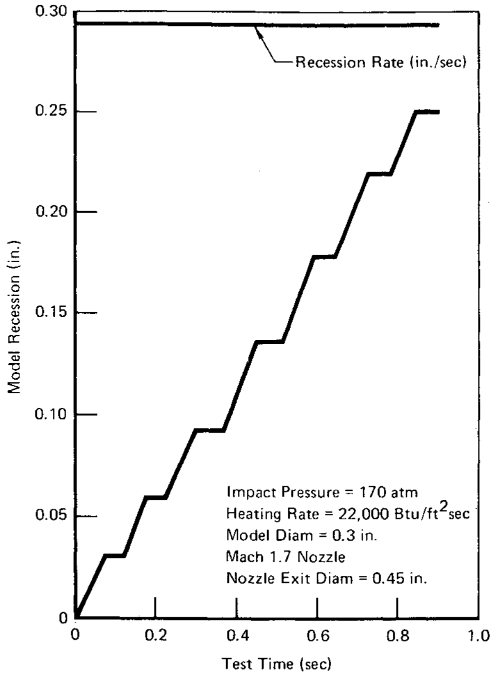

Fig. 4 Recession of experimental graphite at 170 atm.

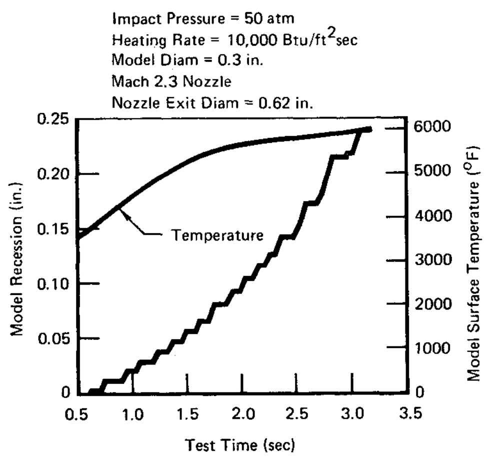

Fig. 5 Recession and temperature histories of experimental graphite.

by radiation pyrometers. A typical recession history for a 0.3-in.-diam. hemisphere-cylinder graphite composite model tested at 170 atm is shown in Fig. 4. Using an analytical expression for the curve fit to these data and differentiating the function with respect to time yields the model recession rate history also presented in Fig. 4. Additional recession data and a surface temperature history for a similar model tested at a lower pressure (50 atm) but higher Mach number (2.3) are shown in Fig. 5.

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Round Trip Mars Missions Using Looping Trajectories in the 1980-2000 Time Period

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ORBITAL transfers which make more than one revolution have been known for some time.[1,2] However, when the transfer is interplanetary, the long trip times involved have dissuaded mission analysts from considering trajectories of more than one revolution. For example, standard Earth to Mars trajectories (Types I and II—Fig. 1a) have trip times ranging from 0.5 to 1.5 yr whereas looping trajectories (Types III and IV—Fig. 1b) have trip times ranging from 2 to 3 yr. Since the energy requirements for looping trajectories are sometimes significantly less than for standard transfers, it would be advantageous to use looping trajectories if the trip time problem can be alleviated.

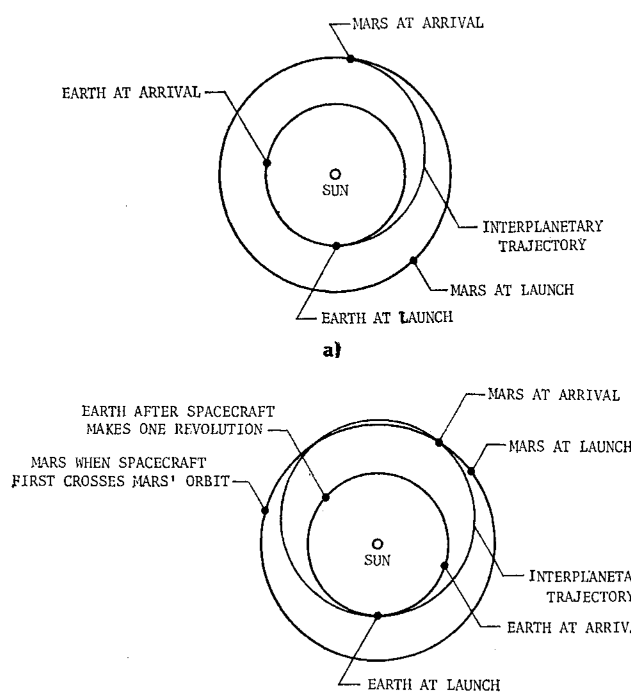

Fig. 1 Two types of Earth to Mars trajectories: a) standard (less than one revolution about the sun); b) looping (more than one revolution about the sun).

