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Interplanetary Exploration and Settlement Using The Phoenix Launch Vehicle

The exploration and settlement of the moon and Mars is currently considered a distant dream by the mainstream American space effort. It doesn't have to be. This article describes how a low-cost, reusable, single-stage-to-orbit (SSTO) launch vehicle, the Pacific American Launch Systems' Phoenix, could make lunar settlement and Mars exploration feasible in the short term and for a fraction of the cost of methods currently under consideration.

The Phoenix launch vehicle has been described in detail in past issues of the *C.S.R.* (last month's issue, for example). Briefly, the Phoenix is a vertical-takeoff-and-landing launch vehicle, capable of delivering 19,500 lbs. of crew or cargo into low earth orbit (LEO). The Phoenix can provide a payload with a 30,000 ft/sec velocity change (delta-V). The propellants are liquid oxygen and liquid hydrogen burned at a high average oxidizer/fuel mixture ratio. The Phoenix can be built using existing technology (see "A Single Stage To Orbit Thought Experiment" on page 5), but its payload can be increased further using more advanced propulsion methods and structures.

Two outstanding features of the Phoenix concept are its capacity for orbital refueling and its water-cooled heat shield design.

The ability of the Phoenix to be refueled in orbit is the key to performing many of its most ambitious missions. Once fully refueled in low earth orbit, the Phoenix could then deliver its 19,500 lb. cargo weight to a high geostationary orbit, onto an interplanetary trajectory, or to a soft landing on the surface of the moon (once on the moon, the Phoenix would still have sufficient propellant remaining to return another 19,500 lbs. to LEO or to a landing on the Earth).

For lunar and interplanetary operations requiring many refueling operations, a cryogenic propellant depot for Phoenix vehicles would be deployed in low earth orbit. This would decouple the scheduling of refueling from the lunar or interplanetary transit flight departure times. Also, the surface to mass ratio of a large depot reduces boil-off of propellants. Several fuel depots in orbit would allow more frequent refueling flights from Earth. To remove the mechanical heat introduced into the cryogens by fuel transfers, or to aid in reducing boil-off, radiators, refrigerators and pumps will be needed. These could be powered by solar cells or by burning part of the cryogens for power generation.

The tanks needed for the depot could be Phoenix mainstage propellant tanks clustered around a docking module. The added mass of refrigerators, pumps, batteries, solar arrays and the like would probably be less than 10,000 lbs. Given a Phoenix empty weight of about 30,000 lbs, a depot storing about 8 lunar flights worth of fuel would weigh about (4 x 30,000) + 10,000 = 130,000 lbs. This could be launched in about 7 flights.

In the Moon and Mars Phoenix missions described below, all orbital braking and reentry operations around Earth or Mars are assumed to use aerobraking procedures. Aerobraking is the entry of a space vehicle into the outer layers of a planetary atmosphere to reduce the vehicle's velocity. This reduction in velocity enables the spacecraft to either reenter the planet's atmosphere for landing, or to brake into an orbit around a

> This article is based on two papers: "A Single- Stage Vertical Takeoff and Landing Space Transport for Lunar Settlement Establishment and Resupply," by PacAm president Gary C. Hudson and Dr. Michael Hyson (presented at the 2nd Lunar Bases and Space Activities of the 21st Century Conference in Houston, April 5-7, 1988), and "Employing A Chemical Rocket VTOVL/SSTO for High Velocity Mars Round Trip Travel," by Gary Hudson (presented at the AIAA 24th Joint Propulsion Conference and Exhibit in Boston, July 11-13, 1988).

target planet (a process called "aerocapture"). Aerobraking can save enormous quantities of propellant compared with unassisted rocket braking to accomplish the same goals (not only does an aerobraking vehicle avoid carrying the propellant for the rocket braking maneuvers, it also avoids carrying whatever propellant would have been required to haul the braking propellant all the way to the target planet!)

The Phoenix is protected from structural heating during atmospheric entry by active water cooling, which greatly facilitates the use of aerobraking procedures. The water cooling is accomplished by the transpiration of water from storage tanks through perforations in the outer skin. This concept, using a single heat shield design, permits reentry at a wide range of orbital or escape velocities simply by varying the water mass flow rate (water flow rate is determined only by water tank pressure and total volume can be adjusted precisely for each heating case). Active cooling permits the Phoenix to use aerobraking for interplanetary missions, such as the Mars mission, which requires very high velocity aerobraking captures at both Mars and earth. The mass of water required is typically a few thousand pounds, far less than the propellant that would be required for rocket braking.

