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REPRESENTATIVE OPTIONS FOR HUMAN EXPLORATION OF PLANET MARS

H.H.Koelle

Technische Universitaet Berlin
Aerospace Institute
Marchstr.14
D-10587 Berlin

Abstract

The human exploration of Mars remains an issue of interest to the space enthusiast and the general public as well. NASA has developed a Mars Reference Mission which is supposed to serve as a basis for detailed discussions among the specialists. It is a split mission concept proposing multiple expeditions to the Mars surface with a three six-person crews. Other program options are not considered. To complement this NASA reference mission, this report summarizes five different program options from a single mission with a crew of six to a permanent Mars Base with about 100 people. The primariy characteristics including performance and cost data are presented. In addition an attempt is made to determine the relative benefits expected to be

derived from these mission concepts. Benefit/cost ratios indicate which program options are the most promising ones to be recommended for further study. Additional refinements of the proposed concepts and improved tools for program analysis are proposed.
This report comprises 47 pages, 40 tables, 19 figures and 17 references.

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1.Introduction

Ever since Wernher von Braun has proven in his "Mars Project"[1] , published in 1951, that Mars expeditions are feasible with current chemical propellants, many studies have been made to assess the chances for human exploration of Mars[2-9]. The SATRUN V Moon rocket was the first launch vehicle that had a payload capability of over 100 metric tons to Earth orbit, which was at that time considered the minimum required to prepare a Mars expedition. Mission studies in the early sixties concentrating on the 1984/86 launch window, produced a lot of insight into the problems involved[2,3]. Political and budgetary problems lead to an end of these studies in the mid sixties.

The National Space Commission, mandated by the US Congress re-assessed the situation in the mid- and late eighties. The result of these studies were summarized by the Synthesis group recommending a return to the Moon to stay and going on to Mars[5]. President Bush accepted this recommendation and presented it to Congress. Three month later the Berlin wall came down, the cold war came to an end and the national priorities changed drastically. The Space Exploration Initiative(SEI) proposed by President Bush was not approved by the US Congress.

Nevertheless, the human exploration of Mars remains an issue of interest to the space enthusiast and the general public as well[4,6,7]. After the completion of the International Space Station (ISS) in 2002, the question will come up again: What comes next? - To be prepared for such a discussion NASA has developed "Human Exploration Development Strategy (HEDS), and as an element of this, a Mars Reference Mission[8]. This latest study is supposed to serve as a basis for detailed discussions among specialists. It is a specific split mission concept proposing multiple missions with three six-person lunar expeditions. Other program options have not been considered. An other important contribution to this discussion was provided by the International Academy of Astronautics (IAA). It compiled a report on the present state-of-the-art with respect to Mars Exploration which can serve as a basis for further detailed studies[9].

The report presented now, attempts to complement the NASA reference mission and analyses five different program options, from a single mission to a Mars base with over 100 people. The primariy program characteristics, including performance and cost data are presented. This report summarises some selected options for the human exploration of Mars, but not yet taking into consideration commonalities with the Moon or other space programs. It remains a task of the future to determine the interdependencies with such programs. However, as a special feature in this category of program planning studies, an attempt is made to determine the relative benefits expected to be derived from these Mars program options. Benefit/cost ratios will be derived to indicate which concepts are the most promising ones to be recommended for further study.

2. MARS logistics and mission archtitecture

2.1 Mission requirements

Because the subject of interplanetary flight mechanics is covered extensively in the literature only the velocity requirements of Mars missions are summarized here.

EARTH to MARS requirements

Low energy departure to trans Mras injection (TMI) requires a minimum of 3,700 m/s arriving at Mars with 5,870 m/s. The orbital velocity low Mars orbit is 4,720 m/s, thus the difference of 1,150 m/s must be taken out by aero-braking or rocket propulsion. Aero-braking is preferred particularly for fast transfer mission profiles. About 200 m/s are required for midcourse maneuvers and orbit control, i.e.lowering gradually perigee altitude to circular. Adding about 500 m/s for the landing maneuver, the total velocity increment required totals about 700 m/s. This delta v requirement depends, however, on the vehicle design concept and mission profile chosen, it needs verification for each specific case considered.

MARS to EARTH requirements

Ascent to low Mars orbit (LMO) requires a delta v of 4,200 m/s, to a high elliptic orbit (HEMO) of 5,400 m/s. A minimum energy Hohmann transfer back to Earth from LMO requires a minimum of 1,900 m/s and from HEMO = 650 m/s for slow transfers. A direct flight from the surface of MARS to Earth transfer orbit requires a minimum of 6,100 m/s for a slow return (Hohmann) trajectory.

2.2 Space vehicle mass models and performance

Methane ($CH4$) and liquid oxygen is used for all missions on the Mars side, other than in the direct return mission, where liquid hydrogen and liquid oxygen must be used in a single stage vehicle. The engines used in these space vehicles will be clusters of the RL 10 family.

