FIGURE 1.1
The Mars Direct hab and Earth return vehicles (ERV) within their aerobrakes.

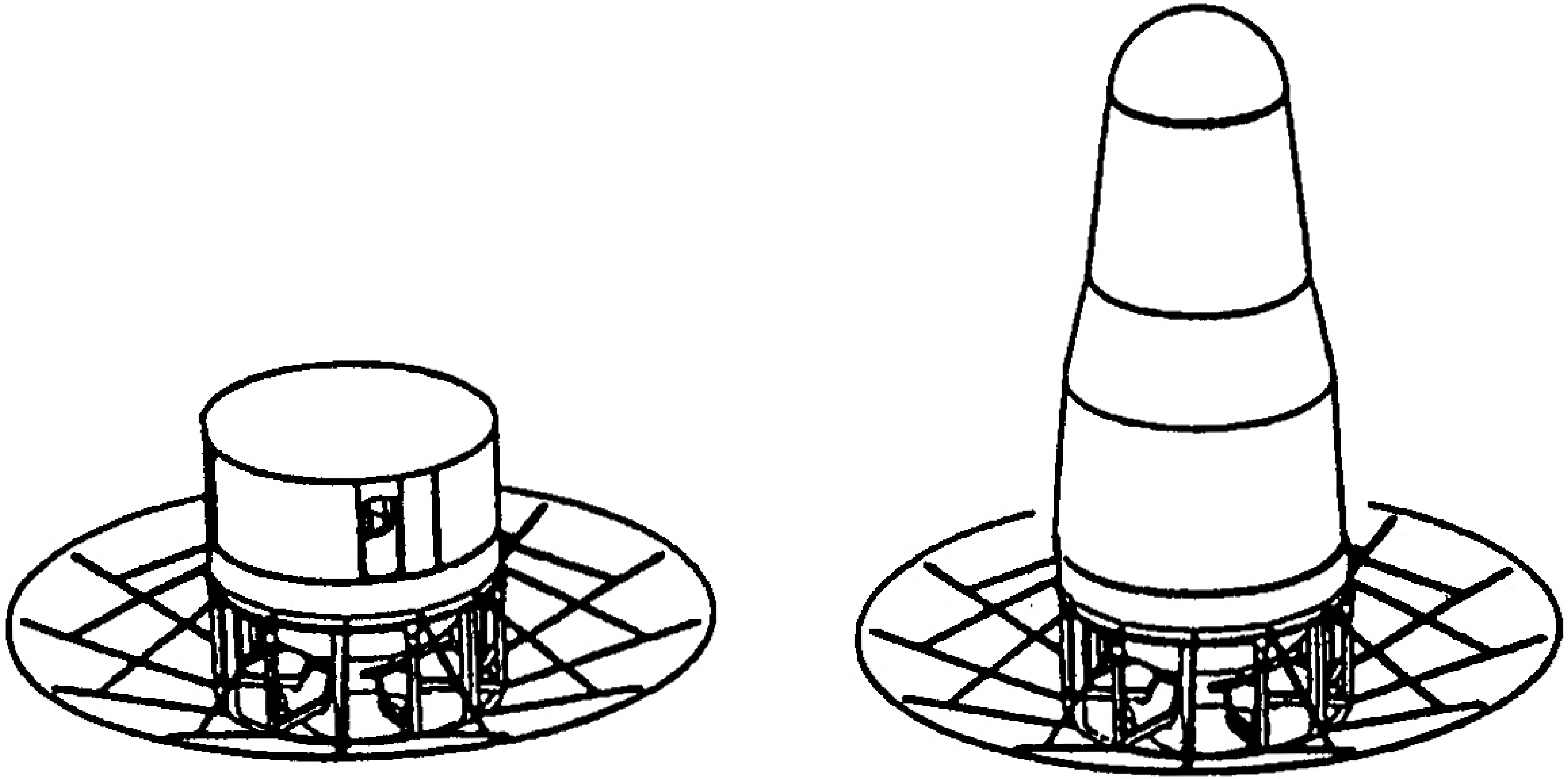


FIGURE 1.2

The Mars Direct mission sequence. The sequence begins with the launch of an unmanned Earth return vehicle (ERV) to Mars, where it will fuel itself with methane and oxygen manufactured on Mars. Thereafter, every two years, two boosters are launched. One sends an ERV to open up a new site, while the other sends a piloted hab to rendezvous with an ERV at a previously prepared site.

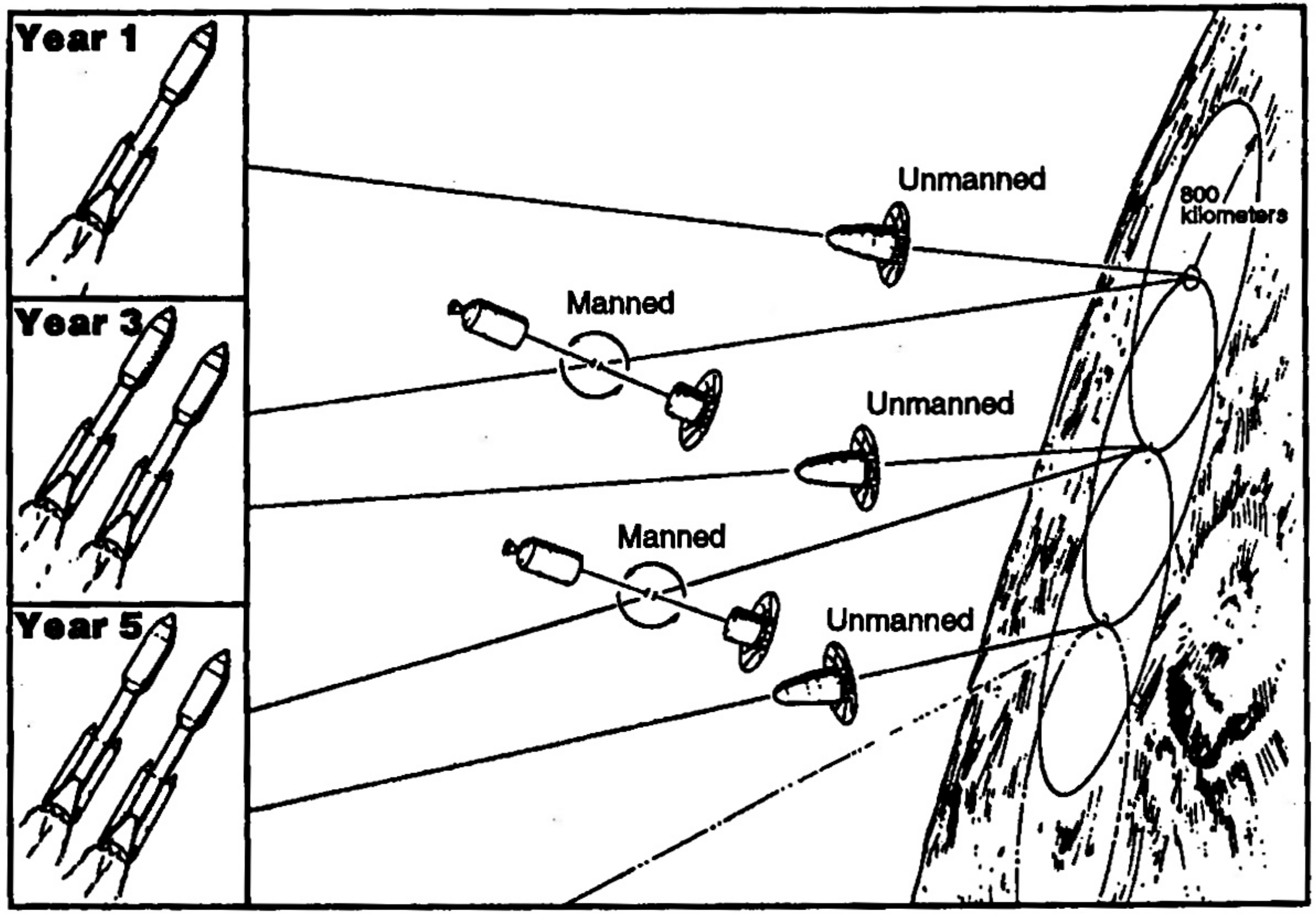


FIGURE 1.3
Linking Mars Direct habs to establish the beginnings of a Mars base. (Artwork by Carter Emmart.)

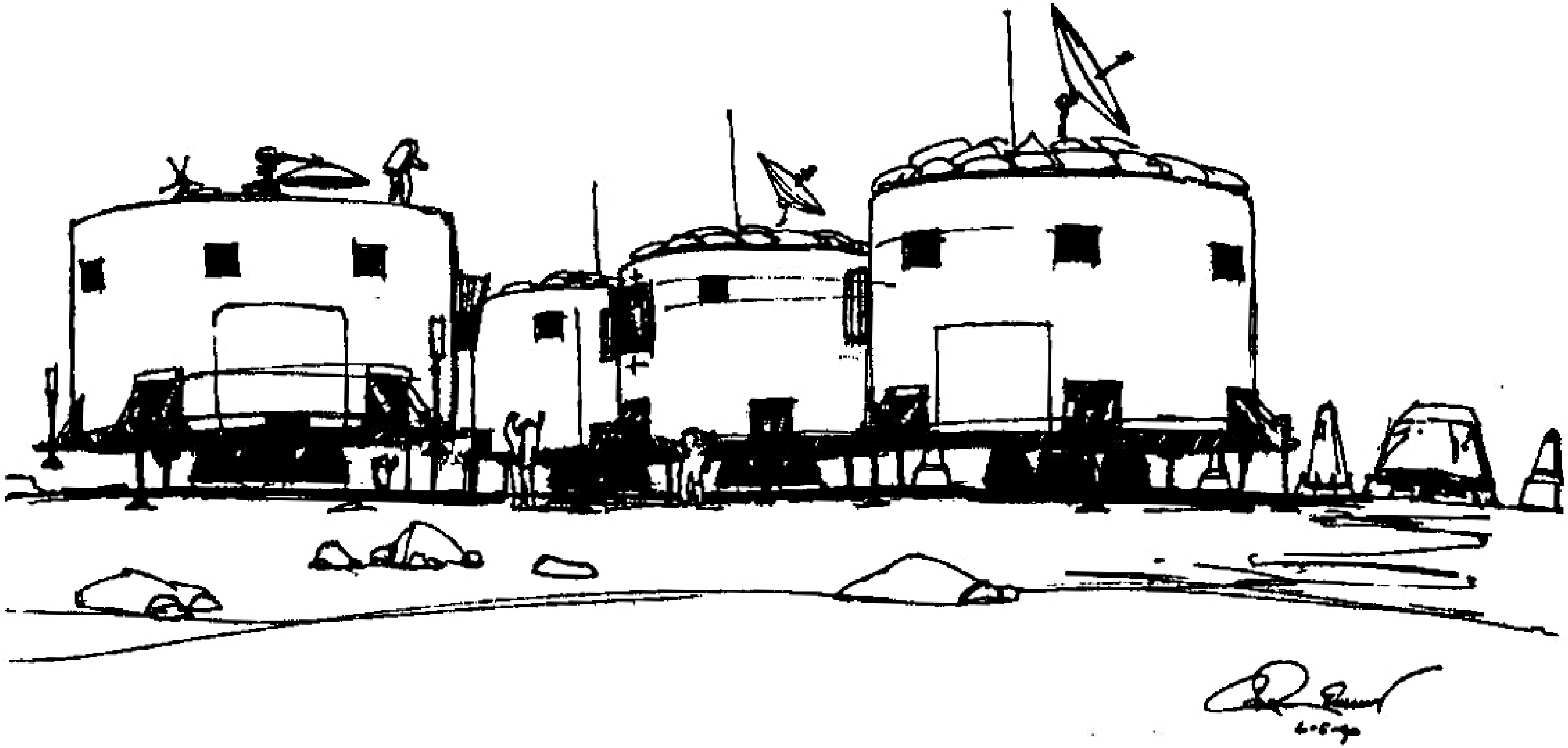


FIGURE 3.1
Booster evolution from Shuttle C to Shuttle Z to the Ares.