Phoenix Cost Estimates:

Pacific American has done a number of studies to analyze the cost of developing, building, and operating a fleet of Phoenix launch vehicles. **Table 1** on pages 3 and 4 consists of excerpts from an expansive spreadsheet program designed to help in this analysis. The table shows estimated cost figures for Phoenix operations, with one column showing numbers based on low-cost assumptions, and the other column based on more conservative assumptions. Following are details on how some of these cost numbers were arrived at:

Development Costs: Pacific American has estimated that the total development of the Phoenix vehicle could be completed over a 3-5 year period for under $300 million dollars, *less than the recurring cost of a single Space Shuttle launch.* This estimate has been controversial, even in the face of evidence to support the assertion (the SR-71 "Blackbird" advanced aircraft cost $165 million to develop in 1962, and represents a more difficult technical development effort than a simple aluminum ballistic single-staged launch vehicle). Therefore, PacAm has also stipulated a higher, more conservative development cost of $655 million based on a Lockheed-sponsored internal study in 1987. **Table 1** contains estimates based on both figures, as well as on similar variations in per/vehicle costs and the number of vehicles built.

Vehicle Operational Lifetime: Pacific American has estimated that the Phoenix launch vehicles may have a useful lifetime of up to 1000 missions, an estimate supported by calculations involving propellant tank thermal cycles, combustion chamber thermal cycles, cryogenic pump lifetimes, and airframe life. However, PacAm is again allowing for a more conservative 500 flights per vehicle (in either case, it is likely that as a Phoenix vehicle ages, it would be delegated to perform less critical tasks, such as unmanned fuel tanker missions and the like).

Operations Costs: Operations costs were based on figures taken from advanced high speed aircraft operations, and are based on the number of support personnel required as well as launch site costs. A fleet of about 8 SR-71 advanced aircraft operates about 400 flights per year with a crew of about 48 support personnel per aircraft and a burdened cost per man of $130,000 per year. PacAm estimates on the number of ground personnel required to fly the Phoenix range from 10 for the low cost case to 25 for the more conservative case. PacAm also estimates that, with reasonable turnaround times, each vehicle could easily fly at least once a week (the more pessimistic estimate of about once a month is shown in the "conservative" column of the table).

Table 1 shows a cost per pound to low earth orbit of about $52, and a cost per pound to the lunar surface of a little over $570.00--and this is using the more conservative set of assumptions. Still, the extreme sensitivity of the delivered cost per pound is illustrated by the wide range in the calculated costs. Clearly, to keep costs down, extra effort must be made to achieve low manufacturing costs, reasonable reuse rates, and low ground operations costs if we are to meet the objective of extending human settlement into the solar system.

Lunar Settlement Using the Phoenix

An inexpensive and reliable space means to transport cargo and personnel to and from lunar settlements is the key to lunar exploration in the twenty-first century. The use of the Phoenix launch system as this means of transportation presents a number of advantages:

Since the Phoenix launches and lands vertically using rocket braking, it could be used for lunar landing missions without modification. Utilization of a single low cost transportation system for all phases of the lunar base project reduces development time and cost. One vehicle used in many modes allows one to have a larger fleet size and more trips per vehicle as opposed to using fewer flights of several specialized vehicles. Since there is only one vehicle, operators can achieve high flight rates and lower costs quickly. Large fleet sizes, number of flights and experience minimize the number of personnel per flight needed for operations. These advantages far outweigh the raw propulsion advantage that might be gained with specialized orbital transfer vehicles and the like.

PacAm's costing of the lunar settlement uses analogies based on existing hardware, in particular undersea habitats, and on existing resupply requirements based on figures for bases in Antarctica. The numbers based on these analogies are shown in the second part of **Table 1**.

Surprisingly to some, using undersea habitats as a guideline tends to result in lunar habitats that are highly overqualified for their mission requirements. For example, undersea bases must deal with the problems of high pressure, water, corrosion, dirt and weather. In addition, underwater structural loads are large and primarily compressive. By contrast, the maximum pressure differential of space habitats is 14 lbs/in^2 with the loads primarily tensile. While heat rejection is a problem in space, overall, the space and lunar environments seem more benign than the sea. Therefore, PacAm's costs and weights certainly *overestimate* costs for comparable facilities.

William Busch designed an undersea habitat called Aquarius. It is a cylinder 9 feet in diameter and 42 feet long and supports 6 people for 30 days. It has double locks for locking people in or out without changing the internal pressure. The hatches are designed for positive or negative pressure and can open either direction. Internal sliding doors allow isolation of different sections, again, so decompression can be performed without altering pressure in the entire structure.

Aquarius displaces 448 tons and weighs 75 tons. Half of this weight is a support structure that ties it to the bottom of the sea. Therefore, 37.5 tons was taken as the weight of the pressure vessel, or about 6.25 tons per crew member. **Table 1** assumes that the lunar habitat's pressure vessel or vessels would weigh the same amount for each of 12 crew members, or about 75 tons in all. This assumption results in a structure which is over-designed for a lunar application by a factor of about six (the cost of the lunar habitat pressure vessels is also assumed to be the same per pound as the cost of the Aquarius pressure vessels--about $57).

Following are details on some of the factors important to the establishment and maintenance of a lunar settlement:

Survey Flights. So much is known of the moon that a few flights to survey the prospective sites will probably be all the new exploration required. The Phoenix can literally hover a few feet over potential sites and abort if the terrain is too rough or if other problems arise.