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Table 1 Standard and looping trajectory characteristics for 1980–2000

Trajectory designation[a]	Launch date	Arrival date	V_∞, km/sec launch	V_∞, km/sec arrival	V_∞, km/sec total	DLA deg	DPA deg	Communication dist. 10^8 km
A1	9/7/81	3/12/84	3.725	2.563	6.288	10.8	23.4	1.346
A2	10/7/83	3/2/86	3.407	2.490	5.896	14.1	11.3	1.965
A3	10/16/85	2/20/88	3.147	2.496	5.644	23.2	−5.3	2.580
A4	10/26/87	2/9/90	3.139	2.679	5.819	24.4	−15.8	3.091
A5	11/11/89	1/22/92	3.116	2.925	6.041	23.1	−23.7	3.487
A6	12/11/91	1/31/94	3.065	3.284	6.350	22.6	−33.0	3.552
A7	1/9/94	2/10/96	3.254	3.818	7.072	8.2	−32.8	3.534
A8	8/26/96	3/6/99	3.938	2.603	6.540	7.3	29.9	1.283
A9	9/25/98	2/23/01	3.553	2.499	6.052	6.7	19.8	1.880
B1	11/26/81	9/19/82	3.055	3.050	6.105	25.9	−29.5	2.353
B2	12/26/83	9/28/84	3.466	3.542	7.008	11.2	−30.8	1.735
B3	5/4/86	11/17/86	2.966	3.168	6.134	−45.9	4.7	1.501
B4	7/12/88	1/25/89	3.463	2.608	6.071	14.2	.9	1.804
B5	8/18/90	7/26/91	4.104	2.627	6.731	−.6	39.2	3.590
B6	9/16/92	8/24/93	3.596	2.436	6.032	13.3	14.4	3.429
B7	10/16/94	9/3/95	3.163	2.535	5.697	22.4	−7.8	3.043
B8	11/14/96	9/12/97	3.019	2.873	5.891	27.8	−25.3	2.549
B9	12/14/98	10/7/99	3.233	3.417	6.649	13.7	−31.2	2.081
C1	8/23/81	7/26/82	2.538	3.779	6.318	−5.8	25.3	3.395
C2	9/2/83	8/24/84	2.681	4.231	6.912	−12.7	36.9	3.686
C3	2/18/86	9/23/86	2.425	3.489	5.914	11.0	12.5	2.142
C4	5/18/88	12/1/88	3.158	3.120	6.278	−30.6	24.0	1.508
C5	7/15/90	4/12/91	3.470	3.353	6.824	2.7	−48.1	1.666
C6	7/24/92	5/11/93	3.026	2.847	5.873	6.1	−39.8	2.300
C7	8/3/94	6/10/95	2.721	2.965	5.687	3.0	−7.4	2.852
C8	8/12/96	7/9/97	2.597	3.461	6.058	−3.4	19.2	3.294
C9	8/22/98	8/8/99	2.638	3.977	6.616	−10.4	34.8	3.623
C10	2/7/01	9/6/01	2.632	3.742	6.373	26.8	8.7	2.122
D1	3/16/81	5/2/73	3.204	2.933	6.137	7.6	−46.6	3.568
D2	3/6/83	5/11/85	2.926	2.844	5.770	11.5	−33.2	3.426
D3	2/23/85	6/10/87	2.758	2.988	5.746	6.8	−12.7	3.073
D4	2/13/87	6/19/89	2.661	3.195	5.856	2.1	8.2	2.550
D5	2/2/89	7/19/91	2.601	3.576	6.177	.5	15.9	1.919
D6	1/23/91	7/28/93	2.729	3.816	6.545	−7.8	32.4	1.289
D7	11/16/93	11/17/95	2.952	3.065	6.017	−27.9	35.9	3.669
D8	3/25/96	4/15/98	3.310	3.007	6.318	9.7	−58.8	3.563
D9	3/15/98	5/14/00	3.005	2.853	5.858	7.4	−37.2	3.529
D10	3/4/00	5/24/02	2.773	2.882	5.655	7.9	−17.7	3.273

[a]A1–A9 are looping Earth to Mars trajectories. B1–B9 are standard Earth to Mars trajectories. C1–C10 are standard Mars to Earth trajectories. D1–D10 are looping Mars to Earth trajectories.