It remains to be determined when and to what degree these propellants required on Mars, can be produced by in-situ resource utilization (ISRU) systems. This is also a matter of the availability of electric power on the Mars surface. Representative mass and performance data of typical space vehicles required as elements of a Earth-Mars transportation system such as including:
* Earth orbit departure vehicles
* Mars landing vehicles
* Mars ascent vehicles
* Mars orbit departure vehicles
* Earth return vehicles
* E-M-E orbit to orbit ferry vehicles
must be analysed in detail to arrive at mass, performance and cost data which enter the analysis of alternative mission concepts.

Table 2-1: Overview of representative characteristics of some selected space vehicle required for Mars landing and return missions (masses in metric tons)

	Mars cargo lander	Mars crew lander	Mars ascent to LMO	Mars ascent to HEMO	Mars LMO departure	Mars HEMO departure	Mars direct to Earth
c (m/s)	3700	3700	3700	3700	3700	3700	4500
delta v(m/s)	700	700	4200	5400	3 130	3428	6200
mass ratio	1.208	1.208	3.11	4.55	2.33	2.526	3.966
init.mass(t)	120	90	19.6	30.5	110	120	203
dry stage	6.5	6.5	3	3.2	5.4	5.5	13
residuals	0.5	0.5	0.3	0.5	1.3	1.5	3.0
propellants	22	18	13.3	23.8	62.8	72.5	152
cut-off mass	96	72	6.3	6.7	47.2	47.5	51.0
payload	89	65	3	3	40.5	40.5	35.0
propellant mass fraction	0.77	0.72	0.816	0.865	0.921	0.930	0.921

A tentative list of all identified items required for the Mars infrastructure and conceptualization of alternative mission architectures must be prepared and filled with representative data before the number of supply flights can be determined with satisfactory accuracy. Although a very large number of different mission architectures can be envisioned, only five typical architectures are included in this analysis to establish the trends to be expected with program size.

2.3 Alternative Mars mission architectures

The first step to is to select a limited number of typical individual Mars program options. This architecture could be quite different in case a lunar base and lunar propellants would be available. Options using lunar propellants can be included in the analysis as soon as it becomes clear that a lunar program will preceede a Mars program and that lunar propellants can become available at reasonable cost. One study has shown that cost reductions in the order of 10 percent are possible[12]. However, this can not be expected soon only in due course of development. Thus, only such mission concepts are choosen for analysis that use propellants from Earth or such produced on Mars as suggested by Zubrin[4,6,8]. The possibility to use nuclear propulsion for the departure from Earth orbit as proposed in the NASA reference mission has not been included in this study, because of its high front-end cost, the schedule delays expected and the problem of public acceptance.

In developing mission architectures for Mars exploration one has to be aware of the large numbers of parameters which are controling the performance, cost and benefit of Mars programs. Table 2--2 attempts to list these parameters in the area of Mars infrastructure and space transportation systems.

Table 2-2: Mars Program architecture attributes and variables

Surface installation:

1. Duration of program life-cycle,
2. Temporary or permanent human residence
3. Size and growth rate of crew on Mars surface
4. Timing of first crew landing
5. Duty cycle of Mars crew members
6. Degree of self-sufficiency
7. Quality of habitat provisions
8. Mix of surface power plants
9. Degree of crew mobility
10. Degree of redundancy of Mars surface equipment
11. Philosophy of testing Equipment
12. Availability of human skills
13. Spare time concept for crew
14. Philosophy of crew training
15. Maintenance and repair philosophy

Space transportation system:

1. Crew size per vehicle during transfer
2. Frequency of flight missions
3. Number of vehicles per crew mission during a launch window
4. Flight duration for cargo and crews
5. Degree of assembly /refueling of space vehicles in Earth orbit
6. Abort provisions
7. Radiation shielding for crew
8. Provisions for artificial gravity
9. Degree of reusability of Earth-Mars-Earth ferry vehicle
10. Propellant type/combination for Earth departure stage
11. Method of entering Mars orbit
12. Degree of reusability of Mars ascent vehicle for crew
13. Propellant combination and origin for Mars ascent vehicle
14. Propellant combination and origin of Mars orbit departure vehicle
15. Methode of returning to Earth orbit or surface

Two group judgements were made among the members of the IAA Moon-Mars Committee in 1997. These resulted in a preliminary specification for the selection of specific mission architechtures. They indicated the preference of the options for the architecture of typical piloted Mars Exploration Programs in the range of the parameters as presented in table 2-3. On this basis five typical mission modes were selected for further analysis. These are summarized in tables 2-4 and 2-5.