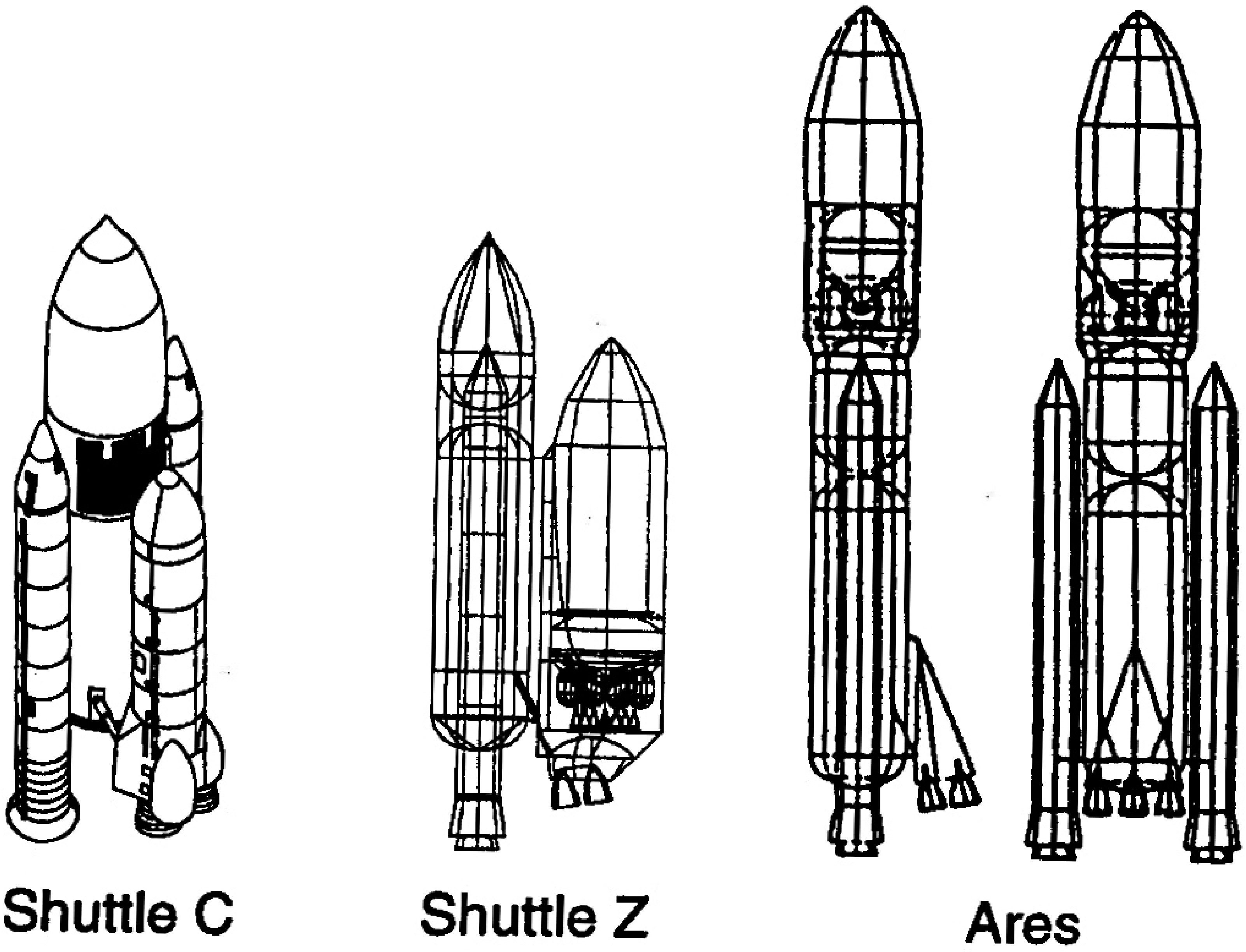


FIGURE 4.1

Opposition and conjunction. At opposition, Mars stands directly on the opposite side of the Earth from the Sun. At conjunction, Mars stands behind the Sun as seen from the Earth.

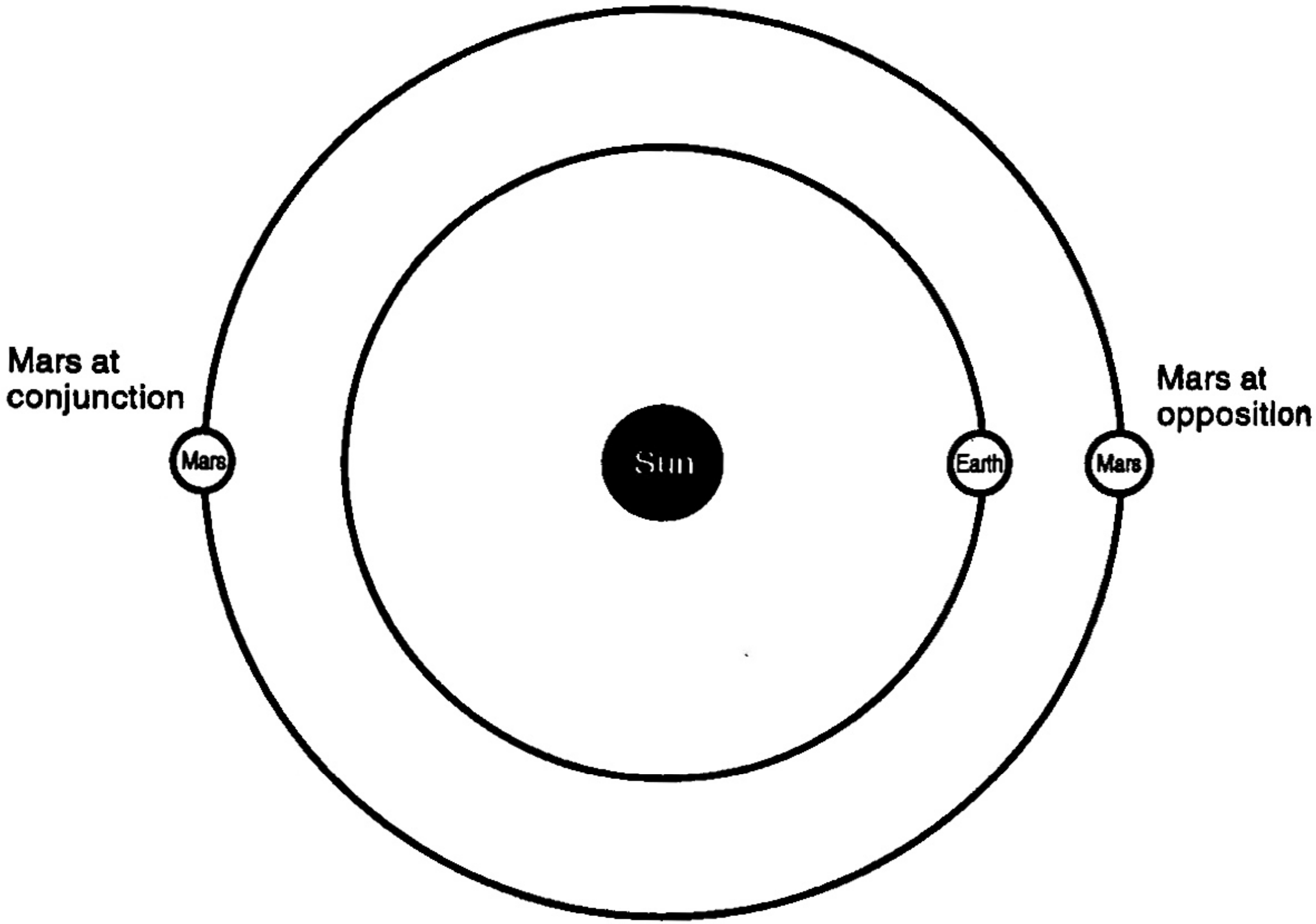


FIGURE 4.2
Trajectory Options to Mars: (A) Hohmann transfer orbit; (B) Fact Conjunction mission; (C) Opposition mission.

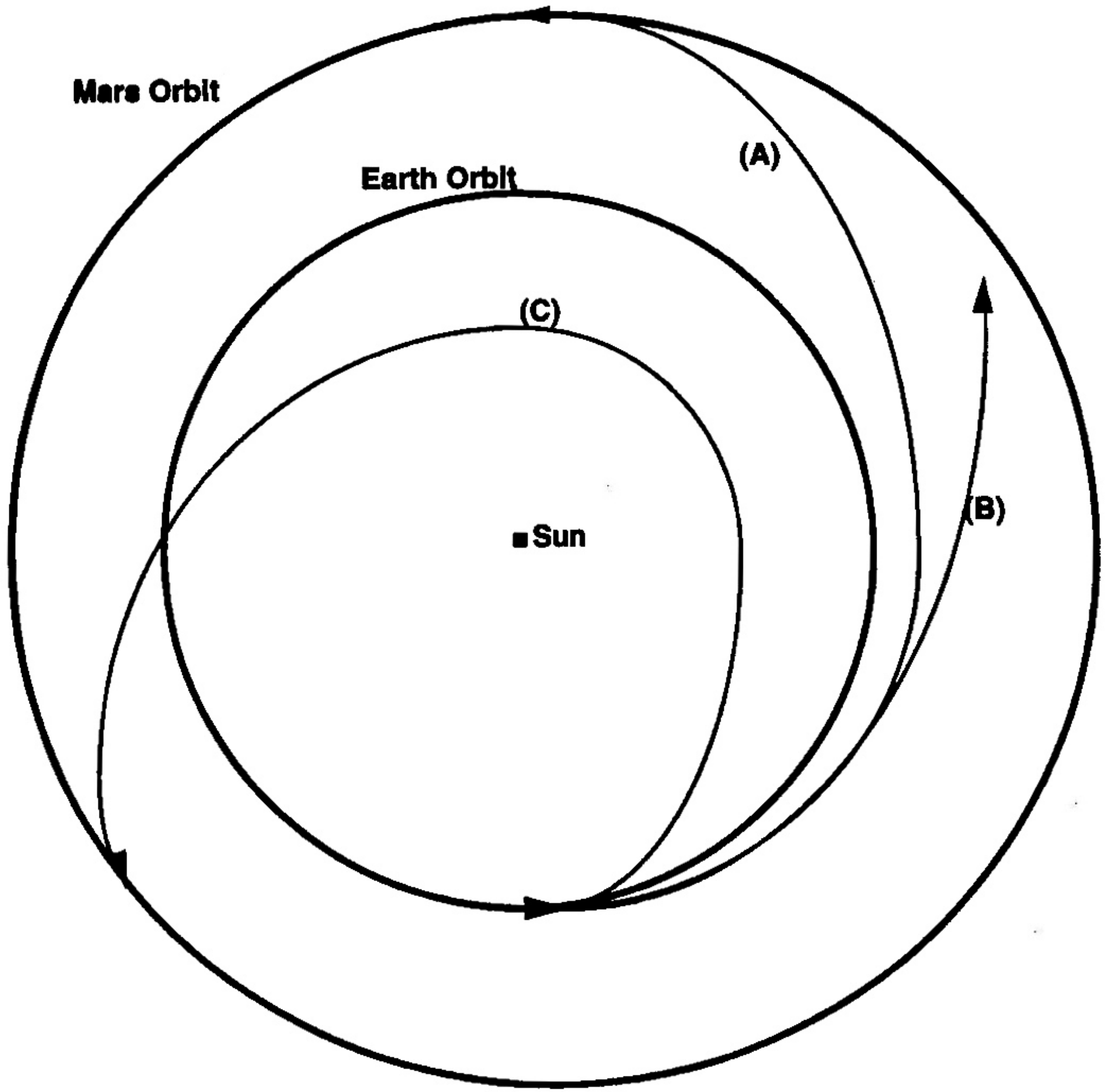


TABLE 4.1.
Flight Times and Stay Times of Mars Missions

	Conjunction	Opposition
Outbound transit time	180 days	180 days
Inbound transit time	180 days	430 days
Mars stay time	550 days	30 days
Total mission time	910 days	640 days
Mission propulsive ΔV	6.0 km/s	7.8 km/s
Venus flyby needed?	No	Yes
Average mission radiation dose	52 rem	58 rem
Zero gravity exposure	360 days	610 days
Mission cost	Lowest	Highest
Mission accomplishment	Highest	Lowest
Mission risk	Lowest	Highest

TABLE 4.2
Free Return Trajectories between Earth and Mars

Departure Velocity	Orbit Period	Time to Earth Return	Transit to Mars	Mars Aeroentry
A 3.34 km/s	1.5 years	3 years	250 days	Easy
B 5.08 km/s	2.0 years	2 years	180 days	Acceptable
C 6.93 km/s	3.0 years	3 years	140 days	Dangerous
D 7.93 km/s	4.0 years	4 years	130 days	Impossible

TABLE 4.3

Payload Delivery to Martian Surface from 140 Tonne to LEO HLV

Mission	Trans-Mars Injection Stage	Trans-Mars Throw Capability	Payload Delivered to Surface
Cargo	H_2/O_2	46.2 tonnes	28.6 tonnes
Piloted	H_2/O_2	40.6 tonnes	25.2 tonnes
Cargo	Nuclear thermal rocket	74.6 tonnes	46.3 tonnes
Piloted	Nuclear thermal rocket	69.8 tonnes	43.3 tonnes