Settlement Site. The arguments for a polar site are compelling: there are areas at the lunar poles where the sun is always visible near the horizon, providing for continuous solar power. Conversely, there are also areas of perpetual shadow, which may contain volatile deposits. Most importantly, one can launch at almost any time to the lunar pole by performing a plane change at the L1 point. A lunar equatorial settlement is not ruled out by this procedure--low-cost transshipment of supplies can be done through sub-orbital flights or by land transport.

Mass and Crew per Settlement. The Phoenix can soft land nearly 20,000 lbs on the lunar surface after refueling in LEO. Taking the underwater habitat Aquarius as a model, and adding a solar power plant, one must land about 81 tons for the settlement structure. Assuming a minimal settlement of 12 people as an initial crew, and using the tonnages routinely supplied to the United States Antarctica base as a model, some 20 tons per crew per year are needed as resupply. If this proves generous, this rate of supply could mean a fast growing settlement, otherwise the figure represents a completely open-loop environmental system, without any recycling.

Habitat. Housing would be provided by 8 approximately 20 ft. diameter by 20 ft. high cylindrical modules weighing about 10 tons each. These would be launched by the Phoenix to LEO. After orbital refueling, the modules would be soft landed on the moon. Radiation protection would be provided by 2-4 meters of lunar soil, by burying the initial base modules.

Life Support. The hydrogen and oxygen remaining in the Phoenix tanks above that needed for return to

TEXT CONTINUED ON PAGE 8

TABLE 1.		
Phoenix Transport and Lunar Base Costs		
	LOW COST	CONSERVATIVE
Propellant Cost/Flight or Propellant Cost To Fully Refuel For Lunar Return With Payload:		
Propellant Weight (Full Tanks)	415,000 lb.	415,000 lb.
Mix Ratio	10.5	10.5
Weight: Liquid Oxygen (LOX)	378,913 lb.	378,913 lb.
Weight: Liquid Hydrogen (LH)	36,087 lb.	36,087 lb.
Total Propellant Weight	415,000 lb.	415,000 lb.
Cost LOX	$0.05 lb.	$0.05 lb.
Cost LH	$1.80 lb.	$1.80 lb.
Cost LOX/Flight	$18,946	$18,946
Cost LH/Flight	$64,957	$64,957
Propellant Cost	**$83,902**	**$83,902**
Propellant Cost To Refuel For Lunar Return Empty:		
Propellant Weight (Offloaded For Luna Empty Return)	192,448 lb.	192,448 lb.
Mix Ratio	10.5	10.5
Weight: LOX	175,713 lb.	175,713 lb.
Weight: LH	16,735 lb.	16,735 lb.
Total Propellant Weight	192,448 lb.	192,448 lb.
Cost LOX	$0.05 lb.	$0.05 lb.
Cost LH	$1.80 lb.	$1.80 lb.
Cost LOX/Flight	$8,786	$8,786
Cost LH/Flight	$30,122	$30,122
Propellant Cost	**$38,908**	**$38,908**
Phoenix Payload Weight	19,500 lb.	19,500 lb.
Number Of Tanker Flights Required to Refuel:		
Complete Refueling For Lunar Full Return	22	22
Offloaded For Luna Empty Return	10	10
Amortization of Development Costs and Vehicle Costs:		
Phoenix Vehicle Operational Lifetime (No. of Flights)	1000	500
Phoenix Fleet Size	50	25
Development Cost	$250,000,000	$655,000,000
Price/Vehicle	$25,000,000	$100,000,000
Development Cost Amortization/Flight	$5,000	$52,400
Vehicle Cost Amortization/Flight	$25,000	$200,000
Cost of Operations:		
Baseline Example: SR-71 Advanced Aircraft		
Number of Aircraft	8	8
Support Personnel/Aircraft	48	48
Flights/Year/Aircraft	50	50
Cost/Man Year	$130,000	$130,000
Cost of Support Personnel/Flight	$124,800	$124,800
Site Cost	$5,000,000	$10,000,000
Site Cost/Flight	$12,500	$25,000
Phoenix:		
Phoenix Flights/Year/Vehicle	50	10
Phoenix Support Personnel/Vehicle	10	25
Cost/Man Year	$130,000	$130,000
Cost of Support Personnel/Phoenix Flight	$26,000	$325,000
Site Cost/Flight	$12,500	$25,000
Added Management Cost %	50%	100%
Added Support Cost/Flt	$13,000	$325,000
Phoenix Cost of Operations/ Flight	**$51,500**	**$675,000**
Total Cost/Flight	**$165,402**	**$1,011,302**
Cost/lb to Low Earth Orbit	**$8.48**	**$51.86**

