CONF-8804105--2

UCRL--98567

DE90 008356

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THE OLYMPIA PROJECT

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Prepared For Invited Presentation In The
"Moon, Mars and Beyond" Session
of the
4th National Space Symposium
of the
United States Space Foundation
Colorado Springs, Colorado
12-15 April 1988

Lawrence
Livermore
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ABSTRACT

Manned exploration of the inner solar system—typified by a manned expedition to Mars—this side of the indefinite future involves fitting a technical peg into the political hole. If Apollo-level resources are assumed unavailable for such exploratory programs, then non-Apollo means and methods must be employed, involving greater technical and human risks, or else such exploration must be deferred indefinitely. Sketched here is an example of such a relatively high-risk alternative, one which could land men on Mars in the next decade, and return them to Earth. Two of its key features are a teleoperated rocket fuel-generating facility on the lunar surface and an interplanetary mission-staging space station at L_4*, which would serve to enable a continuing solar system exploratory program, with annual mission commencements to points as distant as the Jovian moons. The estimated cost-to-execute this infrastructure-building manned Mars mission is \$3 billion, with follow-on missions estimated to cost no more than \$1 billion each.*

Background

Without a sea change in American public opinion, the U.S. space program will never again enjoy the resource levels—approximately 1% of the GNP—attained by the Apollo Program at its peak. However, the present American technology base for space exploration would require Apollo Program-levels of expenditure for a comparable period in order to execute a manned expedition to Mars, primarily because our extant space transportation capability is comparable to that which we had in the early '60s; only the late-model Titans have no analog in the American launcher inventory a quarter-century ago. Because the Congress realizes that operating at 15-25% of the Apollo Program's pace would create a going-to-Mars program which would accomplish its goal so far into the future as to be of no present interest, no such stretched-out program will be commenced.

Is Mars thus unattainable, as far as the eye can see? Will featherless bipeds not tread the sands of Mars in our lifetimes? To us, the answer seems to depend critically on whether risks—programmatic, technical and human risk—significantly greater than those perceived

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* *Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-eng-48 with the University of California. Opinions expressed herein are those of the authors only, and are not necessarily those of the Laboratory, the University or the DoE.*

to have been taken in the Apollo Program come to be seen as acceptable, whether higher-risk alternative routes to inner solar system exploration are seriously considered. Specifically, *whether or not manned expeditions to Mars get underway in the foreseeable future will be determined by whether the levels of technical innovation necessary to engender the required overall economies-of-execution have risk levels associated with them which are determined to be acceptable.*

In order to provide a substantive starting-point for serious discussion of this fundamental point, we present here one such alternative approach. This may not be the lowest risk or the highest benefit-to-risk approach, but it appears to us to be one which features near-term realizability, an attractively low cost, and acceptable levels of risk.

The View From The Bottom Of The Gravity Well

As has long been realized, a manned expedition to Mars—or any other planet—which proposes to return its explorers to Earth is greatly complicated by the requirement to lift its human cargo out of two moderately deep gravity wells, those of the terrestrial and the mission-planet surfaces. This requirement, stacked on top of the minimum of three major rocket burns necessary to get from the Earth to the mission planet and back again and coupled into the basic rocket equation, seemingly implies that every ton of crew, souvenirs and ship returned to Earth will be associated with a minimum of several thousand tons of mass lifting off of the Earth's surface. Since the returned mass apparently must be several tons, at a bare minimum, one is apparently contemplating a launch of at least a half-dozen Saturn V-sized vehicles, followed by orbital assembly of their payloads, to constitute a single expedition. This is a tall order for our shriveled national space transportation capabilities: we would have to use the entire Space Shuttle fleet for nearly three years to orbit a single mission's components. This is simply not in the cards, for the remainder of this century.

Study of where the mass is invested and how it is spent immediately suggests that the Apollo Saturn V upper-stage fuel pair of cryogenic hydrogen and oxygen—the propellants also used by the Soviet Energia—are strongly advantaged over the more conventional storable propellants employed by Titans and Deltas. The Δv demands of interplanetary missions are so severe that very high specific impulse propellants are literally exponentially preferred. Compared to light metal-oxygen propellants used in modern solid-fuel rockets, the H_2-O_2 combination offers nearly twice the specific impulse (480 vs. 290 seconds), which implies mass ratios more than an order-of-magnitude different for interplanetary lander missions.

Secondly, it becomes clear that hauling propellants up from the Earth's surface is indeed a very expensive way to acquire them. Literally any other propellant point-of-origin along the entire route is strongly preferable; the terrestrial gravity well is a notably deep one. One is thereby sharply motivated to seek alternative fuelling points, even relatively exotic ones.

The Moon As A Fuel Dump

The Moon is known, from analyses of the returned Apollo samples, to be an inexhaustibly large source of premium rocket propellants: like that of Earth, the lunar soil is composed of tens of percent of metals with high-enthalpy oxides and of oxygen itself; moreover, its major components typically contain 0.01% by weight of lightly bound hydrogen gas, most of which can be liberated merely by roasting to temperatures as low as 500°C. At least as importantly, the Moon is perched on the very lip of the terrestrial gravity well, so that rocket propellants picked up there can be used mostly for real interplanetary transfer purposes, rather than expended almost entirely to merely propel some residual fraction out of the grip of Earth's gravity.