TABLE 4.5
Mass Allocations for Mars Direct Mission Plan

Earth Return Vehicle	Tonnes	Hab	Tonnes
ERV cabin structure	3.0	Hab structure	5.0
Life-support system	1.0	Life-support system	3.0
Consumables	3.4	Consumables	7.0
Electrical power (5 kWe solar)	1.0	Electric power (5 kWe solar)	1.0
Reaction control system	0.5	Reaction control system	0.5
Communications and information management	0.1	Communications and information management	0.2
Furniture and interior	0.5	Lab equipment	0.5
EVA suits (4)	0.4	Crew	0.4
Spares and margin (16 percent)	1.6	EVA suits (4)	0.4
ERV cabin total	11.5	Furniture and interior	1.0
Aeroshell	1.8	Open rovers (2)	0.8
Light truck	0.5	Pressurized rover	1.4
Hydrogen feedstock	6.3	Field science equipment	0.5
ERV propulsion stages	4.5	Spares and margin (16 percent)	3.5
Propellant production plant	0.5		
Power reactor (80 kWe)	3.5		
ERV total	28.6	Hab total	25.2

Velocity change, or ΔV ("delta-V"), measured in units of speed, such as kilometers per second (km/s), is the fundamental currency of rocketry. If you have spacecraft with a given dry mass M (i.e., empty of propellant), and a certain amount of propellant, P, and a rocket engine with an exhaust velocity C, the following equation, known as "the rocket equation," shows how big a ΔV the system can generate:

$$(M + P)/M = e^{\Delta V/C} \tag{1}$$

So the quantity $(M + P)/M$, known as the vehicle's "mass ratio," increases exponentially in proportion to $\Delta V/C$. If $\Delta V/C = 1$, then the mass ratio equals $e^1 = 2.72$. If $\Delta V/C = 2$, the mass ratio equals $e^2 = 7.4$. If $\Delta V/C = 3$, the mass ratio equals 20.1. If $\Delta V/C = 4$, the mass ratio equals 54.6.

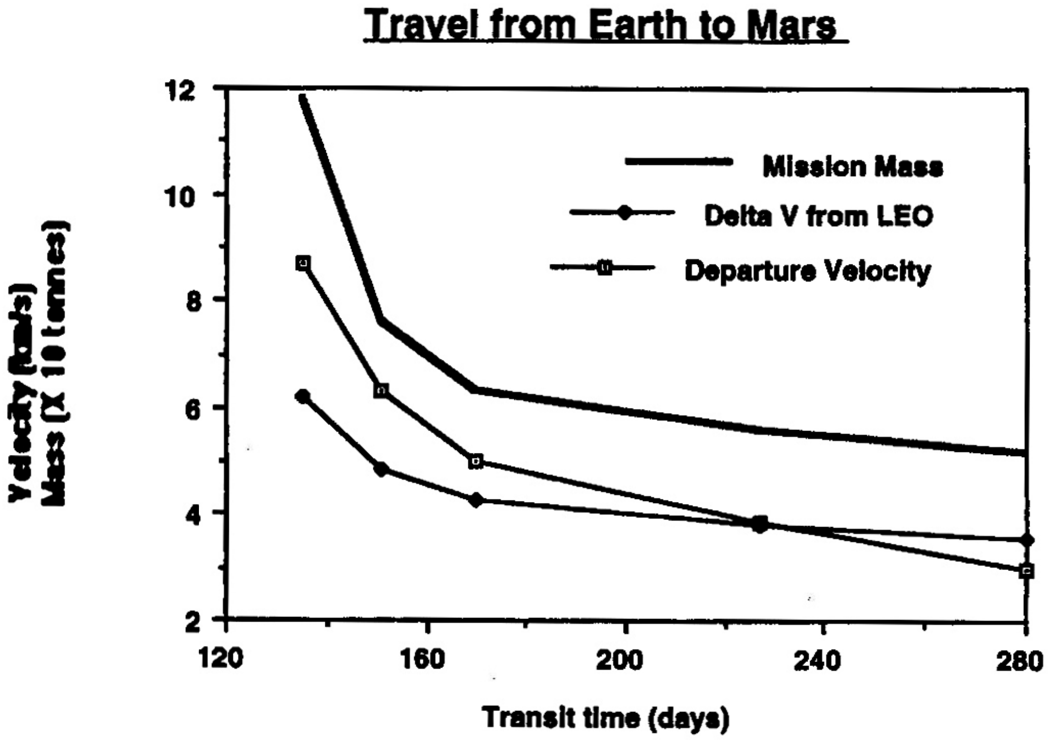


FIGURE 4.3

Relationship between average transit time, departure velocity, ΔV, and spacecraft mass for a 20-tonne spacecraft leaving low Earth orbit (LEO) for Mars. Spacecraft propulsion is hydrogen/oxygen with a specific impulse of 450 seconds. Note that mission mass rises steeply for transits less than 170 days.

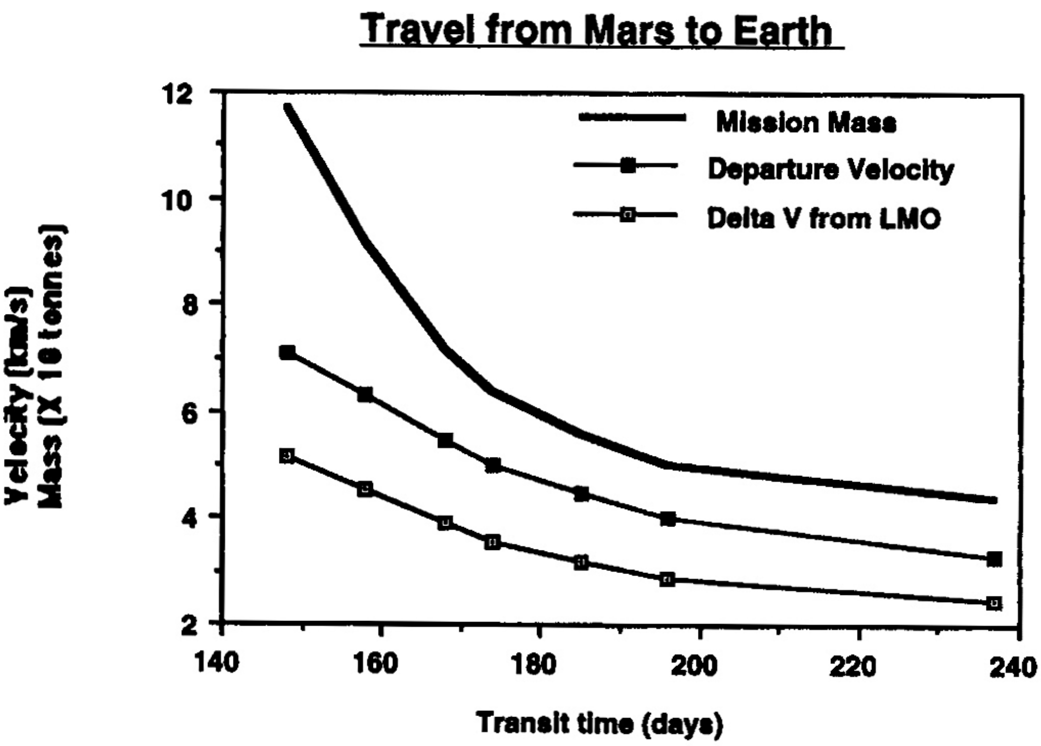


FIGURE 4.4

Relationship between transit time, departure velocity, ΔV, and spacecraft mass for a 20-tonne spacecraft leaving low Mars orbit (LMO) for Earth. Spacecraft propulsion is methane/oxygen with a specific impulse of 380 seconds. Note that mission mass does not begin to rise sharply until you attempt to reduce transit times below 170 days.

TABLE 5.1

Estimates of Cancer Risk Due to Chronic Radiation Doses Totaling 100 rem

Type of cancer	Probability of Fatal Cancer within 30 Years
Leukemia	0.30%
Breast	0.45%
Lung	0.40%
GI, including stomach	0.30%
Bone	0.06%
All other	0.30%
Total	1.81%

TABLE 5.2

Radiation Dose Experienced on Mars Missions

	Conjunction	Opposition
Cosmic rays in transit	31.8 rem	47.7 rem
Solar flares in transit	5.5 rem	9.6 rem
Cosmic rays on Mars	10.6 rem	0.8 rem
Solar flares on Mars	4.1 rem	0.3 rem
Total average dose	52.0 rem	58.4 rem

FIGURE 5.2

Tethered artificial gravity system requires two objects swinging around a mutual center of gravity. For Mars Direct, the hab (on the right) is counterbalanced by the spent upper stage (on the left).

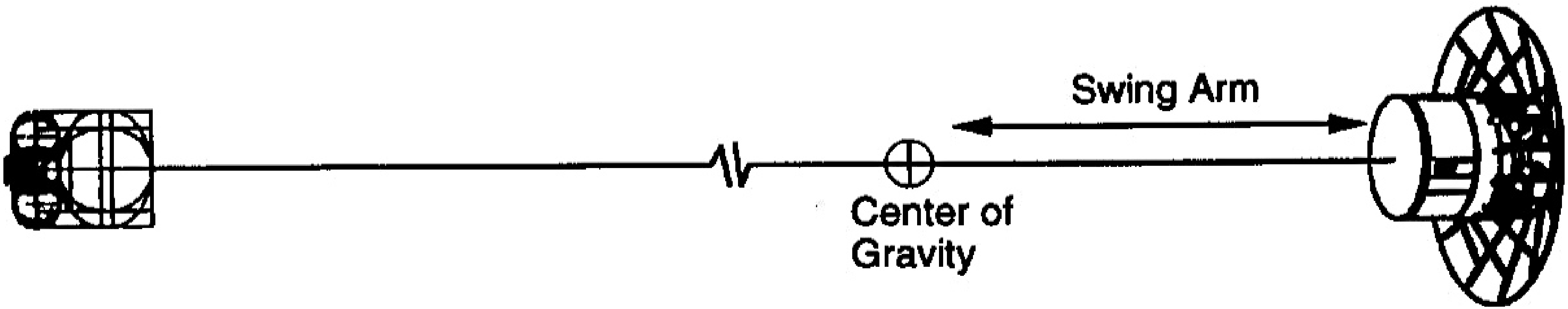


TABLE 6.1
Surface Features of Interest in the Exploration of Mars

Feature	Distance from Base (km)	Direction
Ophir Chasma	<300	southwest
Juventae Chasma	<300	southeast
Slope and bedrock material	<300	south
Cratered plateau material	<300	east
Chaotic material	<300	east
Degraded crater material	<300	south
Hebes Chasma	600	west
Center of Lunae Planum	650	north
Northern plains	1,200	northwest
Kasei Vallis	1,300	north
Viking 1 landing site	1,400	northeast
Paleolake site	1,500	northeast
Volcanic flows	2,000	west
Pavonis Mons	2,500	west

TABLE 6.2
Potential Bipropellants for Use in Mars Mobility Vehicles

Bipropellant	Energy Density	
	W-hr/kg	*W-hr/liter*
Hydrogen/carbon dioxide	25,833	416
Hydrazine/carbon dioxide	1,329	1,111
Hydrogen/oxygen	3,750	1,312
Carbon monoxide/oxygen	1,816	2,144
Methanol/oxygen	2,129	2,093
Methane/oxygen	2,800	2,380

The Sabatier reaction produces methane and water from carbon dioxide and hydrogen and is written as:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (1)$$

This reaction is exothermic, that is, it releases heat, and will occur spontaneously in the presence of a nickel or ruthenium catalyst (nickel is cheaper, ruthenium is better).

The water produced is condensed and then transferred to a holding tank, after which it is pumped into an electrolysis cell and subjected to the familiar electrolysis reaction, which splits water into its components, hydrogen and oxygen:

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (2)$$

The oxygen so produced is refrigerated and stored, while the hydrogen can be recycled back to the Sabatier reaction (1).

electrolysis unit into a third chamber where it is reacted with carbon dioxide in the presence of an iron-chrome catalyst to produce carbon monoxide and water as follows:

$$CO_2 + H_2 \rightarrow CO + H_2O \tag{4}$$

This reaction is mildly endothermic, but will occur at 400°C, which is well within the temperature range of the Sabatier reaction. If reaction (4) is cycled with reactions (1) and (2), the desired mixture ratio of methane and oxygen can be produced with all the energy required to drive reaction (4) provided by thermal heat output from the Sabatier reactor.