Table 2-3: Range of options for Mars program attributes

parameter:	preferred option
1. duration of stay at Mars	full cycle with option to extend to permanent presence
2. propulsion system	high energy chemical propulsion with option for nuclear propulsion in due course
3. mission frequency	frequent missions using each launch window
4. propellant supply	Earth, lunar and Mars propellants as appropriate and cost-effective
5. trip time	cargo 9 months, crew 4 - 6 months
6. vehicle crew size	6-8 per vehicle
7. fleet size	two identical crew vehicles and one or two seperate cargo vehicles per mission
8. size	
9. Earth departure orbit	low Earth orbit, lunar orbit - if more cost-effective
10. arrival orbit Mars	aerobrake into elliptical Mars orbit, followed by gradual descent
11. radiation protection during transfer	to provide a 95% chance for survival without severe damage to crew members
12. artificial gravity during transfer	0.3 g during transfer to Mars after midcourse manouver, none on return leg
13. abort capability	at Earth departure either into elliptical Earth orbit or to Mars orbit/surface
14. arrival orbit upon return	direct Earth entry, or aerobrake into elliptical Earth or lunar orbits for pickup

	respectively
15. equipment available on Mars	extensive - including life support, propellant production and mobility
16. Mars power plant	solar & nuclear in case of Mars propellant production or solar & fuel cells for small base
17.training of Mars crew	selectively on the Moon, but all must have been in a space before departing for Mars
18.testing of Mars equipment	preferably on the Moon, at least in the environment of Earth orbits

The behaviour, the performance and the cost of a Mars installation, seen as a dynamic system, is primarily determined by the variables used in the following table to differentiate between mission concepts or programs. Five programs were selected to cover the range of interest. These five program options have been analysed with the help of analytical simulation models and computer codes avaialble to the author[10,11]. This is the range of options prefered by those participating in these preliminary assessments. In selecting attributes for typical programs it was possible to analysed five detailed program options in simulation studies.

Table 2-4: Individual Mars program architectures selected for further analysis

program attributes and parameters	single expedition	multiple expeditions	Mars outpost	Mars laboratory	Mars base
OPTION	1	2	3	4	5
1. Assembly of space vehicles in Earth departure orbit (yes or no)	yes	no	no	no	no
2. Earth Departure orbit (LEO or HEO/ L2)	LEO	LEO	LEO	LEO	LEO
3. E-M-E passenger ferry vehicle (expendable, reusable)	exp	exp	exp	exp/ reuse	reusable
4. Number of space vehicles per human mission during a specific launch window	1	1	2	4	6
5. Crew size per vehicle (mission) during transfer	6	6	6	12	16
6. Propellant type for Earth departure stage TMI - (LH2/LOX or LH2 nuclear)	LH2/ LOX	LH2/ LOX	LH2/ LOX	LH2/ LOX	LH2/ LOX
7. Propellant source for TMI stage Earth only = E, or E plus lunar LOX = lulox)	E	E	E	E	E
8. Propellant source for Mars ascent vehicle (CH4-LOX Earth- and/or Mars produced)	E	E/M	E/M	E/M	M
9. Type of Mars ascent vehicle for crew (expendable, reusable)	exp	exp	exp	exp/ reuse	reuse
10. Propellant of Mars orbit departure lo vehicle (CH4-LOX,LH2-LOX, Earth or Mars)	CH4 lox-E	CH4/ lox-E	CH4/ lox-E	LH2/ lox-E	LH2/ x-E
11. Earth capture maneuver (direct, LEO or HEO with pickup)	dir entry	dir entry	dir entry	dir + Leocap	Leo cap
12. Gravity provisions during transfer (zero g, or low g, one way or both ways)	zero both	zero both	grav E-M	grav E-M	grav both
13. Mars power plant type (solar only, solar & nuclear)	solar	both	both	both	both
14.Maximum crew size on Mars surface during life-cycle	6	6	12	50	100
15. Duration of operational life-cycle (years)	3/7	8	15	30	25

There is an other way to make a cut through these program options and specify the parameters in the four groups: Mars surface infrastructure, mission profile,vehicle design and crew system. This leads to a different matrix as shown below, it assists in checking whether or not the attributes selected are compatible with each other.