		LOW COST	CONSERVATIVE
Transport Cost of Lunar Missions (Cost of Initial			
Flight Plus Cost of LEO Refueling Flights):			
Cost of Lunar Flight (Return With Full Payload)		**$3,804,250**	**$23,259,950**
Cost/Pound		**$195**	**$1,193**
Cost of Lunar Flight (Return Empty)		**$1,819,424**	**$11,124,324**
Cost/Pound		**$93**	**$570**
LUNAR BASE			
Baseline: Aquarius Underwater Habitat:			
Aquarius Base Cost		$4,300,000	$4,300,000
People/Habitat		6	6
Aquarius Wt(habitat+ tie-down)		75 tons	75 tons
Aquarius Wt(pressure vessel)		37.5 tons	37.5 tons
Aquarius Cost/lb. (Discounting Tie-Down)		$57	$57
Lunar Habitat Estimates:			
Number of Crew Members		12	12
Lunar Habitat Initial Weight		75 tons	75 tons
Maximum Habituat Unit Weight = Phoenix Payload		9.8 tons	9.8 tons
Number of Units		8	8
Space Station Electric Power (6 crew members)		50 kw	50 kw
Power/Space Station Crew Member		8.33 kw	8.33 kw
Power/Lunar Habitat Crew Member (10 * Space Station)		83 kw	83 kw
Total Lunar Base Power Needed		1000 kw	1000 kw
Watts/kg Solar Plant		190	190
Weight of Lunar Base Power Plant		6 tons	6 tons
Total Weight of Lunar Base		81 tons	81 tons
Phoenix Flights Required To Install Lunar Base		9	9
Settlement Habitat Costs:			
Cost/lb.		$57	$57
Cost/Base		$9,263,860	$9,263,860
Transport of Base		$15,075,928	$92,177,259
Cost of Installed Base		**$24,339,788**	**$101,441,119**
Resupply Costs:			
Baseline: Antarctic Base Resupply			
Average Number of People at Antarctic Base		2500	2500
Annual Resupply Antarctic Base		50,000 tons	50,000 tons
Tons/Crew Member/Year		20 tons	20 tons
Lunar Base Resupply:			
Phoenix Flights/Crew Member/Year		3	3
Phoenix Resupply Flights/Year/Base		36	36
Annual Cost Resupply and Rotate/Base		**$65,499,261**	**$400,475,661**
Lunar Settlement for One Year:			
Cost of Base + Resupply		**$89,839,049**	**$501,916,779**

A SINGLE-STAGE TO ORBIT THOUGHT EXPERIMENT

from a white paper by Gary C. Hudson

Since the first proposals for single-stage-to-orbit (SSTO) launch vehicles in the late 1940's, the chief criticism of the concept has remained the need for high mass fractions (ratio of propellant weight to loaded weight less payload) required for the concepts to be practical. Whether reusable or expendable, in many critics' minds the impossibility of SSTO remains tied to this issue. The purpose of this article is to dispel the concern over the issue of mass fraction, by means of a thought experiment:

Can any combination of existing or historical hardware, for which we know the precise weights and performance, be combined in a manner to yield a positive payload in low earth orbit in a single stage configuration?

The two systems which we will review are based upon two flown stages. The first concept employs the Saturn S-IVB stage, while the second uses the Shuttle External Tank (ET). In both cases we will baseline the Space Shuttle Main Engine (SSME) as the powerplant (even though higher performance could be achieved with a "clean-sheet" engine design).

Table 2 shows the relative characteristics of both the S-IVB and the ET SSTOs. Reference (1) was used to compile S-IVB data and Reference (2) was used for the ET.

S-IVB SSTO: The S-IVB was designed by the Douglas Aircraft Company in the early 1960's. At the time it was the largest liquid oxygen-liquid hydrogen stage available (it was later overshadowed by the five-times-larger S-II, the second stage of the Saturn V). The S-IVB was used for ten years, as both the second stage of the Saturn IB and the third stage of the Saturn V. In both applications the stage was subjected to far greater loads than it would see in our SSTO application (it should also be noted that the technology in this stage is now nearly thirty years old).

An S-IVB SSTO would be capable of placing about 10,000 pounds payload through a velocity increment of 30,000 feet per second. If the velocity requirement could be lowered to 29,300 ft (typical of a launch from the Cape), the increase in payload could be about 2,200 additional pounds (the weight of a payload fairing and support hardware must be subtracted from this number to obtain true capability).

Work by Phillip Bono in the 1960s (Reference 3) suggested that an S-IVB could be recovered at a penalty of 6,500 pounds. This would suggest that a primitive, but reusable SSTO could be built which would have a payload in the few thousand pound range, using twenty-year-old structural and propulsion technology.

SHUTTLE ET SSTO: A single-stage could also be made out of the Shuttle External Tank by the addition of six SSMEs and a thrust structure to transfer the loads of the engines into the barrel of the tank. To cover this, a generous 30,000 pounds was allotted to the thrust structure weight budget in Table 1. No deletion of unnecessary hardware (such as the SRB load carry-through structure, the orbiter attach brackets, or the tank reinforcing beams) was postulated (a weight savings of at least 10,000 pounds could be made here if desired.) Even so, a payload in the 60,000 pound class could be orbited in the expendable single-stage mode. Again, with a lower target for total velocity change, an additional 12,000 pounds of payload could be obtained.