If our Mars expedition could somehow pick up its rocket propellant requirements from a point near the Moon on its outward-bound leg, its lifting-from-Earth mass budget would drop by nearly a hundred-fold. A very daunting weight-lifting requirement would become almost a trivial one; manned exploration of the inner solar system would become something which we could commence in the twentieth century, rather than a challenge left for our grandchildren. But is this even remotely feasible?

This question resolves naturally into three distinct components. First, the hydrogen and oxygen must be won from the lunar soil on the Moon's surface. Second, the recovered propellants must be transported to some suitable marshalling point reasonably close in gravitational potential to that of the lunar surface, so that they aren't all expended in transportation. Third, if reasonably possible, some fraction of the total required propellant mass should be delivered into low Earth orbit (LEO), in order to lift the mission's crew and vehicle from LEO to the marshalling point—this offers a savings of about 2.5 in the required weight lifted from the Earth's surface to launch the mission.

Now, the Apollo-retrieved lunar soil samples have been found to contain roughly 100 ppm by weight of lightly bound hydrogen, which is just about the soil's own volume of this gas, if the hydrogen is held at sea-level pressure and room temperature. This hydrogen was apparently ion-implanted into the soil's surface particles by the high-energy tail of the solar wind, which impacts the lunar surface directly. Slow mixing of the surface with deeper layers of soil by myriad meteoric impacts over the aeons has apparently resulted in a fairly uniform level of hydrogen impregnation, as deeply as the Apollo coring sampled. Experiments with these samples have established that the bound hydrogen, which is apparently located in the most superficial micron-deep layers of soil particles, can be liberated by lightly roasting the soil, to temperatures of around 500°C. At least as importantly, typically 300 ppm of water can be liberated by roasting to temperatures of less than 1000°C. Together, these two gases in these quantities provide essentially the ideal H_2-O_2 ratio for a maximum I_{sp} rocket engine (which requires a super-stoichiometric hydrogen fraction, for mean molecular weight reduction). Also of great longer-term significance for manned exploration of the solar system, of the order of 100 ppm of carbon oxides and of nitrogen and nitrogenous compounds are also liberated by such roasting.

An idealized lunar fuel factory would therefore consist of a heat source capable of generating the required heating rates at the necessary temperatures, a means of transporting this heat and coupling it into a stream of lunar soil, and a means for trapping and storing the hydrogen, water and possibly other gases liberated during this soil-roasting.

Because multi-MW quantities of heat at moderately high temperatures must be supplied for long periods, preferably in a compact, readily transported module, use of an *ad hoc* nuclear reactor is strongly indicated. The feed-stream of lunar soil can apparently be most readily generated by use of a fairly standard trenching machine, suitably mass-economized for work in the low-gravity lunar environment. Heat can be removed from its nuclear fission source and transported into the soil stream provided by the trenching machine most readily by a MHD-pump-driven liquid lithium-7 loop, which can also serve to provide the counter-current flow of heat against the soil stream which minimizes net heat generation requirements.

Vehicle electric power supply of a few dozen kWe is readily realized by semiconductor thermoelectric converters, rejecting their cool-junction heat radiatively from the dozen square meters of sides and front surfaces of the fuel factory module; this system would also serve to dispose of nuclear after-heat during periods in which soil wasn't being processed, e.g., during the periodic fuel transfer intervals. This electric power supply will be adequate for MHD liquid metal pumping, traction, trenching and gas pumping requirements, as well as for control and communications systems needs; it will be backed-up by a small H_2-O_2 fuel cell.

The liquid metal loop also provides the required heat input to the small thermocatalytic cracking unit which renders the gaseous feed-stream into its constituent chemical elements, e.g., decomposes steam into hydrogen and oxygen. Overall, a few percent of the reactor's total thermal output ends up as stored chemical energy of the propellants won from the lunar soil.

Our first-cut design of this system indicates that its functions can be performed within a cube about 2 meters on an edge, whose mass is about 10 tons—much of which is first-order neutron- and γ-ray-shielding of the nuclear reactor heat generator. The design of this system repeatedly invokes the high-vacuum environment of the lunar surface to enable the use of very mass- and volume-efficient multi-layer metal-film "superinsulation" for thermal environment control, and also exploits the remotely controlled, completely unmanned aspects of this fuel factory to permit use of a highly mass-economized nuclear reactor. An artist's conception of this system in operation is shown in Figure 1.

This fuel factory generates about a dozen grams/second, or roughly 1 ton per day of hydrogen-oxygen propellants. It thermocatalytically cracks the liberated water, molecular sieve-separates the hydrogen and oxygen gases, mechanically condenses them to cryogenic liquids and stores these for several-hour working periods, and then transfers them to tanks on a nearby propellant ferry-tug, which has a quad of four tank pairs, each of 10 tonnes capacity. Loading each such ferry is thus the work of about 6 weeks for the fuel factory. The tanks on this ferry are spheres and cylinders of 2.4 meters diameter, for storing and transporting liquid-oxygen and -hydrogen, respectively. Cryogenic conditions are maintained by standard, small heat-leak-cancelling mechanical cryo-coolers, electrically powered from the tug's fuel cell.