Table 2-5: Overview of selected Mars mission options listed by subsystems

op-tion	Mars surface infrastructure	mission profile	vehicle design	crew system
1.	habitat solar power plants rover	LEO assembly of entire crew vehicle, LEO departure, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from low Mars orbit, direct Earth entry	Lox/LH2 booster stage, Lox-CH4 Earth propellants for expendable Mars ascent & orbit departure vehicle, no Mars propellants, cargo flights direct,	single 6-person crew vehicle, choice of 6, or 4 people on Mars surface and 2 remaining in orbit, no artificial gravity during transfers
2.	habitat nuclear & solar power plants, rover propellant production plants	LEO departure, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from high elliptic Mars orbit, direct	Lox/LH2 booster stage, partial Mars propel-lants for ascent vehicle, Lox-CH4 Earth prop.for Mars orbit departure, expendable ascent & cargo flights direct	6-per vehicle, 1 crew vehicle per mission, no artifical gravity during transfer
3.	habitat solar & nuclear power plants rover propellant production plants	no Earth orbit assembly, direct LEO departure,0.3 g E - M , aero-capture to elliptic Mars orbit and slow descent, ascent, depart from low aerocapture, direct Earth entry	Lox/LH2 booster stage, Mars propellants for ascent vehicle , Lox-CH4 Earth propellants for Mars orbit departure, expendable ascent &	6-per vehicle, 2 crew vehicles per mission , partial gravity E-M after mid-course maneuver, on Mars surface 6 - 12,
4.	habitat solar and nuclear power plants rovers propellant production plants	1st phase: see option 3, 2nd phase: refueling Earth prop. & departure from LEO , 0.3 g,aero-capture to LMO and slow descent, crew changes to Mars Bus, ascent, depart from LMO, LEO capture and pick-up by shuttle	Lox/LH2 booster stage, reusable E-M-E ferry vehicle , 0.3 g Lox-LH2 Earth propellants for Mars orbit departure, reusable ascent & return vehicles, cargo flights direct expendable	6 per vehicle, 2 vehicles per fleet, initially 12people on Mars surface growing to 42, artificial gravity Earth-Mars leg after midcourse, none on return,
5.	initial habitat solar 6 nuclear power plants rovers propellant prod.plant	LEO departure after refueling Earth prop., 0.3g,aero-capture to Mars orbit, pick up of crew by Mars-Bus, depart from low Mars orbit,aero-& rocket brake into LEO & pick-up of crew by shuttle, cargo flights direct	reusable HLLV to LEO, 3rd stage modified as TMI with heat shield, reusable crew version providing 0.3 g,, Mars propellants for reusable Mars Bus, expendable TMI and lander for caro delivery	8-per vehicle, 2 vehicles per missin, initially 16 people on Mars surface growing up to 100, artificial gravity on both transfer legs

These five options will now be analysed and presented in some detail.

3. MARS Program Option 1: Single Mars Expedition,

This option comprises one primary mission attempt and a full back-up flight, plus an additional cargo mission for Mars infrastructure delivery preceeding the first crewed flight. The logistic system chosen is based on a Shuttle derived two-stage reusable medium launch vehicle with a payload capability of about 110 metric tons to low Earth orbit, supporting a LEO space operations center.

Program duration: 7 years development + 4/ or 7 years operation with back-up .
Program performance :
Crew of 6 x 425 days on Mars = 7 labor years,
no production on Mars,
6 passenger roundtrips in one mission,
3 year duty cycle in space.

Table 3-1: Summary of program attributes and parameters of program option 1

Program attributes and parameters of Single Mars Expedition
1. Assembly of space vehicles in Earth departure orbit
2. Earth Departure orbit : LEO on Hohmann transfer trajectory
3. Earth-Mars-Earth ferry vehicle: expendable
4. Number of passenger space vehicles during a specific launch window : 1
5. Crew size per vehicle during transfer : 6
6. Propellant type for Earth departure stage TMI : LH2/LOX
7. Propellant source for trans-Mars stage: Earth
8. Propellant source for Mars ascent vehicle : CH4-LOX from Earth
9. Type of Mars ascent vehicle for crew : expendable
10. Propellant of Mars orbit departure vehicle : CH4-LOX from Earth
11. Earth capture maneuver : direct entry
12. Gravity provisions during transfer : zero gravity both ways
13. Mars power plant type: solar only
14. Maximum crew size on Mars surface during life-cycle : 6
15. Duration of operational life-cycle : 4 years , in case of back-up mission 7 years

This program option can also be defined by arranging the parameters in the four groups:
* Mars surface infrastructure,
* mission profile,
* vehicle design and
* crew system.

This leads to a different matrix as shown below, it assists in checking whether or not the attributes selected are compatible with each other.

Table 3-2: Definition of subsystems required for program option 1

Mars surface infrastructure	mission profile:	vehicle design:	crew system
habitat solar power plants rovers	LEO assembly of entire vehicle, LEO departure, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from low Mars orbit on Hohmann trajectory, direct Earth entry	Lox/LH2 booster stage, Lox-CH4 Earth propellants for expendable Mars ascent & orbit departure vehicle, no Mars propellants, cargo flights direct,	single 6-person crew vehicle, choice of 6, or 4 people on Mars surface and 2 remaining in orbit, no artificial gravity during transfers

For planning purposes the infrastructure and supplies required on the Mars surface must be defined in the form of a tentative model and filled with typical data. This is a challenging task, because there is a wide range of estimates possible, from modifications of existing hardware to "gold plated" all new equipment just for this single mission. These estimates have to be improved!