TABLE 6.3
The Martian Year

Month	Number of Sols	Begins on Sol#	Noteworthy Features
Gemini	61	1	Gemini 1, Vernal equinox
Cancer	65	62	
Leo	66	127	Leo 24, Mars at Aphelion
Virgo	65	193	Virgo 1, Summer solstice
Libra	60	258	
Scorpius	54	318	
Sagittarius	50	372	Sagittarius 1, Autumnal equinox
Capricorn	47	422	Dust storm season begins
Aquarius	46	469	Aquarius 16, Mars at Perihelion
Pisces	48	515	Pisces 1, Winter solstice
Aries	51	563	Dust storm season ends
Taurus	56	614	Taurus 56, Martian New Year's Eve

FIGURE 6.1

The Mars Areogator

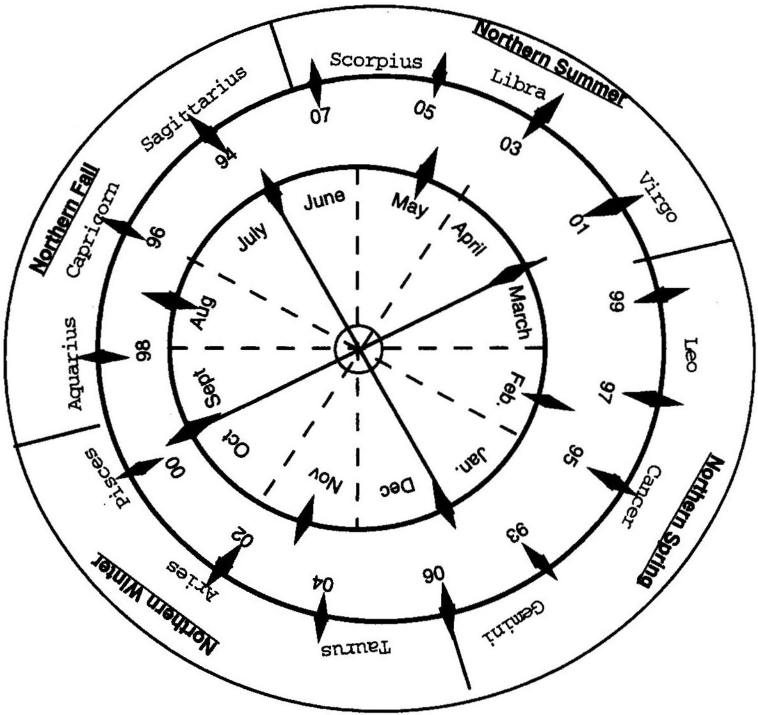
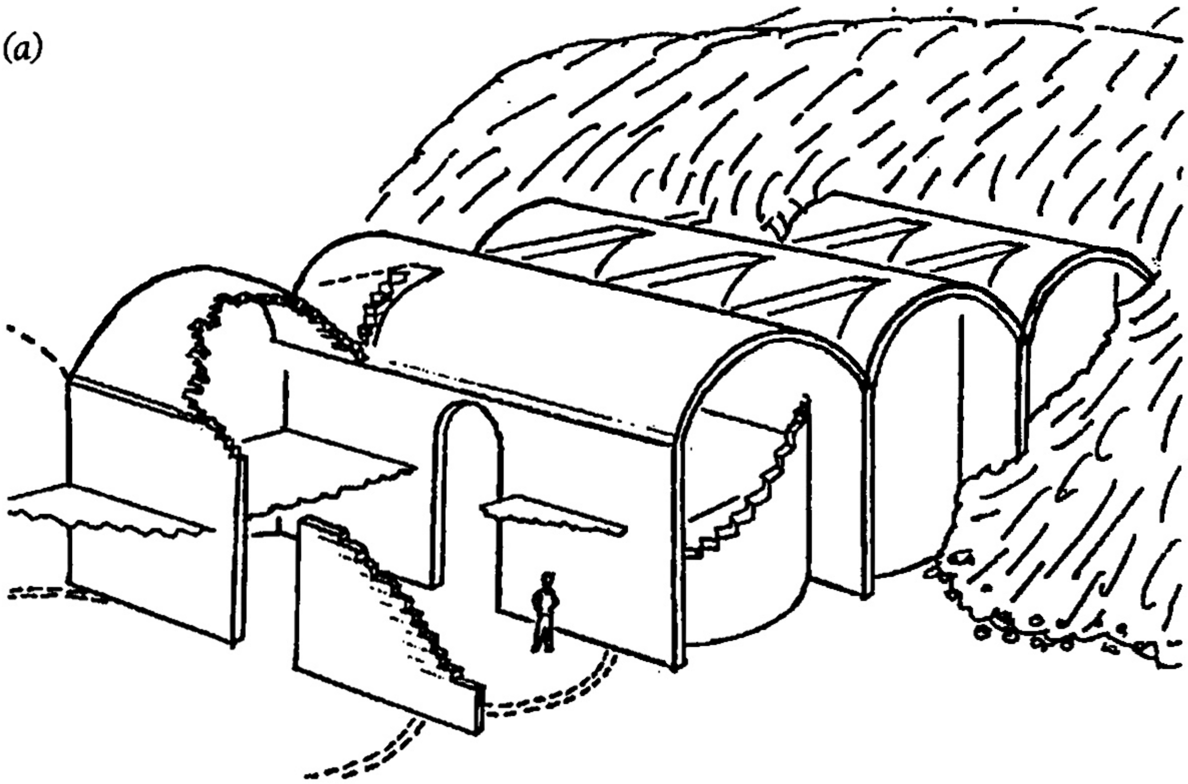


FIGURE 7.1

Roman style vaults either singly or in series (a) can be used to construct large subsurface pressurized habitats, including even spacious atriums (b) on Mars. (Designs by MacKenzie, 1987.)

(a)



(b)

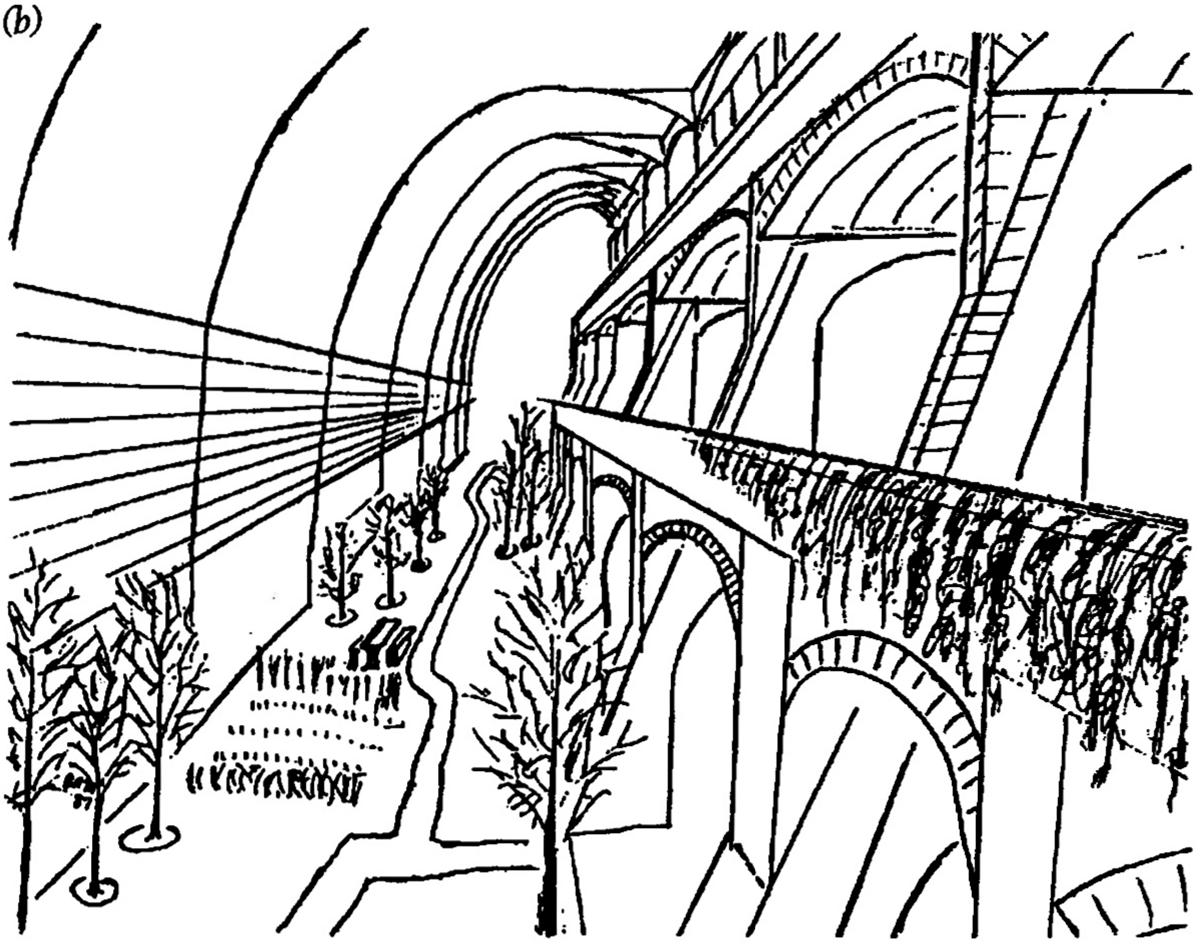
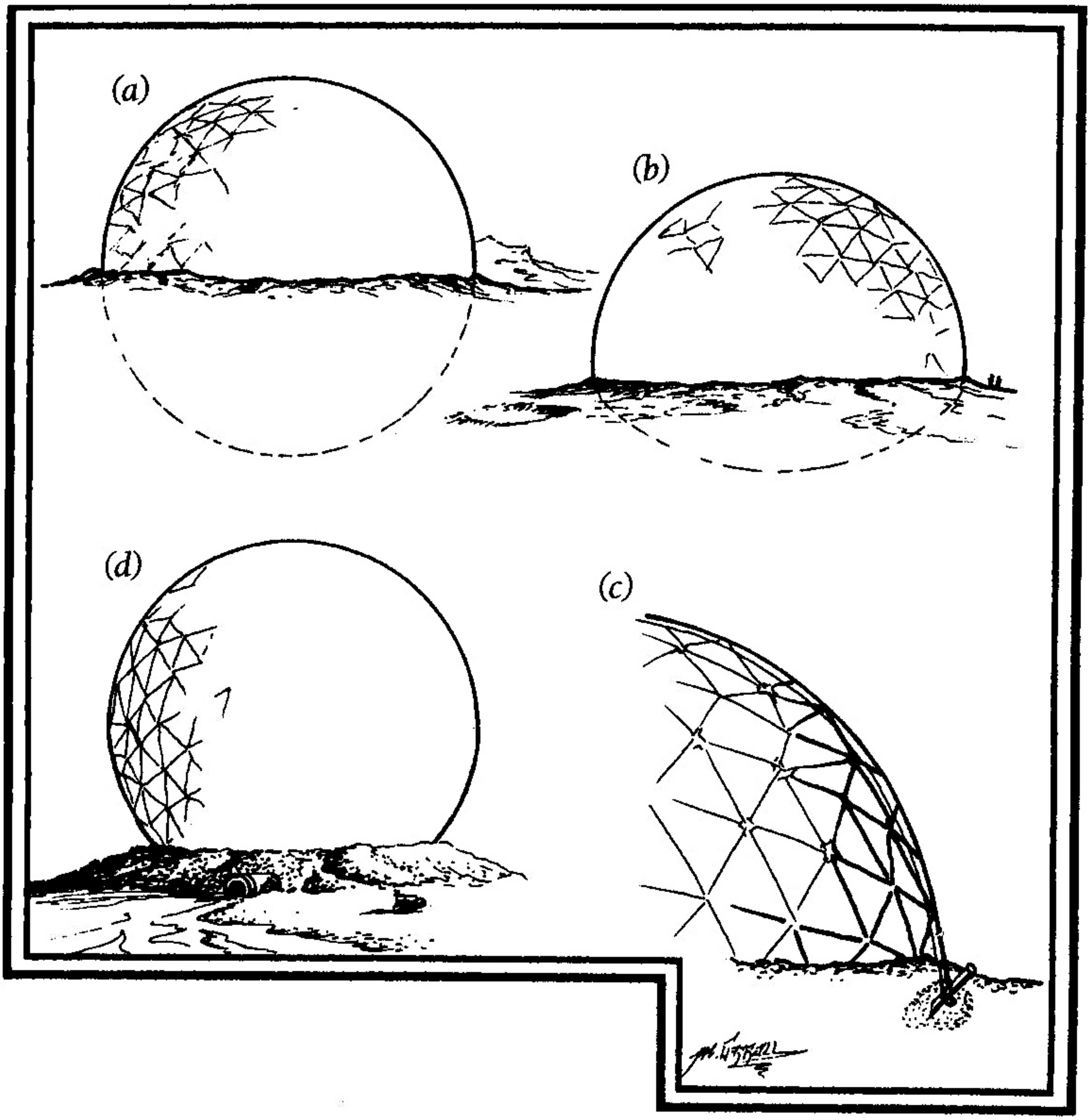


FIGURE 7.2

Methods of construction of domes on the Martian surface: (a) burying half of a spherical dome; (b) burying a dome whose lower half has twice the radius of curvature as the upper half; (c) anchoring a "tent" type dome; (d) a spherical housing complex located entirely above ground, employing Kevlar suspended decks. (Artwork by Michael Carroll.)