The propellant ferry-tug, after being fully loaded by the mobile lunar fuel factory, carries its cargo to a staging point whose gravitational potential is not greatly different from that of the lunar surface. For this purpose, it uses one of our favorite RL-10 engines, a liquid oxygen-hydrogen-burning veteran hailing from the early days of the Space Age which offers 15,000 pounds of throttleable and restartable thrust at an I_{sp} as high as 480 seconds, and which has a magnificent reliability record—all in a 180 kg package. Indeed, this ferry-tug consists of the quad of cryogenic tank-pairs, a couple hundred kilograms of structural members, the RL-10 engine, and a simple guidance and communications package—it, too, is teleoperated.

In Figure 1, you see an artist's rendering of one of the ferry-tugs leaving with a full load of propellants, while another one, recently arrived, is waiting for a periodic fuel-loading event, roughly a kilometer from the fuel factory's warm working area.

On The Lip Of The Terran Gravity Well

The location to which the propellants are hauled by the ferry-tugs is largely a matter of choice. We have selected the fourth Lagrangian point of the Earth-Moon system, for its favorable position at the upper edge of the terrestrial gravity well, its proximity in both spatial and gravitational terms to the lunar surface and its orbital stability; L_5 is just as good, and L_1 nearly so. The ferry-tugs can deliver about half of their lunar lift-off propellant loading to L_4, and still have enough left for the return to the lunar surface, where they routinely touchdown with nearly dry propellant tanks. They're analogous to a large gasoline truck which, tasked with hauling a load of gas across the country from a refinery to a large gas station, arrives at its destination with only half the initial load, having burned the other half in the transcontinental drive.

The staging area at L_4 is where the interplanetary mission vehicles are fuelled, as well as the location from which the lunar systems are teleoperated. An artist's conception of the scene here is shown in Figure 2. For both the space station supporting human activity here and the interplanetary vehicle, we have borrowed heavily from the detailed plans of the Columbus Project for a permanent lunar settlement, which we presented at the 2nd National Space Symposium, two-and-a-half years ago. In particular, both make use of inflatable Kevlar-based modules for human habitation, and employ the life-support systems which we discussed in some detail in that paper. Breathing gas and water are recycled in these systems, but waste products are not; the hydrogen and oxygen loops are closed, but the food-derived carbon and nitrogen loops are open. As a result, approximately 1 kg/person-day of consumables must be provided, ultimately from Earth; the major fraction of this is 0.8 kg/person-day of dehydrated foodstuffs.

As in the lunar settlement of the Columbus Project, each of the six major habitation modules constituting the L_4 station starts service as a long, sausage-shaped empty bag, flexible and airtight. Each has pressure doors at each end, and is filled to 6 psi with a 50:50 mix of nitrogen and oxygen. The walls of each of these modules are made of a strong, metal foil-covered Kevlar-based material. Two complete and independent walls are provided, one within the other; either is sufficient to contain the enclosed atmosphere. The double walls of each module have a total mass of 250 kg, and the two metal pressure door-mounting structures on each end, plus air-lock fractions, add 200 kg more. An additional 250 kg per module is used for space partitioning and mounting attachments, and 200 kg more to (collapsible) furnishing and other basic equipment, including distributed environmental maintenance gear. Each module also requires 100 kg of atmosphere. The total mass of each of the six modules, including their interconnections and external airlocks, is thus about 1.0 tonne, so that the station's structural mass is 6 tonnes.

Station electrical power is provided by fuel cell-backed-up solar photovoltaic power, derived from contemporary 0.3 W/gram amorphous silicon photoconverter assemblies mounted on mil-thick metal foil. One tonne of station mass budget is devoted to 50 kWe of primary power supply (500 kg of usually unsteered photovoltaic sheeting, 150 kg of power conditioning gear, 200 kg of fuel cells and fuel storage, and 150 kg of power distribution, monitoring and control gear), and another 0.5 tonnes to communications systems, including four high-resolution video links to the lunar surface, two to the ferry-tug fleet, and two to the Earth. A year's reserve of life-support supplies for the station's crew-of-five consume another 2.0 tonnes, and central life-support and environmental maintenance equipments also mass 2.0 tonnes, with three-fold redundancy of critical modules. Make-up air storage and initial station air reserves require 0.8 tonnes, and water reserves an additional 0.2 tonnes. In-space personnel and freight maneuvering equipments and their initial fuelling require 0.6 tonnes. The personal effects of the crew add another 0.5 tonnes, and the crew itself is budgeted for an additional 0.4 tonnes. The bottom line of the station-loading mass budget is thus 8 tonnes, and the total mass of the staffed-and-functioning station is therefore 14 tonnes.

Each of the station's fleet of two ferry-tugs has an empty mass of about 3.7 tonnes, consisting of 500 kg for the RL-10 engines and associated propellant plumbing, 250 kg of structure and landing gear, 50 kg of fuel cells and cryostats, 50 kg of video link communications gear, 50 kg of guidance and control and 2800 kg of super-insulated tankage for the 40 tonnes full-loading of liquid hydrogen and oxygen propellants. The fleet thus adds 7.4 tonnes to the total facility's mass budget, plus 2.7 tonnes of initial propellant loading for one of the ferry-tugs, to permit it to land for the first time on the lunar surface. Two additional tonnes are budgeted for 200 tonnes capacity of zero-gee cryogen storage tankage near the station; this consists of a pair of super-insulated bags which hold their cryogenic liquid contents at very low pressures. The fleet-plus-fuel depot thus masses 12 tonnes.