Table 3-3: Mars infrastructure and supply requirements for single expedition

Equipment inventory and operational	ref. mass	ref. vol.	dev. cost	unit prod.	no. units	total mass	tot. oper.

requirements:	(MT)	(m3)	(M$)	cost (M$)		(MT)	cost (M$)
crew training and salaries	0	0	20	10	10yr	0	120
science support	0	0	100	50	10yr	0	600
systems engng. & management	0	0	0	100	10yr	0	1000
pilot Mars station	20	200	500	100	1	20	600
workshop-lab module	30	250	300	200	1	30	500
standard surface habitat	30	350	2500	500	1	30	3000
phys./chem.life support system	3.0	10	500	100	2	6	700
thermal control system	2.0	10	200	100	2	4	400
water storage tank	1.0	5	10	10	1	1	20
EVA equipment	0.2	1	750	50	5	1	1000
ISRU plant -water,air	1.0	5	500	50	2	2	600
3-5 kW PVA power -	2	5	100	10	2	4	120
40 kW surf. solar pp - RFC	26	300	200	50	2	52	300
15 kW DIPS cart	1.5	10	500	50	2	3	600
PMAD and cables	2.0	5	100	10	2	4	120
communication system	1.0	1	100	10	2	2	120
plant growth facility	5.0	10	100	10	1	5	110
open rover for crew	0.5	10	50	10	2	1	70
pressurized rover for crew	5.5	50	200	25	2	11	250
science rover	0.5	1	100	10	4	2	140
science equipment	3	10	100	100	1set	3	200
hand tools,machine tools	10	20	20	10	1set	10	30
consumables (food etc.)	10	20	10	10	1yr	10	20
clothes, hygenic supplies	4	10	20	10	1yr	4	30
spares	4	20	50	50	1yr	4	100
(ascent vehicle) cost included below	36	0	0	0	1	36	0
miscellaneous	5	20	100	100	1yr	5	50
total (with ascent vehicle)	203	1327	7130	1735	-	250	10800

At this time these estimates can not be very accurate, but this is acceptable because the larger part of the cost are those connected with the logistic system. Fairly good models can be used to estimate those[10]. Nevertheles, an attempt has been made to present order-of -magnitude (ROM) figures for the infrastructure above which should be replaced by better ones in due course of the planing process.

A typical distribution of these acquisition and operation cost over the program time as shown in the following graph must be expected for budgeting the Mars infrastructure. It appears possible to smooth the peak somewhat.

Figure 3-1: Financial requirements for the Mars infrastructure versus time

Space vehicles:
The total payload mass of about 250 metric tons and the total volume including multiple units (1,327 + 413 = 1,740 m^3), must be transported to their points of destination by these space vehicles during all phases of the mission. The masses used for the space transportation system in this mission model are slightly modified of those estimated by M.Reichert in his analysis[12].

Logistics balance:
If 250 metric tons(MT) are assumed for the baselined cargo to be delivered to Mars including the surface habitat and the ascent vehicle, then the crew lander vehicle can deliver the 30 MT habitat, the 36 MT ascent vehicle, plus 32 MT other cargo. The remaining 152 MT cargo must be delivered by an extra trans-Mars cargo vehicle, which has a payload capability of 408 MT to Mars orbit. As a one way vehicle it does not carry an Earth return vehicle, thus it can transport two standard Mars landers with a initial mass of 186 MT and a 98 MT cargo each, instead of one. This would leave a reserve capability of (2x98) - 152 = 44 MT. -

Only two crew modules each (flight habitats and Earth entry modules have to be manufactured!)

Table 3-4: Cost summary of the space transportation system for a single Mars expedition

Legend:
ELV = Earth launch vehicle
TMI = trans Mars injection vehicle
MTV = Mars transfer vehicle
MLV = Mars landing vehicle
MAV = Mars ascent vehicle
ELV = Earth landing vehicle
SOC = space operations center

vehicle type	ELV	TMI	MTV	MLV	MAV	SOC*)	total
LC no.launches	35 #)	3	2	3	2	2	-
launch mass (MT)	1900	976	408	186	36	286	-
dry mass (MT)	195.4	27.59	78.33	47.97	5.62	286	-
propellant mass(MT)	1711	540	54	42	26	-	-
payload mass(MT)	110	414	276	98	5	-	-
development cost(M$)	6826	2637	2632	1221	2089	5384	20789
1st unit production (M$)	1228	602	449	296	309	695	-
total prod.cost(M$)	3381	1544	1348	895	619	3829	11617
operating cost (M$)	1344	48	57	54	13	-	1516
total cost logistics(M$)	11550	4230	4037	2171	2721	9203	33920

*) including a 250 MT space operations center in low Earth orbit and a 30 MT flight habitat.
A 6 MT Earth entry capsule (ELV) is an integrated element of the Mars ascent vehicle!
)this results for the reusable ELV in a launch cost of 330 M$ and at 110 MT = 3,000 $/kg to LEO!

The cost estimate is based on table 3-3 above as far as the Mars infrastructure is concerned, and on the results of a simulation run with a computer code available for space transportation systems[10]. The next graph illustrates its distribution versus time, a trend that has not been optimized as yet.

Figure 3-2: Financing requirements for space transportation system - option 1

Cost Summary of Program Option 1(M $):

Cost of Mars infrastructure and supplies 10,800
cost of the space transportation system 33,922
total program 44,722
average annual program cost over 14 years life-cycle 3,195
cost-effectiveness of 7 Mars labor-years 6,390

Figure 3-3: Estimated total budget requirements for program option 1: single expedition

As an alternate, even an expendable launch vehicle could be used, but at higher cost!