As the family friend pointed out to Dustin Hoffman's character in *The Graduate,* the key materials in modern life are made of plastics. Get into plastics and your future is assured, my boy. Well, because Mars, like Earth, possesses abundant supplies of native carbon and hydrogen, opportunities to get into the plastics industry abound there as well.

The key to plastics manufacture on Mars is the production of synthetic ethylene, which itself can be done as an extension of the reverse water-gas shift (RWGS) reaction discussed in Chapter 6 as a means for making oxygen. You may recall the RWGS reaction:

$$H_2 + CO_2 \rightarrow H_2O + CO \qquad (1)$$

We can use this reaction to produce all the oxygen we need on Mars by hitting Martian atmospheric carbon dioxide with hydrogen, discarding the carbon monoxide and electrolyzing the resulting water, storing the oxygen so released and then recycling the hydrogen to make more water, and thus more oxygen, and so forth. But let's say we do things a little differently. Instead of feeding hydrogen and carbon dioxide in a ratio of 1:1 suggested by equation (1), let's feed them together with a ratio of 3:1. Then we have:

$$6H_2 + 2CO_2 \rightarrow 2H_2O + 2CO + 4H_2 \qquad (2)$$

(Yes, I know I could divide all the proportions in equation (2) in half and it would still be the same, but bear with me.) So now we take the water produced by equation (2) and condense it out. Maybe we electrolyze it; maybe we don't. That all depends on whether we would rather have water or hydrogen and oxygen. The key thing, however, is what we do with the rest of the products after the water has been removed. If we choose, we can send the remaining mixture of carbon monoxide and hydrogen into another reactor, where in the presence of an iron-based catalyst they can be reacted in accordance with:

$$2CO + 4H_2 \rightarrow C_2H_4 + 2H_2O \qquad (3)$$

Bingo. C_2H_4 is *ethylene,* a great fuel and the key to the petrochemi-

FIGURE 7.3

Truck, oven, and slag pile system for extracting water from Martian soil. (Artwork by Michael Carroll.)

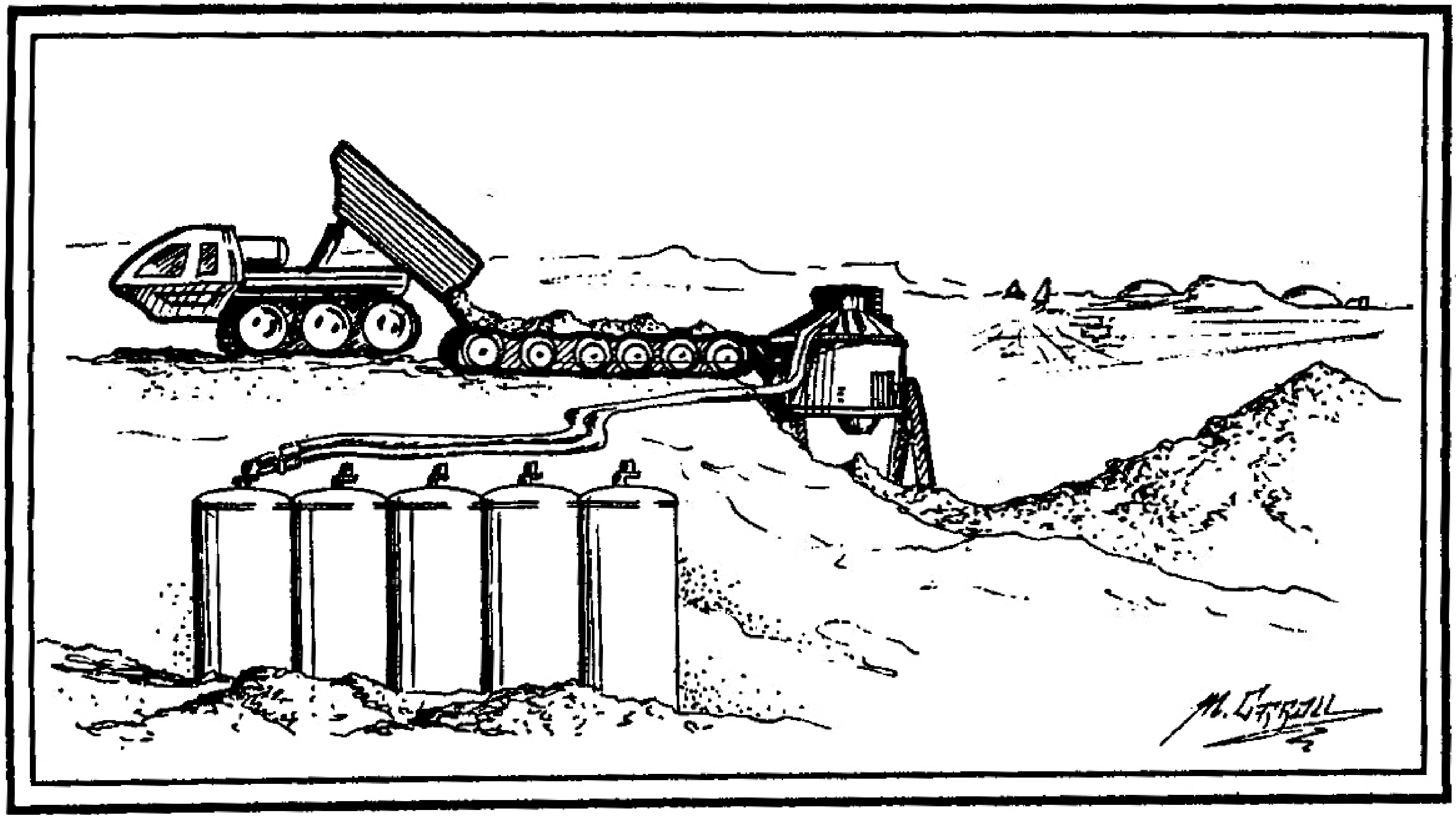


FIGURE 7.4

Mobile methods of extracting water from Martian soil: (a) soil eater on wheels; (b) mobile microwave system with skirt; (c) portable greenhouse dome with condenser. (Artwork by Michael Carroll.)

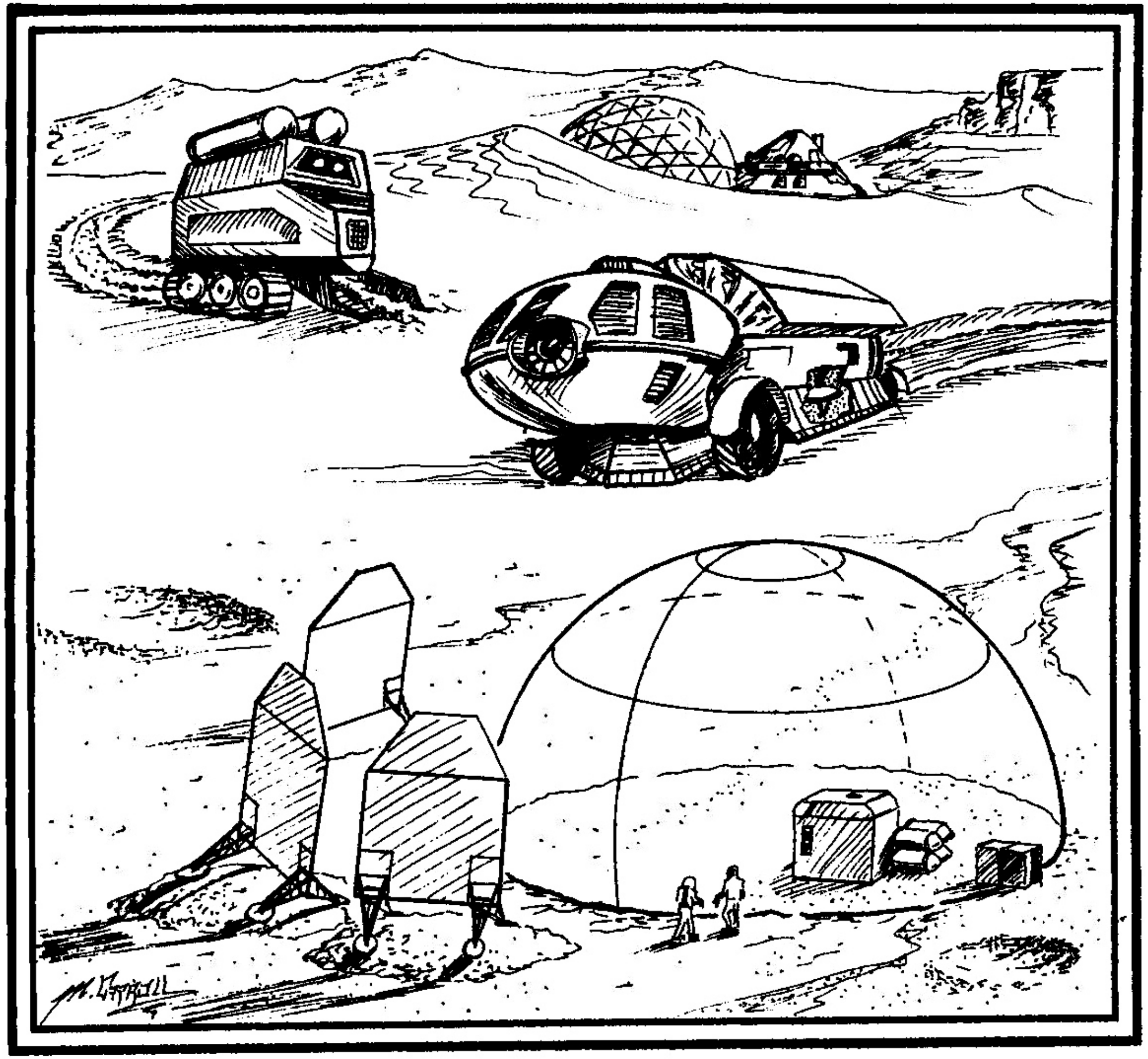


TABLE 7.1

Comparison of Plant Nutrients in Soils on Earth and Mars

Element	Terrestrial soil (average)	Martian soil (estimated average)
Nitrogen	0.14%	Unknown
Phosphorus	0.06%	0.30%
Potassium	0.83%	0.08%
Calcium	1.37%	4.10%
Magnesium	0.50%	3.60%
Sulfur	0.07%	2.90%
Iron	3.80%	15.00%
Manganese	0.06%	0.40%
Zinc	50 ppm	72 ppm
Copper	30 ppm	40 ppm
Boron	10 ppm	Unknown
Molybdenum	2 ppm	0.4 ppm

This material is so ubiquitous on Mars that it gives the Red Planet its color, and thus indirectly, its name. Reducing hematite to pure iron is straightforward, and, as mentioned both in the Old Testament and in Homer, has been practiced on Earth for some three thousand years. There are at least two candidate processes suitable for use on Mars. The first, as discussed earlier in this chapter, uses waste carbon monoxide—reaction (1), above—produced by the base's RWGS reactor as follows:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \quad (4)$$

The other uses hydrogen produced by the electrolysis of water.

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (5)$$

Reaction (4) is slightly exothermic and reaction (5) is mildly endothermic, so after heating the reactors to startup conditions, neither will require much power to run. In the case of reaction (5), the hydrogen needed can be obtained by electrolyzing the water waste product, so the only net input to the system is hematite. Carbon, manganese, phosphorus, and silicon, the four main alloying elements for steel, are very common on Mars. Additional alloying elements such as chromium, nickel, and vanadium, are also present in respectable quantities. Thus, once the iron is produced, it can readily be alloyed with appropriate quantities of these other elements to produce practically any type of carbon or stainless steel desired.