The L_4 staging facility thus has a total mass emplacement requirement of 26 tonnes in order to commence operations. This certainly isn't negligible, but neither is it the largest mass budget for a space station-plus-space ferry system which has ever been considered.

Getting There From Here

How might this 26-tonne mass space station be emplaced in high earth orbit? For that matter, how is the 10-tonne mass of lunar fuel factory to be located on the lunar surface? If RL-10-engined space transport systems are employed, then each of these systems must be launched from low Earth orbit (LEO) with about 50 tonnes of total mass. Such payloads could be launched from Earth in two Shuttles each, followed by orbital assembly—if cryogenic hydrogen and oxygen may be transported in the Shuttle cargo bay. Alternatively, they could each be launched intact atop the Titan and Delta follow-on vehicles which have been designed and implementation-scheduled in considerable detail by Martin and McDonnell-Douglas, respectively. These very interesting ELVs each are capable of launching 110,000 pound—50 tonne—payloads into LEO at recurring costs of $200 million, less than $2000/lb, and could do so as soon as 30 months after the "Go" order is given. Yet two other alternatives are worthy of some thought: either the Apollo Saturn V of yesteryear or the Soviet Energia booster of today could orbit *both* of these payloads in a single launch(!)

The Energia option has the immense advantage of requiring an existing booster. The Titan/Delta-derivative ELV option could first put the lunar propellant factory into place, and then emplace the L_4 staging facility after the lunar factory had demonstrated its functionality and had propellants—and life-support materials—ready for first pick-up; all this for a total launch cost of $0.4 billion. (Incidently, the non-recurring expense—the NRE—to create the Titan/Delta-derivative ELV capability—the up-front cost to be sustained over a two-year period—has been carefully estimated to be $0.3 billion, so that the total cost-from-the-present-time of transporting from the Earth the lunar fuel factory onto the Moon's surface *and* the interplanetary mission-staging space station to L_4 would be $0.7 billion. Of this, only $0.5 billion need be initially risked; not until the lunar fuel factory was known to be working would the staging space station be launched toward L_4.)

So now we've emplaced the interplanetary analogs of an oil well and refinery and the gas station which serves up its products to the customer vehicle. What does this vehicle consist of, and what's involved in getting it to the gas station at L_4 to fuel up for the Mars trip?

The easy way to answer this question is to determine what has to be returned to Earth at mission's end, and what is to be landed on Mars at the mission's mid-point. After these items and their associated masses are known, everything else comes out by turning the crank on the rocket equation. The choices we've made, and the resulting numbers, are shown in Table I.

We want to return a total package mass of 10 tonnes to Earth, 5 tonnes of which gets thrown away just prior to atmospheric reentry and 5 tonnes of which soft-lands, Apollo Return Module style. In order to support the needs of the crew on the trip home from Mars, we have to pack 1.4 tonnes of consumables; we therefore have to leave Mars with 11.4 tonnes. Now we carried to Mars 17.6 tonnes of systems and materials which we left on the Martian surface as a legacy for the second expedition, which presumably will use their landed mass to support a long-duration settlement, leveraged off the basic necessities left by this first expedition; this is of course in the fine tradition of Arctic and Antarctic exploration. We also left our 1 tonne Mars-to-Deimos ascent module on Deimos. In addition, we had to have 2 tonnes of consumables for the Earth-to-Mars trip, 0.5 tonne for the propellant tankage ditched in the Mars landing and take-off, and 14 tonnes more propellant tankage for the Earth-to-Mars and Mars-to-Earth legs of the trip. A total of 48 tonnes of mass which has to be lifted from the Earth and fuelled-up at the L_4 station is thus required for this first Mars expedition. The mission fuelling requirement which has to be serviced at the L_4 station is 205 tonnes, roughly a year's output from the lunar fuel factory via the ferry-tug system. The expedition vehicle thus masses 253 tonnes, as it leaves L_4.

Now a single Titan/Delta-derivative vehicle could insert this 48 tonnes of mission vehicle into LEO. From whence comes the 78 tonnes of hydrogen-oxygen propellants needed to loft this vehicle from LEO to L_4? Obviously, it could be sent down from the L_4 station, but this is attractive only if atmospheric braking of fuel shipments into LEO is considered to be feasible. (Rocket descent into the Terran gravity well to LEO depth and followed by the climb back out to L_4 would permit one of our fully-loaded ferry-tugs to deliver only about 6 tonnes of propellant per trip, and three years of lunar fuel factory output would be required to deliver enough propellants to LEO to fuel the LEO-L_4 transit.) If this isn't seen to be feasible, then another two Titan/Delta-derivative vehicle launches must be employed, for a total of three required to launch the mission. (A bonus of this option is that an additional 9 tonnes of equipments and supplies for the L_4 station can be carried along, using the full payload-lofting capacity of the three advanced ELV launches.)

The Bottom Line

But what would all this cost, and how long would it take to do, from the present starting point? What's the bottom line of all these design considerations?