Option 1A: same mission, but with expendable medium launch vehicle:

The production cost would increase by 28.163 B $, the operating cost would decrease by about 567 M $ and the development cost would be reduced by about 1.1 B $. Thus the total cost difference would be about 26.3 B $ and the program cost would be 44.7 + 26.3 = 71 B $ which is an increase of about 59 percent! -

This is not an attractive alternative and will not be considered any further!

4. Mars Program Option 2 : Multiple expeditions

This is a modified NASA Reference Mars Mission, employing a **reusable** heavy lift launch vehicle(HLLV) with an expendable LH2/LOX trans Mars injection stage, it is bases on a split mission concept with 3 separate flights per mission.
Program duration: 7 years development + 7 years operation.
Program performance :
1 cargo only mission plus 3 crewed mission attempts
with (6 x 600) days on Mars = 20 labor-years on Mars at 67% mission reliability,
4 back-up vehicles included (4 out of 12 flights total)

Table 4-1: Summary of program attributes and parameters of program option 2

program attributes and parameters of multiple split missions :

1. No assembly operations or other operations in LEO required
2. Earth Departure orbit : low Earth orbit, cargo on Hohmann-, crew on fast transfer trajectories
3. E-M-E passenger ferry vehicle : expendable
4. Number of vehicles per during a specific launch window : 3
5. Crew size per vehicle and mission : 6
6. Propellant type for Earth departure stage TMI : LH2/LOX
7. Propellant source for trans-Mars injection stage : Earth propellants only
8. Propellant source for Mars ascent vehicle CH4-LOX Earth- and Mars produced
9. Type of Mars ascent vehicle for crew : expendable
10. Propellant of Mars orbit departure vehicle : CH4-LOX from Earth
11. Earth capture by direct entry
12. Gravity provisions during transfer: zero g both ways
13. Mars power plant type: solar & nuclear
14. Maximum crew size on Mars surface during life-cycle : 6
15. Duration of life-cycle: 7 years dev. + 7 years operation

or defined by subsystems:

Table 4-2: Definition of subsystems required for program option 2

Mars surface infrastructure:	mission profile:	vehicle design:	crew system:
habitat nuclear and solar power plants rovers propellant production plants	LEO departure, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from high elliptic Mars orbit, direct Earth	Lox/LH2 booster stage, partial Mars propellants for ascent vehicle, Lox-CH4 Earth propellants for Mars orbit departure, expendable ascent & flights direct entry into Mars atmosphere,	6-per vehicle, 1 crew vehicle per mission, no artifical gravity during transfer

Similar as for option 1, at this stage of the analysis the mass and cost estimates for the infrastructure required on the Mars surface can be only of the rough order of magnitude (ROM) type, but this is acceptable, because they represent only about one quarter of the total cost. The logistics cost are about 75% and should be estimated with the cost estimating relationships available which probably have an accuracy of about 10%. A first estimate, using in some cases the mass estimates of the NASA Mars reference mission, has lead to the following results for the infrastructure and supplies required on Mars, including mission support and Mars operations:

Table 4-3: Mars infrastructure requirements for multiple split missions - option 2

Equipment	ref	ref.	dev.	unit	no.	total	tot.

inventory and operational requirements:	mass (MT)	vol (m3)	cost (M$)	prod cost (M$)	units	mass (MT)	oper. cost (M$)
crew training and salaries	0	0	10	12	10yr	0	130
science support	0	0	100	60	10yr	0	700
systems engng.&management	0	0	0	120	10yr	0	1200
pilot Mars station	30	200	500	100	1	30	600
workshop-lab module	30	250	100	200	1	30	300
surface habitat	30	350	2500	500	4	120	4500
phys./chem.life support system	3	10	500	100	2	6	700
thermal control system	2	10	200	100	2	4	400
water storage tank	1	10	10	10	1	1	20
EVA equipment	0.2	5	500	50	5	1	750
ISRU plant	1	5	500	50	2	2	600
10 kW solar power plant	2	10	200	20	2	4	240
3 kW PVA power	2	5	100	10	2	4	120
15 kW DIPS cart	1.5	10	100	50	2	3	200
160 kW nuclear power plant	12.5	100	2000	500	2	25	3000
PMAD and cables	3	10	150	25	2	6	200
communication system	1	1	50	10	2	2	70
plant growth facility	5	10	100	20	2	10	140
open rover for crew	0.5	10	50	10	4	2	90
pressurized rover for crew	6.0	50	100	25	2	12	150
science rover	0.5	1	50	10	4	2	90
science equipment	5	20	150	150	1	10	300
hand tools,machine tools	10	20	20	10	1	10	30
hydrogen feedstock	5	30	0	5	3	15	15
consumables (food etc.)	10	20	10	20	3	30	70
clothes, hygenic materials	4	10	10	10	3	12	40
spares	4	20	50	50	3	12	200
Mars ascent vehicle partly fueled	12	300	0	0	4	48	0
misc. and reserves	61	30	100	100	1	61	400
TOTAL	240	1497	7140	2327	61	462	15255