On Earth, after steel, the second most important metal for general use is aluminum. Aluminum is fairly common on Mars, comprising about 4 percent of the planet's surface material by weight. Unfortunately, as on Earth, aluminum on Mars is generally present only in the form of its very tough oxide, alumina (Al_2O_3). In order to produce aluminum from alumina on Earth, the alumina is dissolved in molten cryolite at 1,000°C and then electrolyzed with carbon electrodes, which are used up in the process, while the cryolite is unharmed. On Mars, the carbon electrodes needed could be produced by pyrolyzing methane produced in the base's Sabatier reactor, as described in Chapter 6. This process can be written:

$$Al_2O_3 + 3C \rightarrow 2Al + 3CO \quad (6)$$

Aside from its complexity, the main problem with employing reaction (6) to produce aluminum is that it is very endothermic. It takes about 20 kWh of electricity to produce a single kilogram of aluminum. That's why on Earth aluminum production plants are located in areas where power is very cheap, such as the Pacific Northwest.

The feedstock for manufacturing silicon metal, silicon dioxide (SiO_2), makes up almost 45 percent of the Martian crust by weight. In order to make silicon, you need to mix silicon dioxide with carbon and heat them in an electric furnace. The resulting reaction is:

$$SiO_2 + 2C \rightarrow Si + 2CO \qquad (7)$$

Once again, we see that the required reducing element, carbon, is a by-product of the Mars base propellant production system. Reaction (7) is highly endothermic, although nowhere near as bad as the alumina reduction reaction (6), and the energy burden involved in reducing silicon is not remotely comparable because the quantities needed tend to be much less.

For some purposes, the silicon product of reaction (7) is good enough for use. For example, you can use it to make silicon carbide, a strong heat-resistant material (it's used in tiles to protect the Space Shuttle from the heat of reentry). However, it is evident that any hematite impurities present in the reactor feedstock will also be reduced, resulting in iron impurities in the silicon product. To produce hyperpure silicon, then, good enough for computer chips and solar panels, another step is needed. This is accomplished by bathing the resulting impure silicon product in hot hydrogen gas, causing the silicon to turn into silane (SiH_4). At room temperature or above, silane is a gas, so it can easily be separated from hydrides of the other metals, all of which are solids. Then, if you want completely pure silicon, all you have to do is pipe the silane to another reactor where you decompose it under high temperatures, thereby producing pure silicon and releasing the hydrogen to make more silane. The silicon can then be doped with phosphorus or other selected impurities to produce exactly the kind of semiconductor device you need.

Up till now, virtually all the Martian propellant combinations we have discussed, such as methane and oxygen, have required the vehicle utilizing them to carry both fuel and oxidizer in its tanks. We don't do things that way on Earth. On Earth, whether it's burning gasoline in your car or wood in your fireplace, all you do is provide the fuel. The oxidizer comes from the oxygen in the air. Since the oxidizer in general makes up about 75 percent of the reacting mixture, this latter approach is clearly a far more efficient way to go. Well, there is very little free oxygen in the Martian atmosphere; it's almost all carbon dioxide. Not many things will burn in carbon dioxide, but silane will, in accordance with:

$$SiH_4 + 2CO_2 \rightarrow SiO_2 + 2C + 2H_2O \quad (8)$$

In reaction (8), 73 percent of the propellant mass is carbon dioxide, only 27 percent is silane. Some of the products are solids, so you can't use this system in an internal combustion engine. But you could use it to fire the boiler of a steam engine, and you could use it in a ramjet engine or for rocket propulsion.

TABLE 7.2
Characteristics of Mars Geothermal Fields

Time since active (million years)	0.5	5	10	20	50	>150
Depth to reach 0°C (km)	0.29	0.65	0.91	1.29	2.04	3.53
Depth to reach 60°C (km)	0.62	1.38	1.95	2.76	4.35	7.53
Depth to reach 100°C (km)	0.84	1.87	2.64	3.73	5.88	~10
Depth to reach 200°C (km)	1.38	3.09	4.36	6.17	9.73	~17
Depth to reach 300°C (km)	1.92	4.30	6.09	8.61	~13	~24
Probable land available (1,000 km^2)	5	50	100	200	500	plenty

TABLE 8.1

Transportation in the Inner Solar System

	Earth		Mars	
	ΔV (km/s)	Mass Ratio	ΔV (km/s)	Mass Ratio
Surface to low orbit	9.0	11.40	4.0	2.90
Surface to escape	12.0	25.60	5.5	4.40
Low orbit to lunar surface	6.0	5.10	5.4	4.30
Surface to lunar surface	15.0	57.60	9.4	12.50
Low orbit to Ceres	9.6	13.40	4.9	3.80
Surface to Ceres	18.6	152.50	8.9	11.10
Ceres to planet	4.8	3.70	2.7	2.10
NEP round-trip low orbit to Ceres	40.0	2.30	15.0	1.35
Chemical to low orbit, NEP round-trip to Ceres	9/40	26.20	4/15	3.90

TABLE 8.2
Mass of Freighter Missions to the Main Asteroid Belt (tonnes)

	Departure from Earth		Departure from Mars	
	CH_4/O_2	*Chem/NEP*	*CH_4/O_2*	*Chem/NEP*
Propulsion system				
Payload	50	50	50	50
Interplanetary spacecraft	10	150	10	50
Interplanetary tankage	85	19	15	3
Interplanetary propellant	1,220	268	205	37
Total mass in low orbit	1,365	487	280	140
Launch vehicle inert mass	1,365	337	280	90
Launch vehicle tankage	6,790	1,758	88	28
Launch vehicle propellant	97,000	25,127	1,250	401
Total ground lift-off mass	106,520	27,559	1,898	609

FIGURE 8.1

An NTR augmented heavy-lift launch vehicle, capable of transporting 24 colonists one-way to the Red Planet.

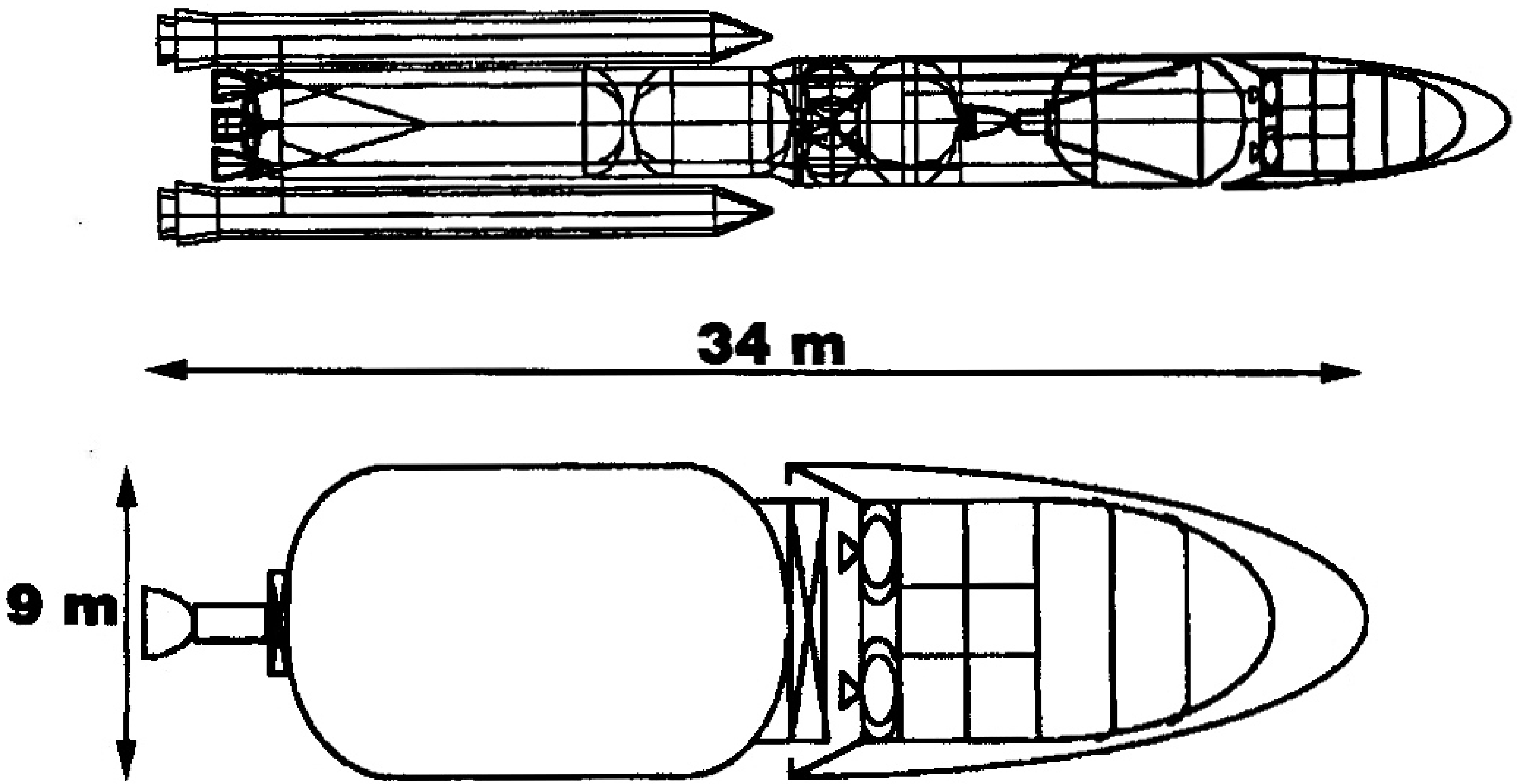


FIGURE 8.2
Colonization of Mars compared to North America. Analysis assumes 100 immigrants per year starting in 2010, increasing at a 2 percent annual rate, 50/50 male/female. All immigrants are between ages 20 and 40. Average of 3.5 children to an ideal Martian family. Mortality rates are 0.1 percent per year between ages 0 and 59, 1 percent between ages 60 and 79, 10 percent per year for those over 80.

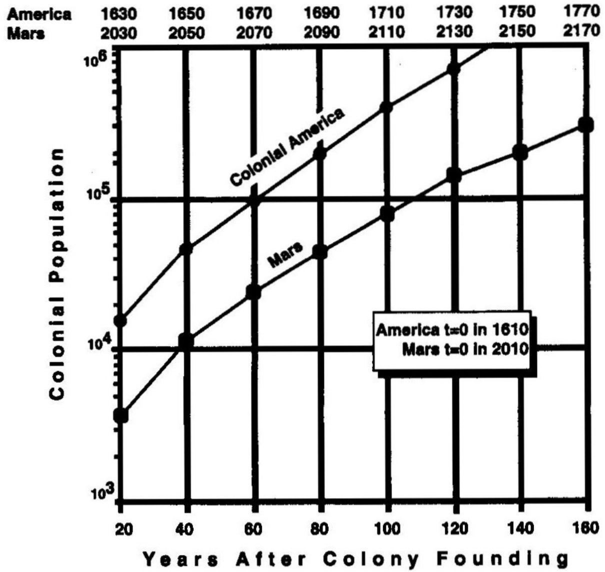


TABLE 8.3

Possible Cost Reductions of Earth-to-Mars Transportation System

	Baseline	Advanced	Reduction Factor	Fare to Mars (1996 dollars)
Baseline mission	—	—	1.0	$ 320,000
Earth to orbit	Rockets	Scramjets	0.3	$ 96,000
Life-support closure	95%	99%	0.7	$ 67,000
LEO escape propulsion	CH_4/O_2	NEP	0.6	$ 40,000
Cycler propulsion	Natural	Magsail	0.7	$ 28,000

FIGURE 9.1

Mars polar cap/atmosphere dynamics. Current equilibrium is at point A. Raising polar temperatures by 4°K would drive equilibria A and B together, causing run-away heating that would lead to the elimination of the cap.