Obviously, if it's done in a traditional bureaucratic setting, Parkinson's Law applies exactly, and it'll take as long and cost as much as you can possibly afford—and then it may not make it. The questions of real interest address the *minimum* time and cost which are *really* required to accomplish this task, in something between the style of NASA in the '60s and the Manhattan Project in the '40s. Once you have these genuinely *minimal* numbers, you can stack on your own choice of time-and-cost multipliers for politics-as-usual, sloth, graft, mediocre management and indifferent staff, legal obstructionism, etc. to arrive at your own estimates for the time-and-cost under prevailing circumstances.

For instance, in the time-and-cost section of the Columbus Project study, we estimated in considerable detail that $0.25 billion of Government expenditure, 6 Shuttle launches and 7 years of effort could establish a permanent lunar settlement, one which would be in place on the five-hundredth anniversary of the Columbus landing in the New World. One year later, NASA management formally expressed the hope that NASA would have Americans back on the Moon within a quarter-century, at an unspecified cost. This establishes a factor-of-three in time—and suggests perhaps a factor of at least ten in cost—between what we believe is the best that Americans could do under contemporary circumstances and what NASA management believes might actually happen.

Against this background, we suggest that the 50 tonne launch-to-LEO capability could be created in 2.5 years at a total cost-to-first launch of $0.5 B; subsequent launches would cost $0.2 B each. As noted above, we are merely echoing quite authoritative estimates in this area. The total *launching* cost to send an expedition to Mars—if the lunar fuel factory and the L_4 staging station were scrapped entirely, and all the mission propellants were simply launched from the Earth—would be the cost of 13 launches of 50 tonnes each, or $2.9 B. The advanced ELV launching rate could be such that the mission vehicle could be fully fuelled in LEO, ready to go to Mars, in a half-decade. To us, these seem remarkably small time-and-cost numbers—the more so as they are such relatively firm ones.

What, then, are the likely time-and-cost numbers for the mission vehicle on the ground, and for the lunar fuel factory and the L_4 staging station?

The mission vehicle itself employs Columbus Project technology pervasively, for crew quarters, life-support, Martian settlement package modules, power supply, environmental maintenance, structure and propulsion. Indeed, the mission vehicle is an edited, mobile version of the lunar settlement of the Columbus Project. Referring to the detailed Project plans, we therefore conclude that this Mars expeditionary vehicle could be ready to launch 5 years after work on it was commenced, at a cost of $0.71 B—with all requisite manpower fully salaried (in contrast to the volunteer labor postulated in the Columbus Project plan).

For the L_4 station, we again invoke the results of the design study for the Columbus Project lunar settlement, as this station is almost entirely a cut-down, in-orbit version of the lunar settlement. The incremental cost to implement the station, over-and-above that of the mission vehicle, is estimated to be $0.48 billion. It would be available perhaps a year earlier, due to its not having a Mars descent/ascent module. To put the station's 26 tonnes of mass in place would involve a launch cost of $0.25 billion ($0.2 B for the launch to LEO and $0.05 B for the L_4 emplacement stage).

The lunar fuel factory's only sophisticated module is its nuclear heat source, which is very similar in both its nuclear and mechanical engineering features to some of the early submarine power plants. It could clearly be running in operational prototype with two years, at about the same time as an electric-heat-source lunar fuel factory prototype would first go into operation. (We say "clearly" because experimental reactors of comparable power ratings and physical sizes were routinely designed and built on these time scales in the '40s and '50s in this country, when the necessary technology base, particularly in computational design and in materials science and technology, was far more rudimentary.) We also believe that both of these prototypes could be performance-optimized and durability-enhanced sufficiently so that a launchable fuel factory could be delivered to the launching pad four years after the design effort commenced—provided that there were the levels of goal-oriented internal discipline against all-new technology creation and NIH parochialism that characterized early reactor prototyping. Two project crews of roughly 100 professionals each for this period, plus properly proportioned supply-and-expense budgets, would imply total costs-to-first module-delivery of about \$0.33 B. To soft-land the fuel factory on the lunar plain would cost \$0.55 B, including the \$0.3 B of NRE for the 50 tonne-to-LEO launch capability.

These first-order Project budget items are summarized in Table II.

The total cost of the first expedition to Mars thus appears to us to be \$2.9 billion: \$0.7 B to build and launch the L_4 mission-staging station, \$0.9 B to build, launch and emplace the lunar fuel factory, and \$1.3 B to build and launch to L_4 the first Mars expeditionary vehicle. We believe that this expedition could leave the Earth-Moon system six years after serious work on it commenced. It would return to Earth three years later, as indicated in the expedition's master schedule, shown schematically in Figure 3.

Epilogue

But why bother with the technical and thus programmatic risks of the lunar fuel factory and the L_4 staging station? Why not just pay the \$3 billion to launch the propellants for the mission vehicle, and save the funds otherwise invested in the fuel factory and the staging station?

It seems to us desirable to the point of necessity to abandon our fundamentally frivolous practice of doing-everything-once in space, and then throwing away the means for doing it, or similar things, again later. The Space Shuttle expressed the right idea, albeit in a politically, programmatically and ultimately technically flawed implementation. *In all of America's subsequent major activities in space, we must discipline ourselves to purposefully do base-building, to create and then maintain the infrastructure on which future accomplishments can be more quickly and less expensively built.* Failure to act on this wisdom—which assuredly didn't originate with us—will continue to induce the near-paralysis-of-will which has afflicted the American space enterprise, ever since the collapse of the Apollo Program with the reckless abandonment of the Saturn V launcher technology.