NASA and the U.S. Air Force are working on designs for advanced, heavy-lift launch vehicles with payloads into low earth orbit of up to 200,000 lbs. Nearly half of this payload could be achieved without spending a dime on new technology. Wise use of newer engines (with high thrust-to-weight ratios, altitude compensating nozzles, high oxidizer/fuel mixture ratios or dual fuel), and modern structures could bring the payload to over 100,000 pounds at little risk, and in a phased developmental program. Recovery of the engines from orbit might reduce operating costs to an affordable level.

We have shown that off-the-shelf (or out-of-the-museum) flight-proven aerospace components can be combined to conclusively demonstrate the feasibility of SSTO. The addition of a dash of innovation, combined with the remarkable advances in the state-of-the-art of materials, propulsion and avionics technology which have occurred since the S-IVB, Shuttle ET and SSME were designed, would strongly suggest that a fully reusable, durable, and inexpensive SSTO could be fashioned without breakthroughs or further technology programs.

No one is proposing that either of the conceptual vehicles discussed above actually be built. Rather, this thought experiment suggests that a sensible and low-risk program be initiated to explore the limits of present technology before spending vast sums on unproven or speculative programs.

The nation faces a crisis in space transportation in part due to the desire of some to freeze out new ideas which do not require large programs with attendant high costs and manpower requirements. If we are to solve our space transport problems, we must return to doing what we do best: building hardware.

TABLE 2: Data for SSTO versions of the S-IVB and the Shuttle ET

	S-IVB	Shuttle ET
Gross Lift-off Weight (lbs.)	330,885	1,826,096
Number of SSME(s)	1	6
Specific Impulse (average)	425	425
Propellant Volume (cubic feet)	13,254	73,081
Average Prop. Density (lbs./cu. ft.)	22.2*	22.2
Propellant Weight (lbs.) at 6:1 mix ratio	294,000	1,622,532
Thrust/Weight at liftoff (109% engine power level)	1.24	1.34
Mass Fraction	0.92	0.92
Delta-V (feet/second)	30,000	30,000
Mass Ratio	8.971	8.971
Injected weight (lbs.)	36,885	203,564
Empty Weight Profile (lbs.):		
Basic vehicle	22,300	68,000
SSME(s)	+3,000**	42,000
Thrust Structure	NA	30,000
Residuals (0.25% as achieved by S-IVB)	725	4,000
Avionics	500	500
Total:	26,525	144,500
Payload (injected wt. - empty wt.)***	**10,360**	**59,064**

* assumes 5.5:1 mix ratio is changed to 6:1 ratio without increasing tank volume, i.e., a floating bulkhead.
** The SSME weighs 3000 lbs. more than the J-2 engine normally used on the S-IVB.
*** any fairing weight and payload support provisions must be deleted from these numbers.

REFERENCES:

(1) Osterhout, W. L., "Saturn Data Summary Handbook." Douglas Missile and Space Systems Division (date unknown).

(2) _______, "Space Shuttle External Tank System Definition Handbook, Volume 1, Configuration & Operation." Martin-Marietta, Michoud; April, 1983.

(3) Bono, Phillip, et alia; "The Saturn S-IVB as a Test-Bed for Booster Recovery." Douglas Eng. Paper 3808, presented at the 6th European Symposium on Space Technology, May 23-25, 1966, Brighton, England.

earth can be used as the first source of extra water. PacAm analysis of the cost of manufacturing oxygen on the moon and shipping it to LEO by rocket propulsive means indicates that it is not cost-effective compared to simply flying it into earth orbit on a Phoenix. However, anything produced on the lunar surface could be valued at anywhere from $93 to $570 per pound (the cost of resupply from Earth according to **Table 1**). An oxygen plant *for lunar consumption* could pay for itself and its transport in a matter of months. However, for this study PacAm has assumed a more or less open ecology where there is complete resupply and complete rotation of the crew every 3 months.

Power Generation. Initial power generation is a major consideration, since the first lunar night must be survived by the lunar settlers as did the colonists at Plymouth Rock who had to survive the first winter. Nuclear power systems would be practical and effective, but would require a major investment in new technology. Amorphous silicon solar cells based on existing systems could provide power, and hydrogen and oxygen could provide storage (fuel cells and heaters could use the hydrogen and oxygen directly, or a combined Rankine and Sterling cycle might be used to power generators). Again, residual oxygen and hydrogen from the Phoenix could be used to meet initial power needs.

Lunar Settlement Cost Estimates:

Preliminary scheduling of production of vehicles and launch operations suggests that the settlement can be installed with about 150 flights over about a year and a half. At the end of this period, some 20 Phoenix vehicles are in use. Therefore, with 20 vehicles, only about 8 flights of each vehicle will have been flown. Using the conservative Lockheed development estimate of $655 million and the per/vehicle price of $100 million, the total capital cost for the lunar fleet and development combined is about $2.7 billion.

Using orbital refueling, the cost per pound to the moon comes out to about $570 per pound for the conservative case. Based on **Table 1**, a Phoenix fleet could place a 12 person settlement on the moon in two years from the start of launches for an estimated cost of about $100 million. The cost of complete crew rotation every 3 months and with generous resupply of 20 tons/year/crew would be about $400 million per year. Therefore, the Lunar settlement would cost only about $500 million to install and operate for year one--not a trivial amount of money to be sure, but considerably less than the numbers that have been tossed out by NASA and others.