The NASA reference mission assumes the availability of a small production plant to provide life support products and propellants for the Mars ascent vehicle. This in-situ resource utilization (ISRU) plant was estimated to have the following characteristics and is taken into consideration in these estimates[8]:
Initial plant mass 653 kg, power requirement 3.6 kW, output: 85 kg/day (life support and propellants), a smaller plant is complementing the initial plant with a mass of 238 kg, 2.3 kW, output: 30.8 kg/day (propellants only).
The input required to run the plant is 0.5 MT LH2 for each metric tonne of CH_4.The production requirements for a 6 person crew and a 400 expedition is estimated as follows: 5.8t CH_4; 20.2t LOX; 23.2t water; 4.5t oxygen and 3.9t N_2/Argon.

Transportation requirements : in summary
4 crew return vehicles from HEMO = 3 x 110 = 440 MT incl .1 back-up
Requirements on Mars surface = 462 MT
Life cycle total = 902 MT

Figure 4-1: Estimated annual budget requirements for the Mars infrastructure of multiple Mars expeditions

Mass Balance:
4 Earth return vehicles in Mars orbit (1 back-up) = 440
3 fast crew transfer vehicles land 65 MT on Mars including habitats = 195
3 cargo vehicles land up to 89 MT including 3 Mars ascent vehicles = 267
total capacity to Mars surface = 462
2 back-up vehicles for Mars deliveries(65 + 89) (=164)

This requirement will be satisfied by the choice of the following space transportation system that is based on a reusable heavy lift launch vehicle, an expendable trans-Mars injection stage, a Mars landing vehicle, a Mars ascent vehicle, an Earth return vehicle and an ballistic crew module for the landing on Earth.

Reusable Earth launch vehicle with Mars injection stage

A three stage *reusable* heavy lift launch vehicle (HLLV) of about 6,000 MT launch mass is capabable to carry a payload of about 375 MT into a low Earth orbit at about 160 km altitude[14,15]. This leads to 85 - 120 MT payloads to be sent onto a Mars transfer trajectory with an expendable TMI stage, depending on the travel time and year of departure in the 15 year cycle using up to 7 launch windows.

The mass model of the third stage of this HLLV, as well as the variation of Mars transfer payload versus delta v required in low Earth orbit, is illustrated in the following tables and diagram. Gross payload capability of three stage reusable NEPTUNE launch vehicle (concept of the TU Berlin) with launch mass = 6,000 metric tons to 160 km LEO orbit is 416 metric tons maximum.

The launch mass is not a fixed parameter, it may be smaller if the lunar and Mars payload requirements would allow this. In prinziple, a smaller launch vehicle leads to higher launch rates, and reduced cost, but on the other hand increases the cost of space operations. An optimum sized launch vehicles is thus the result of an integrated space program, yet to be determined.

Using the preliminary launch mass of 6,000 metric toins, and considereing a ten percent design reserve, the nominal initial mass of TMI stages is **375** MT.

Table 4-4: Mass model and payload capability of Trans-Mars injection stage (TMI)- (metric tons) - Launch mass in 160 km orbit for direct TMI = 375 MT):

m-LEO launch	375	375	375	375	375	375
m-dry	40.3	38.2	36 .6	35.2	32.3	29.1
m-prop	278	263	252	242	221	200
m - resid	5.6	5.3	5.1	4.9	4.5	4
m-stage	323.9	306.5	293.7	282.1	257.8	233.5
prop share	0.858	0.858	0.858	0.858	0.857	0.856
m- cargo	51.1	68.5	81.3	92.9	117.2	141.5
m-cutoff	97	112	123	133	154	175
m -ratio	3.866	3.348	3.049	2.820	2.435	2.143
ln r	1.352	1.208	1.115	1.037	0.8899	0.7622
delta v(m/s)	6220	5557	5130	4770 **)	4094 *)	3500

*) typical slow transfer trajectory, **) typical fast trajectory

In addition to the TMI stage several other space vehicles are required in this logistic scenario: Earth launch vehicle (ELV); Earth return vehicle (ERV); Mars landing vehicle (MLV); Mars ascent vehicle (MAV) and crew modules for transfer and Earth entry (CM).Their mass, performance and cost characteritics for this specific option and scenario are summarized in the table above.