The lunar fuel factory and the mission-staging space station in high Earth orbit are exemplary of this principle. They will be assets of the human race essential to the subsequent rapid and economic manned exploration of the inner solar system. Together, they will enable subsequent manned expeditions anywhere within the orbit of Jupiter at costs of less than \$1 billion each, commencing as often as annually.

Acknowledgments

The present study draws heavily on that of the Columbus Project (LLNL Doc. No. UCRL 93621, November 19, 1985, by the same authors), which acknowledged its indebtedness to Danny Hillis, John McCarthy and Marvin Minsky for a seminal discussion at a meeting of the National Citizens' Advisory Committee On Space, and to Edward Teller. We are also indebted to Prof. Teller in the present context for his long-standing and insistent emphasis on fuelling large interplanetary missions with lunar-derived hydrogen and oxygen in high Earth orbit, as well as for tutoring in advanced nuclear reactor design principles.

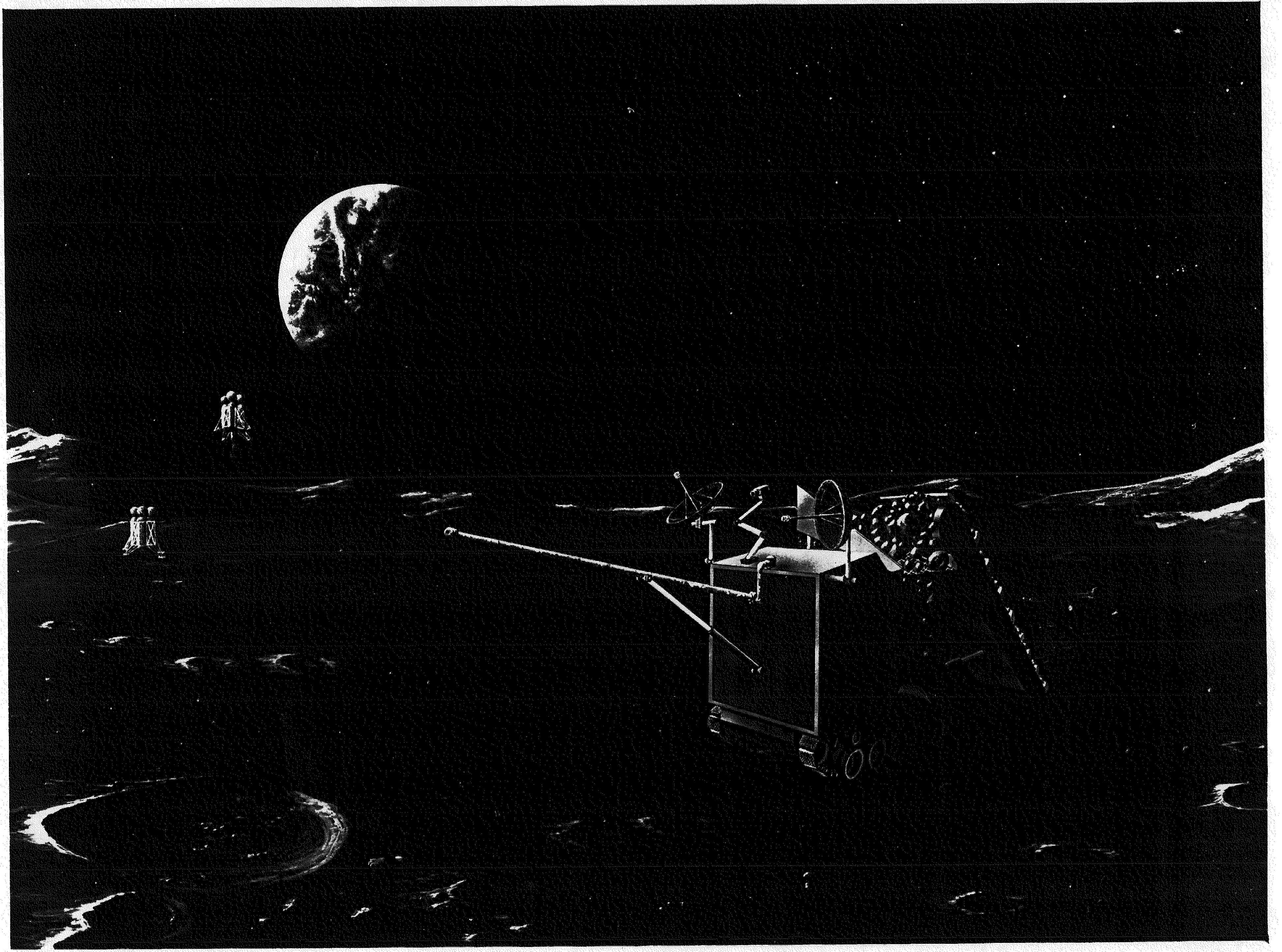

Figure 1

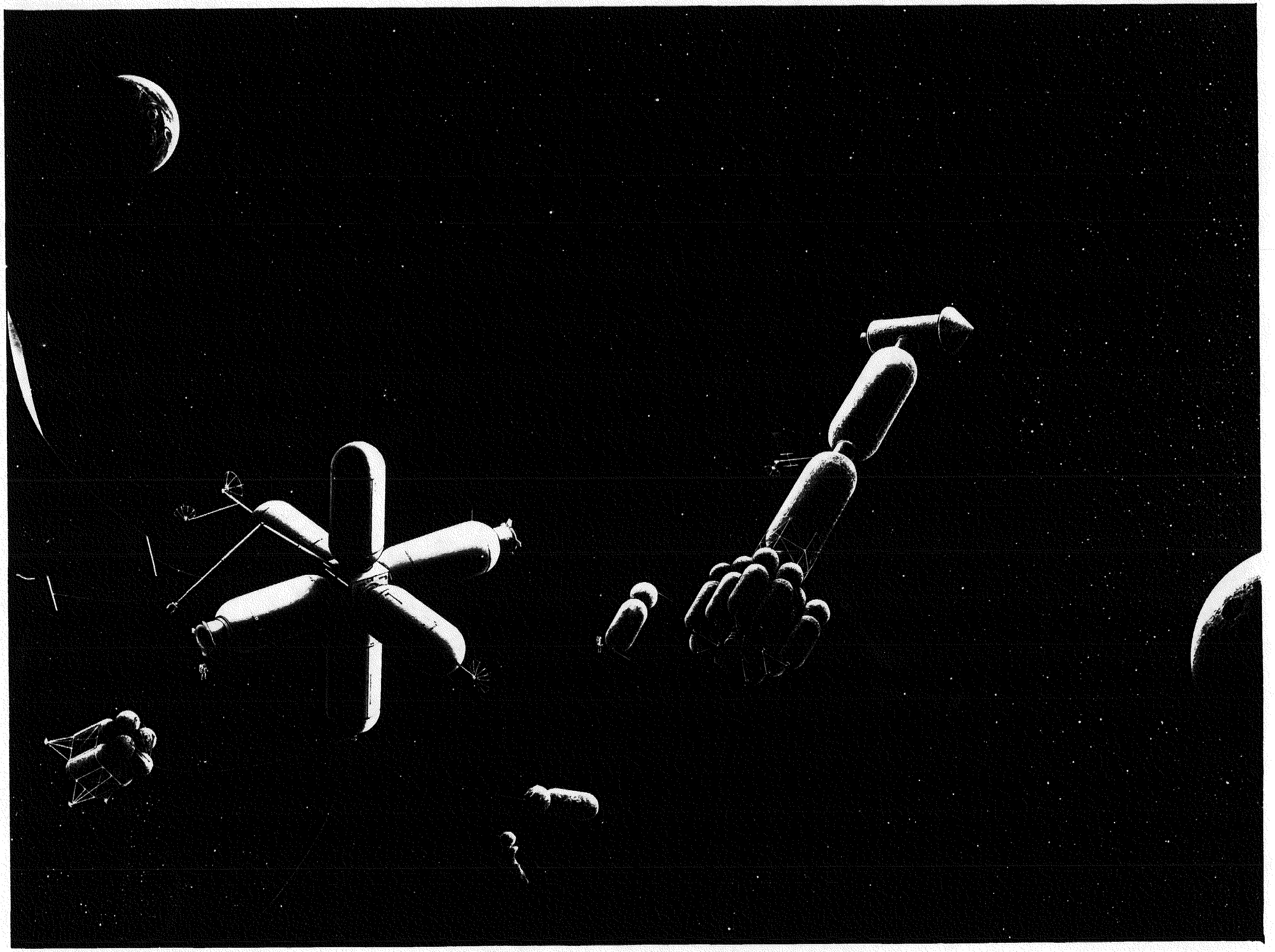

Figure 2

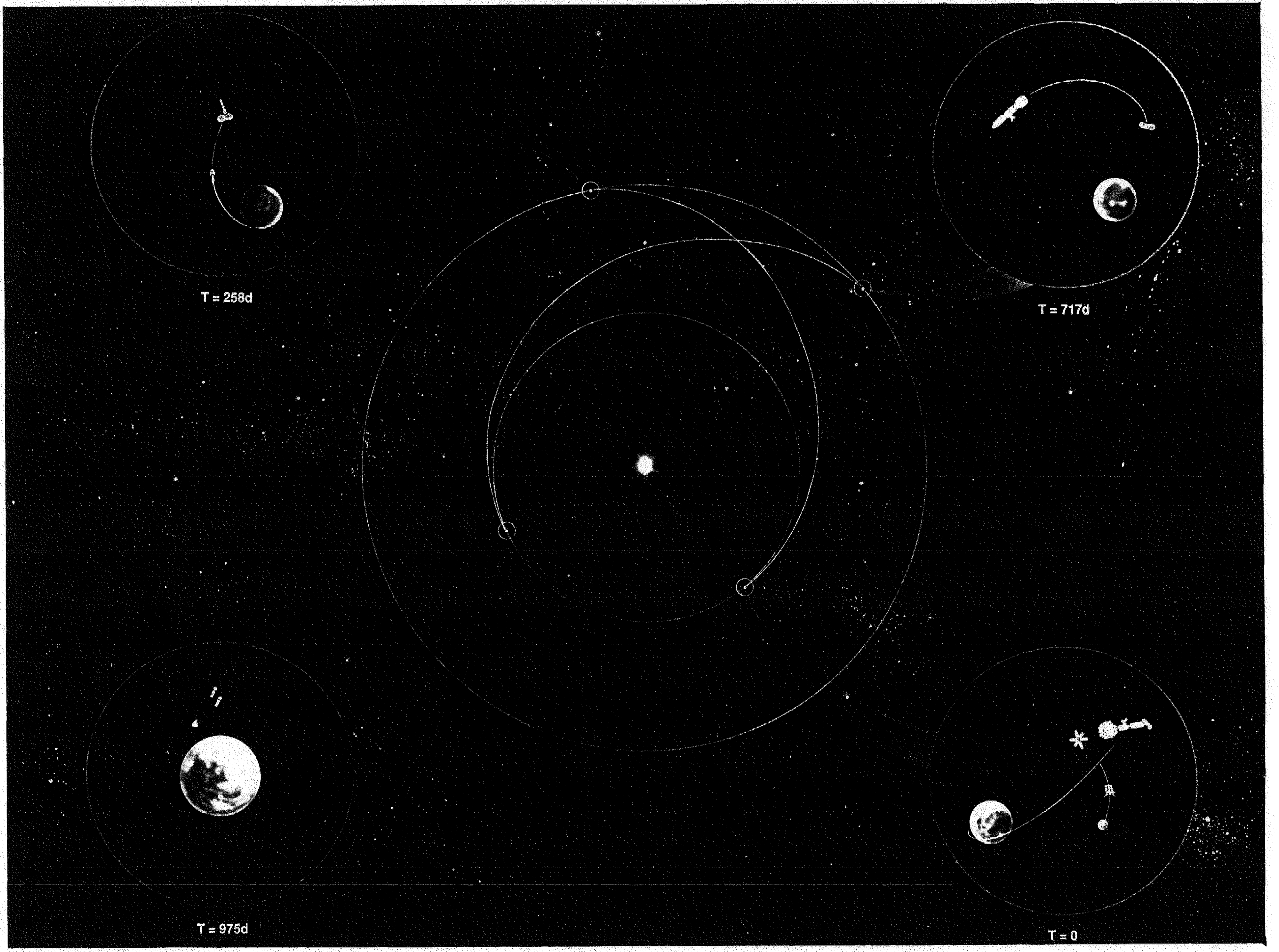

Figure 3

PROJECT BUDGET SUMMARY

(All costs in billions of dollars)

Lunar Fuel Factory		L_4 Staging Station		Mars Mission Vehicle		Project	
0.12	Manpower	0.19	Manpower	0.24	Manpower	0.55	
+ 0.13	S&E	+ 0.18	S&E	+ 0.30	S&E	+ 0.61	
0.25		0.37		0.54		1.16	
+ .08	30% Conting.	+ .11	30% Conting.	+ 0.17	30% Conting.	+ .36	
0.33	Subtotal	0.48		0.71		1.52	
+ 0.3	Launcher NRE					+ 0.3	
+ 0.2	Launcher to LEO	+ 0.2	Launcher to LEO	+ 0.6	Launch to L_4 (3)	+ 1.0	
+ 0.05	Lunar set-down system	+ 0.05	L_4 insertion system	1.31	Total	+ .1	
0.88	Total	0.73	Total			2.92	Total
Operational 4-5 years ARO		Operational 5-6 years ARO		Launch 6-7 years ARO			

Alternate (Direct from LEO)

0.71	Mission vehicle
+ 2.9	Launch to LEO (13)
3.61	Total

TABLE II

MASS BUDGET HISTORY

Leaving LEO for L_4

48T	Mission payload + mission tankage
78T	Propellant + tankage to L_4