Given these parameters, the price of a lunar settlement is not prohibitive, and is even within the reach of private sources of capital, avoiding the complications of either government subsidies or international cooperative funding. With the Phoenix, even the use of industrial ocean-engineering technology would permit the rapid establishment of lunar settlements before the turn of the century.

A Phoenix Mission to Mars

The Phoenix launch vehicle, refueled in low earth orbit, could make a one-way transit to Mars in less than 130 days, and potentially in as few as 90 days. It should be possible to accomplish a round trip mission to Mars, with stay times of ten to forty-five days, solely through the use of chemical propulsion, and with a total mission time of about one year. The Phoenix flight trajectory would require the use of aerobraking at Mars and Earth, plus the use of refueling at Phobos using tankers sent to Mars at an earlier date. The Phoenix could also be used to sortie to and from the Martian surface.

Mission Description:

The vehicles used in this mission consist of two Phoenix E (for Excursion)-class SSTO launch vehicles, as well as two specially-designed Propellant Precursor Tankers (PPTs) and a Logistics/Power Module (LPM) for each set of Mars-bound excursion vehicles (these systems are illustrated in **Figures 1** and **2** on the opposite page).

The proposed reference mission is shown in **Figure 3**. First, the PPTs are launched into LEO as empty payloads aboard cargo versions of the Phoenix (Phoenix C). They are then refueled by Phoenix tankers and dispatched on the Mars transfer orbit. After reaching the planet, they are aerobraked and then circularized at Phobos, where they stationkeep with the Martian moon.

Second, the two Phoenix E (for excursion) SSTOs must be refueled in LEO. They are then launched on a high velocity transit to Mars, where they arrive about 128 days later. During the flight, the vehicles are docked to and are connected by a retractable "astromast"-type open tube with a foldout solar array. They are then rotated