The purpose here is to suggest round trip missions combining a standard trajectory leg and a looping trajectory leg as an alternative to the more conventional trajectories. A summary of standard and looping Earth to Mars trajectory characteristics for the 1980–2000 time period is presented in Table 1. The final column is the communication distance at arrival for outbound legs, and the communication distance at launch for return legs. The trajectories listed in the table have approximately 20-day launch and arrival windows and were chosen on the basis of a minimum total V_∞ (generally associated with smaller spacecraft weights). Naturally, for each of these trajectories there is a surrounding region in which the mission analyst may choose candidate trajectories which minimize some other criterion; however, these are representative transfers from each region.

Several advantages of looping trajectories are apparent from the table. For example, there are two opportunities for a 1983 Earth launch; the B2 trajectory requires a total V_∞ of over 1 km/sec more than the A2. For the same launch opportunity, a Viking-type lander mission could land at the northern latitudes with the looping trajectory (DPA = 11.3) but the standard trajectory (DPA = −30.8) would require a large maneuver for apsidal rotation. In addition, there are several comparisons for which the communication distance (a measure of power requirements) can be decreased by using a looping trajectory. But in all cases, the longer trip times for looping trajectories present a severe problem to the spacecraft developer.

The trip time problem is substantially reduced when round trip missions are considered, as presented in Fig. 2. This figure is the familiar launch arrival date plot modified somewhat to allow round trip mission comparisons. The abscissa is Earth launch date for A and B trajectories and Earth arrival date for C and D transfers. The ordinate is Mars arrival date for the outbound trajectory legs and Mars launch date for the inbound legs. Each transfer listed in Table 1 is plotted with the total V_∞ requirement directly beneath the trajectory designation. As an example of a round trip mission comparison, a B4-C5 and a B4-D5 round trip are indicated on the figure. Both round trips have a standard outbound leg, while the first has a standard return leg and the second has a looping return leg. The various time intervals of interest to a mission analyst can be taken directly from the plot. The mission duration is about 14% longer for the B4-D5 mission, but the distribution of time intervals is radically different. The standard round trip requires a Mars stay time of about 1.5 yr while the B4-D5 mission has a Mars stay time of about 0.1 yr. This difference can have a great impact upon mission planning. The reliability requirements for a 1.5-yr planet stay time before firing an engine to return to Earth could be staggering. The return trip time for the looping return leg is much longer than for the standard leg (2.5 vs 0.7 yr), but a reliable engine is not required at Earth if direct entry or shuttle-tug rendezvous is employed. Another advantage of the looping return leg mission is the decrease of about 0.6 km/sec in total mission V_∞. Even greater savings in V_∞ are seen by comparing other missions displayed in Fig. 1. By choosing trajectories near to A2-C3, a one or two