126T	

Leaving L_4 for Mars

48T	Mission payload
205T	Propellant
253T	

Mars Transfer Orbit Insertion

124T	Propellant used
120T	Payload inserted
9T	Tankage shed
253T	

Insert in Mars Orbit; Land on Deimos

58T	Propellant used
56T	Payload landed
4T	Tankage shed
2T	Consumables used
120T	

Land On Mars

4.7T	Propellant + tankage used
	(Aerobraking)

Mars–Landed Package

1.0T	Crew (5) + gear
1.0T	Ascent module
8.0T	Ascent module propellant
2.1T	Life support gear
1.5T	Powerplant
2.4T	Food (460 d)
3.0T	Habitation modules (3)
1.0T	Cars (2)
3.6T	Misc. gear
4.7T	Lander
28.3T	

Mars Ascent Package

1.0T	Crew + samples
1.0T	Ascent module
8.0T	Propellant & tankage
10.0T	

Earth Transfer Orbit Insertion

12.5	Propellant + tankage used
11.4T	Payload inserted
–1.4T	Consumables used
10.0T	

Earth Return Package

2.0T	Habitation modules (2)
2.1T	Life support gear
0.3T	Power plant
0.2T	Fuel cells
0.4T	RL–10 engines
5.0T	
1.0T	Crew (5) + gear
0.5T	Martian samples
3.5T	Reentry vehicle
5.0T	
10.0T	

TABLE I