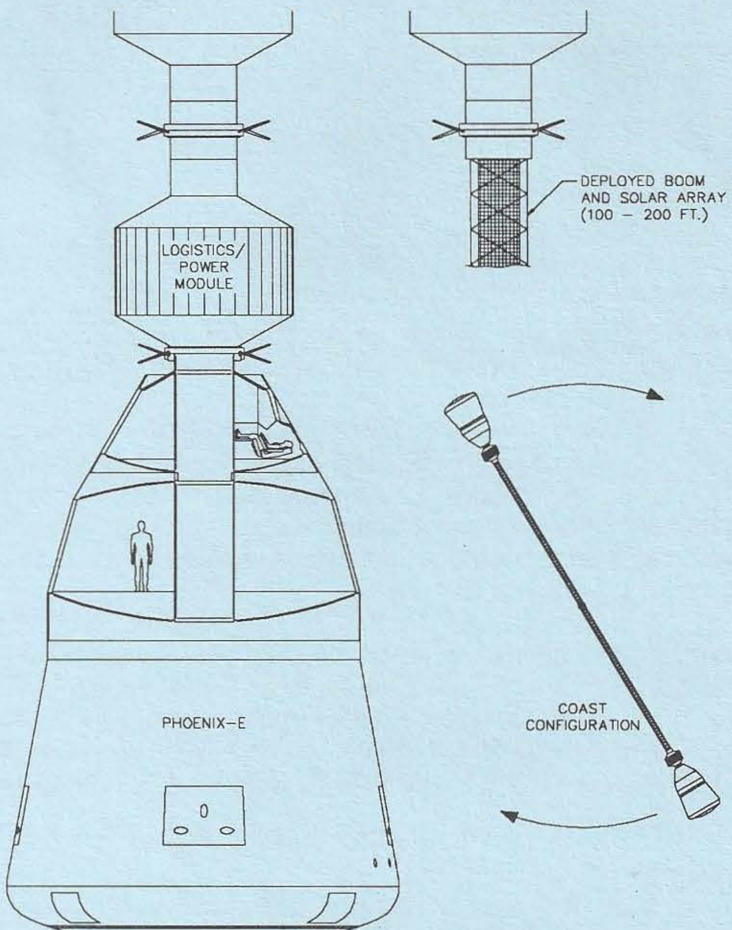


FIGURE 1. PHOENIX–E IN MARS MISSION CONFIGURATION

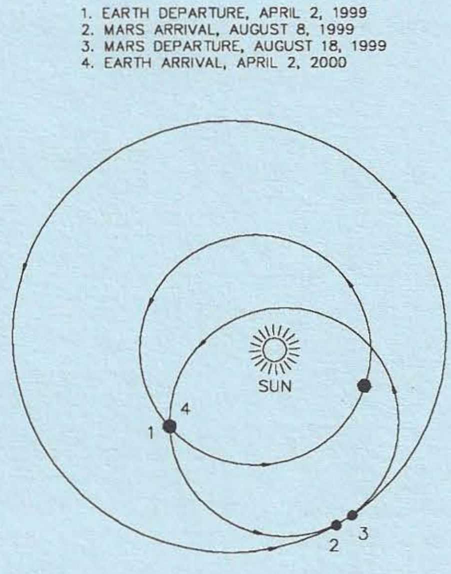
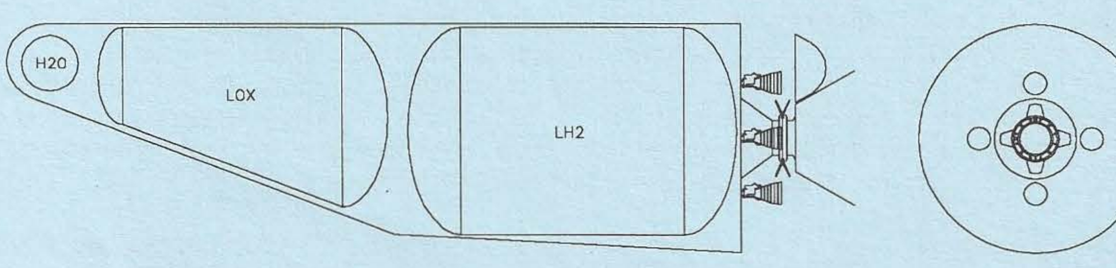


FIGURE 3. MARS REFERENCE MISSION



GLOW (IN LEO):	1,050,000 LBS.
Isp:	450 sec.
PROPULSION:	UPRATED RL–10 (4)
PROP. AT PHOBOS:	400,000 LBS.
EMPTY WT.:	25,000 LBS.
REFUELING FLTS.:	~50

FIGURE 3. PROPELLANT PRECURSOR TANKER

about their common center of mass to generate centrifugal acceleration to mimic gravity for the crew. After circularizing at Phobos, and taking on propellant from the tankers, one vehicle may sortie to the Martian surface for a short stay. After a week to ten days, they perform a final refueling and depart for the transit to earth, aerobraking at earth exactly one year after launch.[1]

The delta-v requirements for this mission are shown in the table below:

Maneuver	ft/sec
Earth orbit departure	23,150
Mars/Phobos circularization	1,867
Mars/Phobos departure	1,867

The Phoenix SSTO can easily provide the delta-v required for both the outbound and inbound legs of the mission. A total of 25,017 ft/sec will be required outbound to permit the Phoenix to circularize at Phobos and rendezvous with pre-positioned stocks of propellant.

Extended stays at Mars might be accomplished by providing more delta-v at earth orbit injection to Mars transfer orbit. This could be performed by using one Phoenix to boost another fully loaded vehicle up to about 7,874 ft/sec before the '"booster" detaches and returns to LEO via an aerobraking maneuver. Significantly higher Mars aerobraking velocities are the result of such an approach, but travel time can be reduced by as much as 30 days outbound, leading to stays at Mars of up to 45 days.

To establish a long-term presence at Phobos with propellant production capability will require that future missions employ the airframe of the PPT as a cargo vehicle. By substituting smaller tanks for the standard cryogenic vessels, it should be possible to transfer up to 400,000 pounds of cargo (for example, a propellant production facility) to Phobos rendezvous. The PPT might also be boosted by means of a nuclear electric tug, since the time to accomplish the transfer is not as important in the case of an unmanned vehicle compared with one which is manned.

Required Technologies and Areas of Development:

Several challenges must be faced prior to realization of the proposed Mars mission scenario. These include the development of the Phoenix Mars excursion configuration and the expendable PPT, perfection of the aerobraking routine using water-cooled heat shields, thermal control of long-duration cryogenic storage vessels, and the means by which artificial gravity may be generated by two rotating transit ships.

Phoenix Mars Excursion vehicle development: The Phoenix E-class launch vehicles will first be developed for use in missions throughout cislunar space and from earth surface to orbit. Accordingly, the additional development necessary for the reference Mars mission is limited to modifications for long term operation, especially with regard to cryogenic propellant storage.

LPM development: The Mars mission calls for the development of a Logistics/Power Module. Each Phoenix-ME would be docked to one of these modules, which would then join the twin vehicles together during coast. The LPM would contain a logistical storage area, power conditioning equipment, and a radiation shelter to protect the crew from solar flares. The fold-out solar arrays and the astromast would also be deployed from the LPM. Use of LPMs, rather than extensively modifying existing Phoenix-E vehicles, permits most of the important functions unique to the Mars mission to be developed as part of a separate component.

PPT development: The tanker development effort will involve design and qualification of a bent biconic airframe, cryogenic propellant tankage and propulsion systems. The chosen propulsion system is the uprated RL10 rocket engine, though other available engines in this class might be employed. Like the Phoenix, the PPT uses a lightweight airframe which employs water cooling.

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1. The trajectory for this mission was derived from a flyby trajectory discussed in a paper titled "Mars Mission Concepts and Opportunities" by A. Young, which appeared in *Manned Mars Missions, Working Group Papers, Vol 1.*, NASA M002, June 1986).