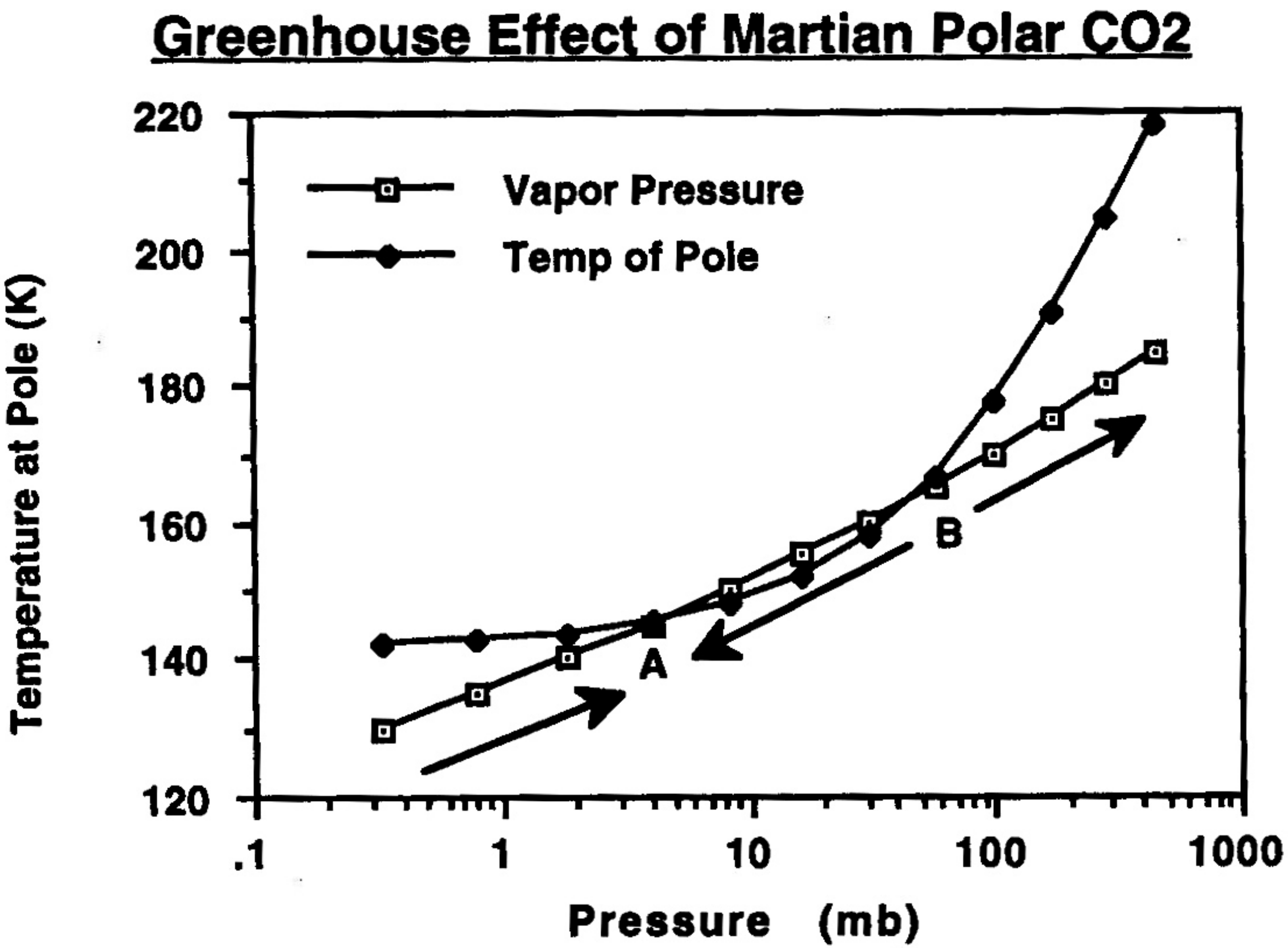


FIGURE 9.2

Mars regolith/atmosphere dynamics under conditions of T_d=20 with a volatile inventory of 500 mb of CO_2.

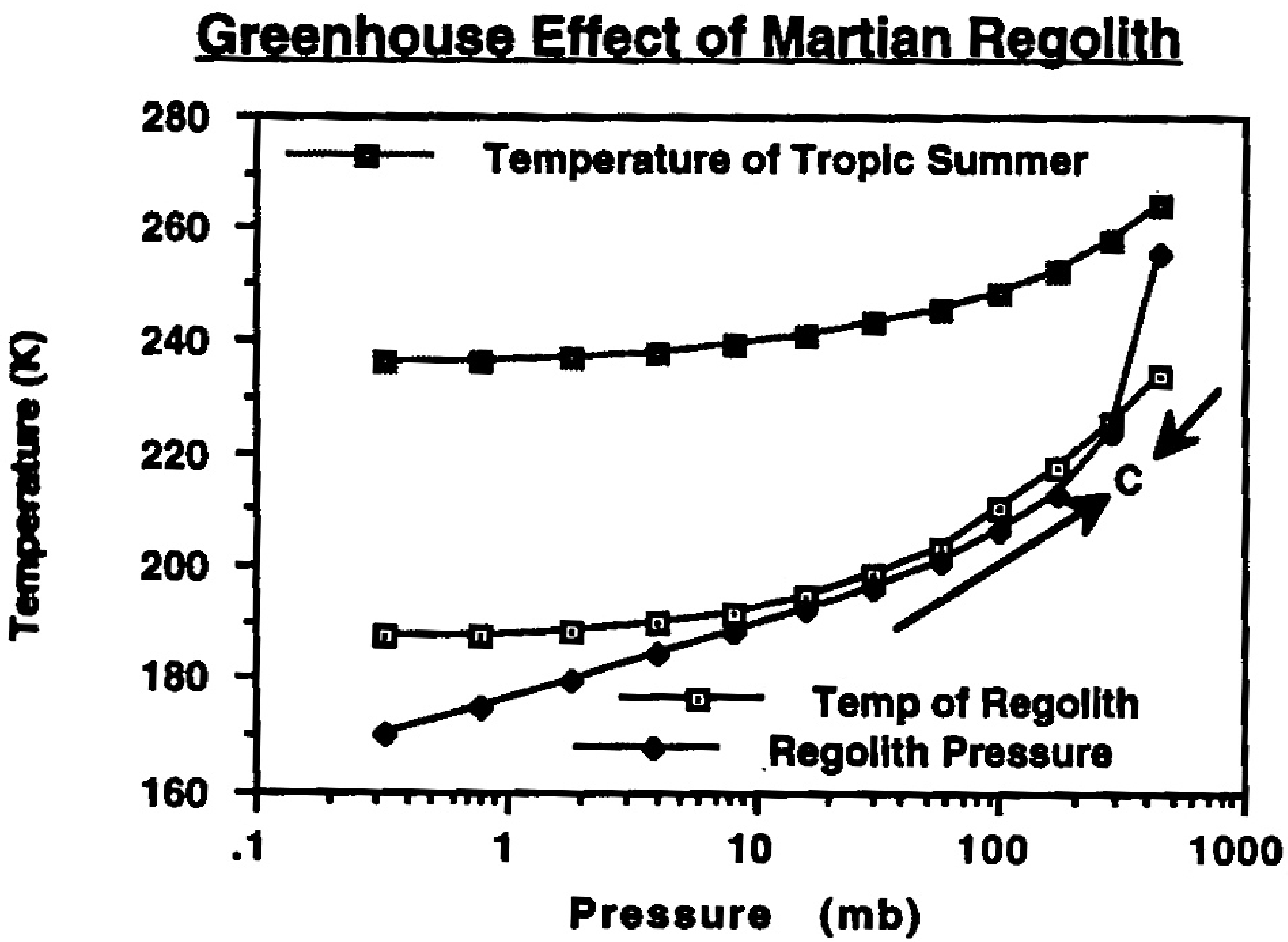


FIGURE 9.4

Equilibrium pressure reached on Mars with a planetary volatile inventory of 500 mb CO_2 after 50 mb polar cap has been evaporated. DT (ΔT in text) is artificially imposed sustained temperature rise.

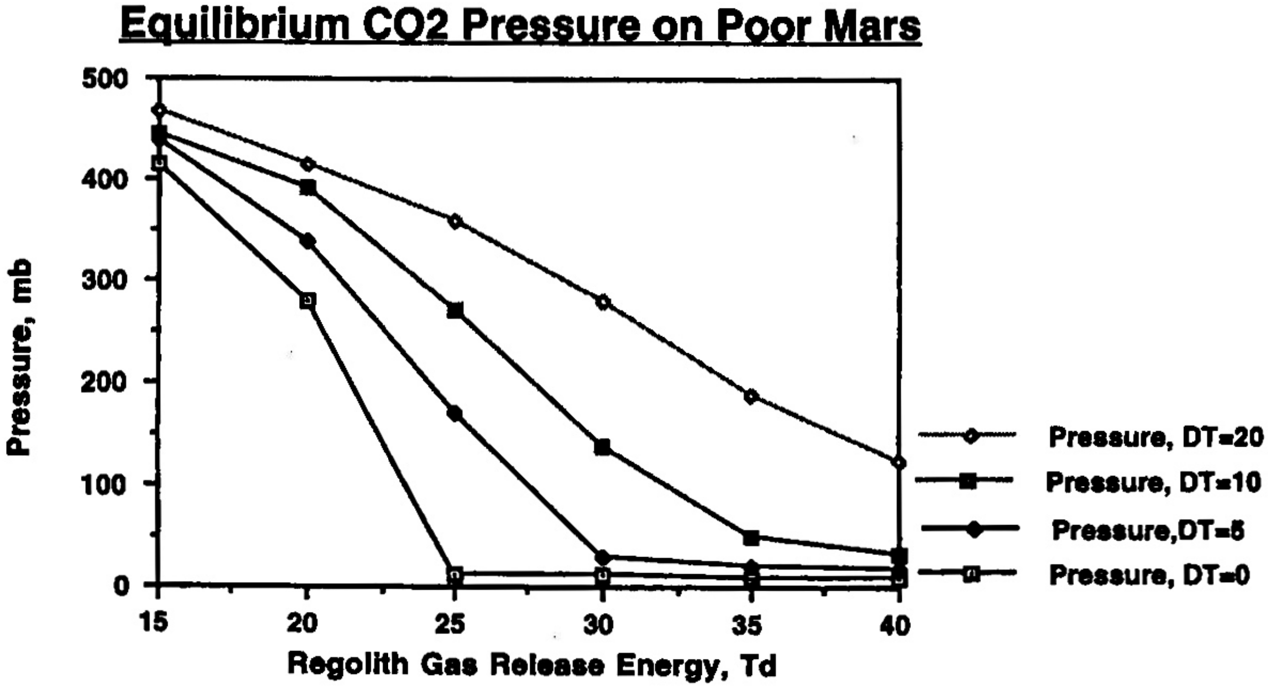


FIGURE 9.5

Equilibrium maximum seasonal (diurnal average) temperature reached on Mars with a planetary volatile inventory of 500 mb CO_2 after 50 mb polar cap has been evaporated.

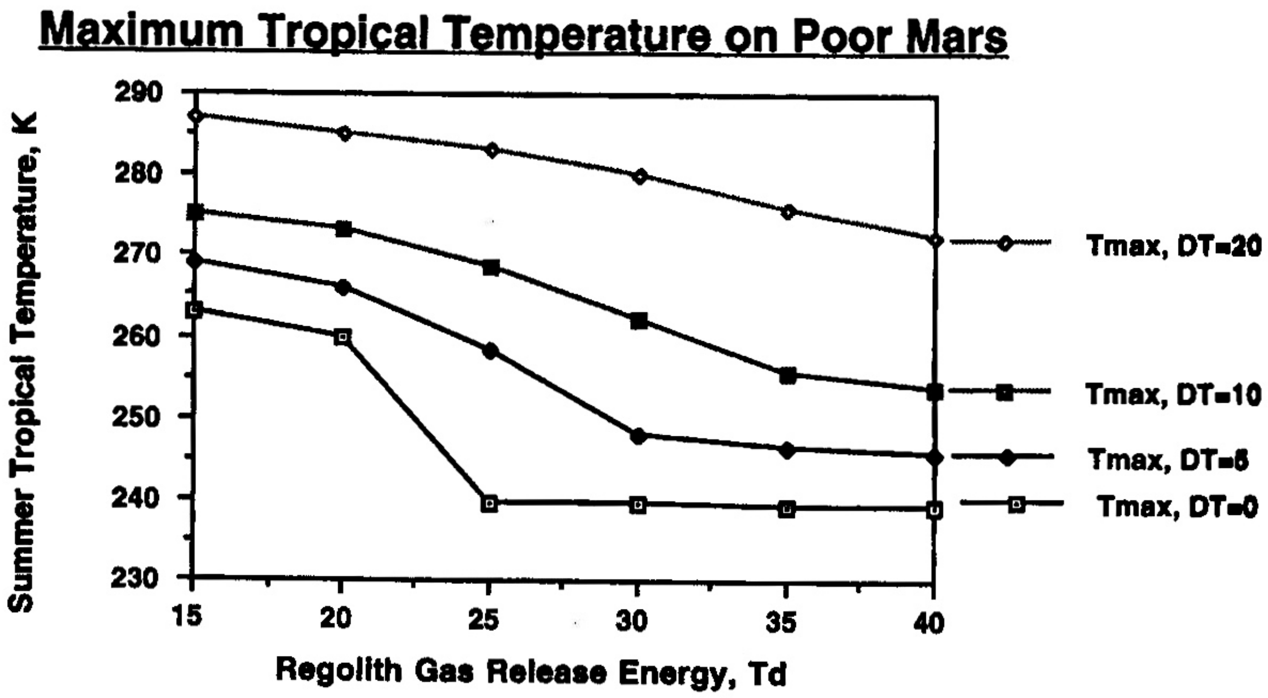


FIGURE 9.6
Equilibrium pressure reached on Mars with a planetary volatile inventory of 1,000 mb CO_2 after 100 mb polar cap has been evaporated.

