442 deg
Orbit C_3	9 km^2/sec^2
Perigee	45.2 nm
Aerodynamic Parameters	
C_L	.405
C_D	1.35
Heat Shield Diameter	40 ft
Curvature	50 ft
Atmosphere	US 62
Controls - Bank Angle - Reversals - Times of Reversal	
Maxima	
Heating Rate	22 $Btu/ft^2/sec$
Dynamic Pressure	21 lbs/ft^2
Deceleration	2.9 g's
Orbit Leaving the Atmosphere	46.6 x 350 nm
Time in Atmosphere	330 seconds
Apogee Burn to Raise Perigee to	280 nm
ISP	482 sec
Propellant	380 lbs
Delta V	406 ft/sec
Perigee Burn to Circularize at	280 nm
ISP	482 sec
Propellant	110 lbs
Delta V	118 ft/sec

exit is less than 15 minutes in most cases. Deceleration forces, dynamic pressure, and heating rates are basically a function of the energy to be dissipated, the time of dissipation and the aerodynamic characteristics of the entry craft. Guidance algorithms are still being investigated but are beginning to show great promise.

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