Aerobraking: The Mars mission requires aerobraking velocities in both the Martian and earth atmospheres significantly higher than those required for Lunar missions. Fortunately, the technology of the water-cooled heat shield is capable of handling the increased thermal flux by means of an increase in water flow.

The Phoenix SSTO has an L/D ratio of about 0.5, which is marginally adequate for the aerobraking task at the velocities of interest. However, it may be possible to reduce drag on the vehicle, thus improving the L/D ratio, by expelling hot gas from the vehicle's aerospike engine which can be run at tank head idle thrust. The reduction in drag may moderate g-loading during the entries, which otherwise can run as high as 5-6 g.

One major concern about aerobraking is the variability of the upper atmosphere at both Mars and earth. Earth atmosphere information may be obtained from local weather satellites equipped with microwave and laser sounders. Mars data could be provided by equivalent sensors aboard the PPTs or through the use of a small probe which is launched from the SSTO ship a few hours prior to atmospheric entry. The probe path information could then be used to make last minute changes in the aerobraking routine.

Thermal Control of Cryogenic Vessels. The storage of cryogens for long durations (over a year) is a necessary technology for the practical application of the Mars mission. PacAm expects that relatively conventional multilayer insulation plus a solar-array powered refrigeration system could provide a low or no-loss cryogenic tank system for use at Phobos. It is possible that the development of the low-earth-orbit propellant storage depot mentioned earlier will address many of these same questions, and the technology developed for that application could be applied to the PPT.

Artificial Gravity. Information obtained to date on human exposure to microgravity indicates that it will almost certainly be necessary to supply artificial gravity for the crew members of any Mars transit ship, especially one that will aerobrake (with associated g-loads) at the conclusion of a long flight. The magnitude of the simulated gravity field must be determined by experiment and the recommendations of life scientists, but the coupled Phoenix system proposed in this paper should be easily capable of a full 1 g if required.

A large number of Phoenix flights will be required to support this mission. Each PPT will require about 50 fuel supply flights by Phoenix tankers, while each of the two Mars excursion vehicles will need about 22-24 flights. A total mission requirement is therefore about 150-160 flights. With a fleet size of ten vehicles each flying once per week, four months would be needed to transfer all the propellant to an orbital depot. More optimistically, a reflight time of once every two days would permit the supply flights to be concluded within one month.

The fact that this many orbital flights are required should not be a deterrent to operating such a mission. The Mars mission would be a rather modest part of the normal traffic model planned for the Phoenix. In addition, others, such as Wernher Von Braun, have seriously proposed large numbers of logistics flights in support of Mars missions.

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Lightsat Funding In Trouble

The Defense Advanced Research Projects Agency (DARPA) Lightsat program is facing almost certain cancellation due to alterations in the Department of Defense (DOD) budgets for the fiscal years 1990 to 1995.

The Lightsat program was intended to demonstrate the usefulness of small, low-cost satellites and launch vehicles to provide on-the-spot satellite services to military ground personnel or perform other missions requiring rapid satellite services. The program was considered by the private launch vehicle industry as an important new potential market for their small expendable launch vehicle concepts (*C.S.R.*, Nov. 1987). Companies which manufacture small satellites were also looking forward to a new market.

In May, $300,000 initial study contracts were awarded to four companies: Lockheed Missiles and Space, TRW Space and Technology Group, LTV Aerospace, and Space Services, Inc. (*C.S.R.*, May 1988). Further Lightsat contracts were to be awarded to a selected company--it is this follow-on funding which is being eliminated.

Lightsat was not specifically targeted for cancellation, but its elimination was put forward as a trade-off for other programs during Defense Department deliberations to rearrange budget priorities for the next five years (Lightsat was expected to cost the DOD about $235 million over this five-year period).

The program has its supporters and detractors. Supporters include the Army, the Navy, and, of course, DARPA. Chief among detractors has been the Air Force, specifically Air Force Secretary Edward Aldridge, who saw the satellite program as an incursion into Air Force turf.

Aldridge is not even trying to pretend his opposition is motivated by anything other inter-service rivalry, explicitly stating that a lightsat program is a good idea if the Air Force is in charge, but not if it is a DARPA program.

Orbital Sciences' Pegasus launcher, also being funded as part of the Lightsat program, is not in immediate jeopardy (*C.S.R.*, May 1988). Funds for at least one demonstration flight (at about $6 million each) are coming out of current funds.

Like many "cancelled" government programs, Lightsat may find a new lease on life if the Congress overrules the Department of Defense.

Note to Subscribers:

I'm working on giving the *C.S.R.* a new look, courtesy of a Wordstar upgrade. The major change is to a Helvetica typeface which I believe is more readable, but I would like to hear if anyone disagrees.

Until next time,

Tom Brosz

Tom Brosz
September 27, 1988

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Address all correspondence to: *Commercial Space Report, P.O. Box 60547, Sunnyvale, CA 94088.* Editor: Tom A. Brosz. Tel: (415) 965-8666. Comments, ideas, or requests for information are welcomed, as are any items which may be of interest to our readers.