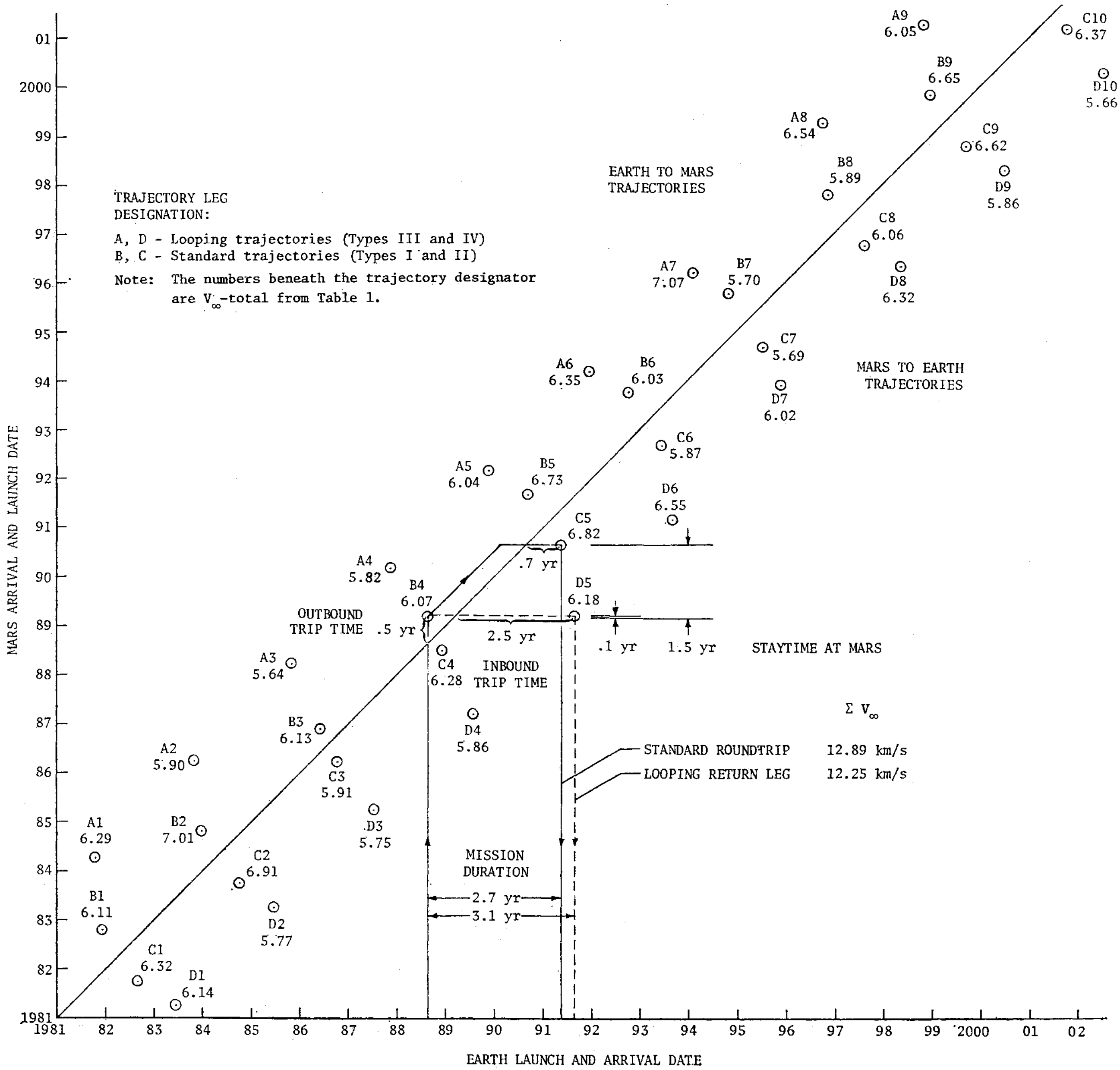

Fig. 2 Comparison of round trip Mars missions.

week Mars stay time mission can be obtained which requires 1 km/sec less than the comparable B2-C3 mission for an increase in total mission time of less than two months. Another interesting comparison is in the 1986 Earth launch date year. There, either the B3-D4 or the A3-C4 trajectories would allow a round trip with a V_∞ savings of 0.5 km/sec. This method thus allows round trip missions in launch years which are unfavorable for standard trajectories.

In summary, looping trajectories offer an attractive alternative to standard trajectories for round trip Mars missions. A slight increase in total mission time can be traded for a significant reduction in Mars stay time with the possible added benefit of a decrease in energy requirements. The same type of trade-off should be available for any planetary round trip mission.

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Errata

Integral Method for Nonlinear Transient Heat Transfer in a Semi-Infinite Solid

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On p. 88, under Eq. (4), the boundary condition should read $(\partial\theta/\partial x)(\theta,t) = N_r(z^4 - u^4)$ and Eq. (8) on p. 89 should read

$$(2/3)N_r{}^2 t = (1/8u^4)[z^2/(u^4 - z^4) + \ldots]$$

instead of $N_r{}^2 t = (1/8u^4)[z^4/(u^4 - z^4) + \ldots]$

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