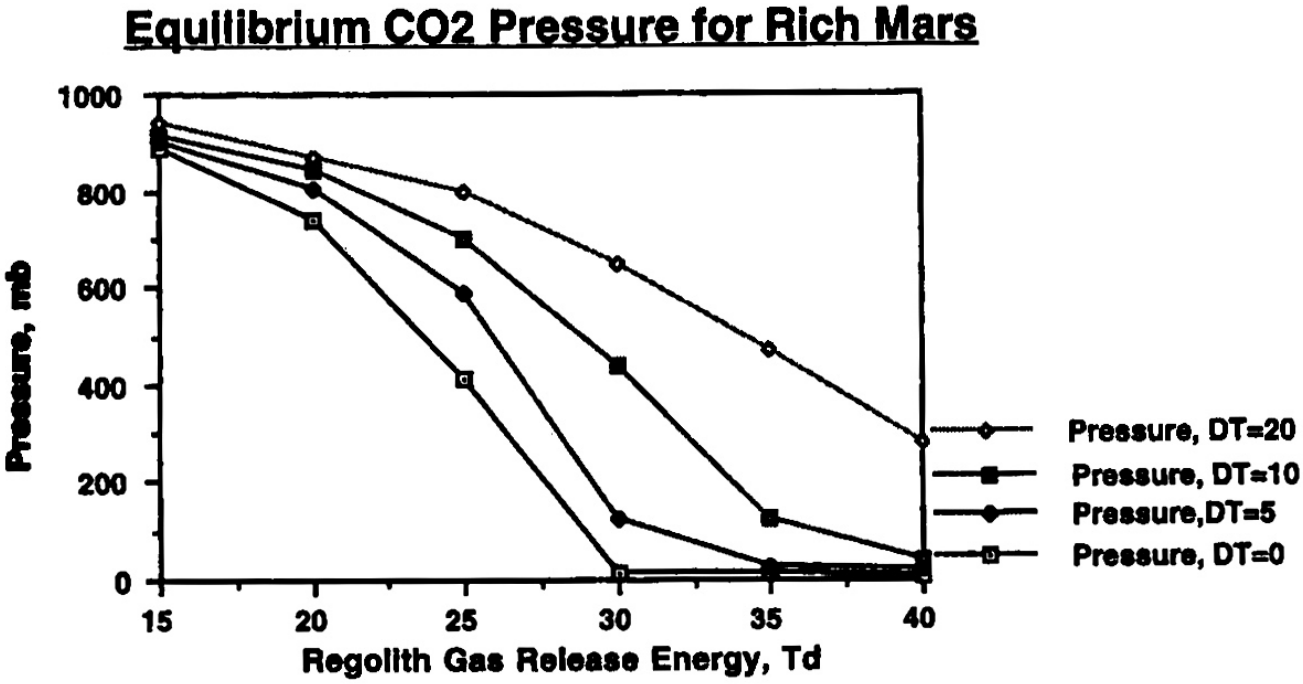


FIGURE 9.7
Equilibrium maximum seasonal temperature (diurnal average) reached on Mars with a planetary volatile inventory of 1,000 mb CO_2 after 100 mb polar cap has been evaporated.

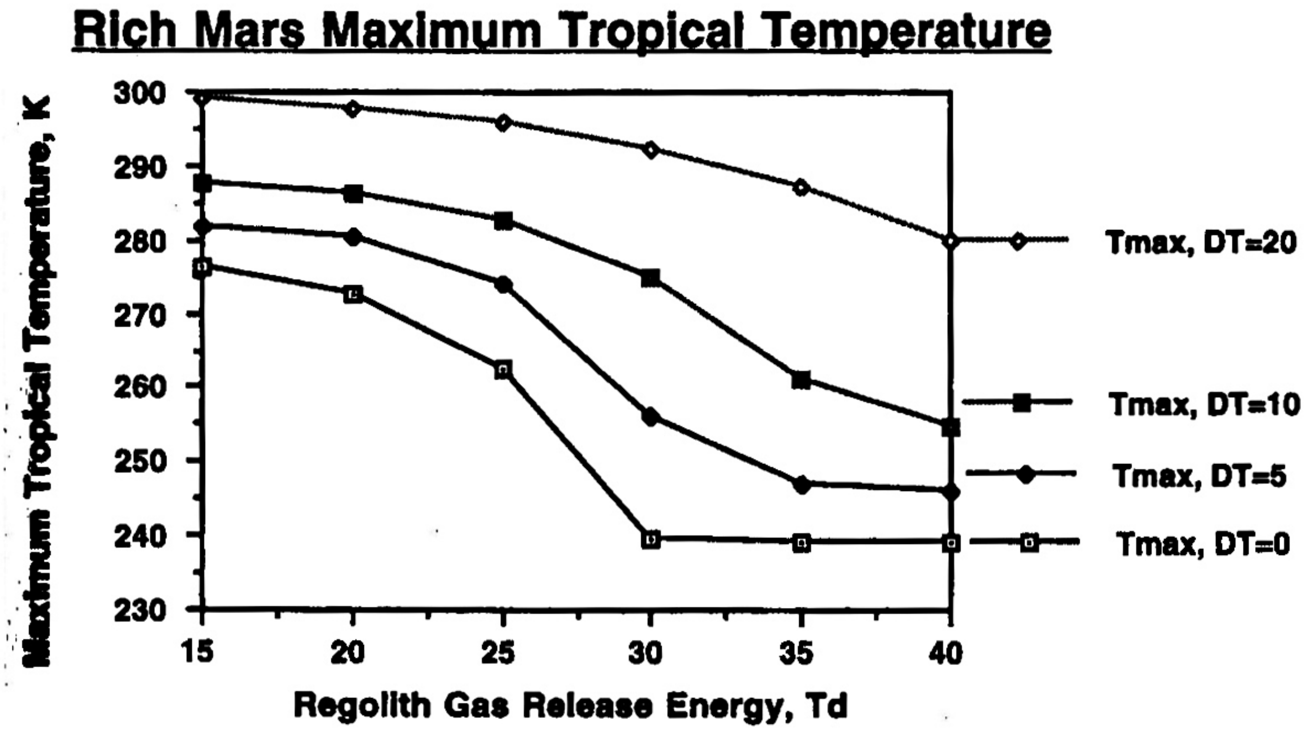


TABLE 9.1
Rate of Outgassing of Atmosphere from the Martian Regolith

Time (Earth years)	Depth Penetrated (meters)	Atmosphere Created (millibars)
1	4	20
4	8	40
9	12	60
16	16	80
25	20	100
36	24	120
49	28	140
64	32	160
81	36	180
100	40	200
144	48	240
196	56	280
256	64	320
324	72	360
400	80	400
900	120	600
1,600	160	800
2,500	200	1,000

FIGURE 9.8

Solar sails of 4 tonnes/km^2 density can be held stationary above Mars by light pressure at an altitude of 214,000 km. Wasting a small amount of light allows shadowing to be avoided.

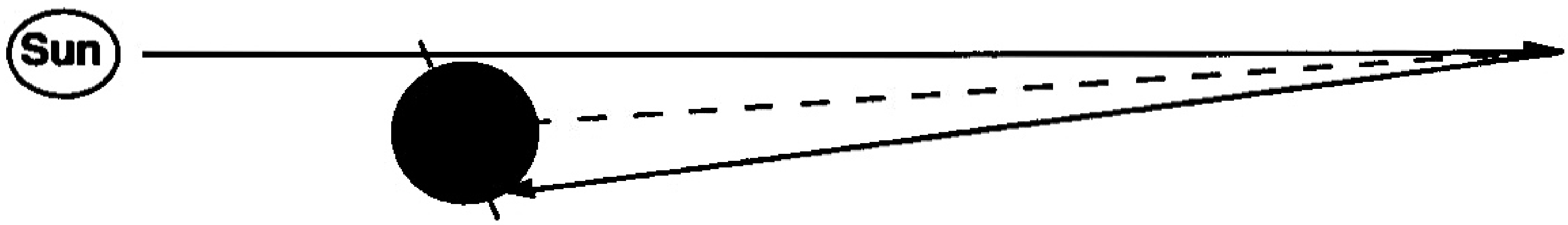


FIGURE 9.9

Solar sail mirrors with radii on the order of 100 km and masses of 200,000 tonnes can produce the 5°K temperature rise required to vaporize the CO_2 in Mars' south polar cap. It may be possible to construct such mirrors in space.

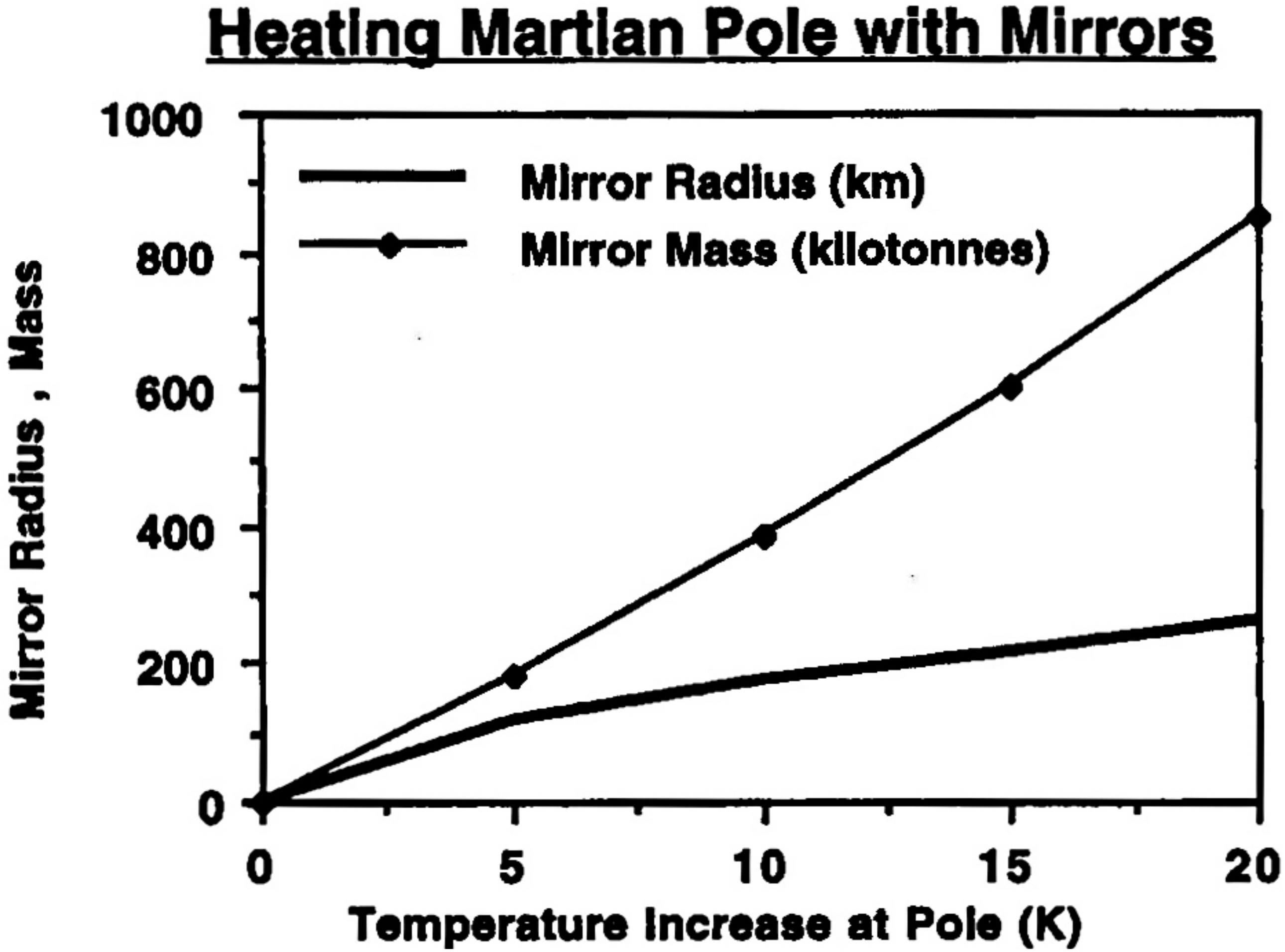


TABLE 9.2.
Greenhousing Mars with CFCs

Induced Heating (degrees K)	CFC Pressure (micro-bar)	CFC Production (tonnes/hour)	Power Required (MW_e)
5	0.012	260	1,310
10	0.04	880	4,490
20	0.11	2,410	12,070
30	0.22	4,830	24,150
40	0.39	8,587	42,933