Table 4-5: Space vehicle overview

	ELV+ TMI [[section]]	ERV	MLV	MAV #	CM *)	total
LC no.launches	12	4	12	4	4 + 4	-
launch mass (MT)	6000	120	110	30.5	35 + 6	-
dry mass (MT)	752	6.5	6.5	6.2	30 + 6	-
propellant mass(MT)	5174	63	22	24	-	-
payload mass(MT)	110	30+6	89	3.0	-	-
development cost(M$)	15615	1387	1734	2246	4838	25820
1st unit production (M$)	2872	163	131	250	696	-
total production cost(M$)	8776	695	1749	832	2902	14954
operating cost (M$)	919	28	59	45	-	1151
total cost logistics(M$)	25309	2110	3542	3123	7740	41825
total cost per flight (M$)	1963	528	295	781	1935	-
direct cost for reuses (M$)	350	181	151	219	696	-

*) including a 30 MT flight habitat, and a 6 MT Earth entry capsules (ELV) ;
#) crew module integrated with ascent vehicle
[[section]]) including 12 units of the expendable TMI stage, stage 1 + 2 = reusable

The funding profile **for the logistic system** of an independend Mars outpost program, not including the Mars infrastructure, is shown in figure 4-2:

Figure 4-2: Estimated annual expenses for the logistics support of multiple Mars expeditions

Adding the cost for the acquisition of the Mars infrastructure and the logistics cost one obtains the total program costs.
Program Cost(million $) :

Mars surface infrastructure and operation 15,255
Development, production & operation of the logistics system 41,825
15 year program total cost for 30 labor-years 57,080
average annual cost during 15 year life-cycle 3,805
Program effectiveness with 20 labor-years (cost per labor-year) 2,854

Figure 4-3: Estimated total annual budget requirements for the option of multiple Mars expeditions

There are several ways to improve this typical model of multiple crewed expeditions to Mars. For example, the IRSU produced Methane propellants on Mars for the return are the equivalent of one cargo flight to the Mars surface which cost about 501 M$ (see table above for recurrent cost = 350 + 151). Such an additional cargo flight would eliminate the need for production of about 80 metric tons of propellants for the Mars ascent vehicle, and therewith the two 160 kW nuclear power plants costing about 3 B $ to develop and to manufacture.

In balance, this would amount to savings of about 2.5 B $. There are additional advantages: It would also eliminate considerable development time (because this capability would not have to be proven on Mars beforehand), it would also reduce undesirable front-end cost, human workload on Mars, mission risk and improve the chances of political acceptability!

Consequently, it should be seriously considered to transport the Mars ascent vehicle fully fueled to the Mars surface, ready to be launched! It appears satisfactory and preferable to limit the production to oxygen, water, Argon, Nitrogen and some Methane for surface propulsion.

5. Mars Program Option 3 : Mars Outpost

This option envisions a crew of 6 to 12 people on Mars using 7 launch windows during 15 operational (Earth) years in a similar operational mode as option 2, but with overlapping duty cycles. This requires an average mission time for the crews of five years instead of 3 years. In contrast to option 2, this mission mode allows permanent use of the infrastructure on the Mars surface, omitting the need of mothballing the facilities and equipment for several months. This will increase the number of Mars labor-years from 20 (option 2) to 124.

Table 5-1 : Summary of program attributes and parameters of program option 3

`program attributes and parameters`

1. No assembly of space vehicles in Earth departure orbit
2. Earth departure orbit from LEO , crew on fast-, cargo on slow trajectories
3. E-M-E passenger ferry vehicle :expendable
4. Number of vehicles during a specific launch window : 3
5. Crew size per vehicle during transfer : 2 x 6 one first crew flight, than 6 per launch window
6. Propellant type for Earth departure stage : LH2/LOX
7. Propellant source for TMI stage: Earth only
8. Propellant source for Mars ascent vehicle: CH4-LOX Earth- & Mars produced
9. Type of Mars ascent vehicle for crew : expendable
10. Propellant of Mars orbit departure vehicle (CH4-LOX Earth)
11. Earth capture by direct entry
12. Gravity during transfer : E-M after midcourse maneuver 0.3 g, none on return
13. Mars power plant type: solar & nuclear
14. Maximum crew size on Mars surface during life-cycle : 12
15. Duration of life-cycle (years): 7 + 15= 22

or described in a different way

Table 5-2 : Definition of subsystems required for program option 3

Mars surface infrastructure:	mission profile:	vehicle design:	crew system:
habitat nuclear and solar power plants rovers propellant production plants	no Earth orbit assembly, direct LEO departure, crew fast,cargo slow trajec-tories, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from low Mars orbit, direct entry into Earth atmosphere	Lox/LH2 booster stage, Mars propellants for ascent vehicle , Lox-CH4 Earth propellants for Mars orbit departure, expendable ascent & return vehicles,	6-per vehicle, 2 crew vehicles per mission ,partial gravity on E-M transfer after mid-course maneuver, on Mars surface 6 - 12,

Estimated logistic requirements for Mars infrastructure and supplies closely related to those of Option 2:

Table 5-3 : Estimates of logistic requirements for Mars infrastructure for option 3

Equipment inventory and operational requirements:	ref mass (MT)	ref. vol (m3)	dev. cost (M$)	unit prod cost (M$)	no. units	total mass (MT)	tot. oper. cost (M$)
pilot Mars station	30	200	500	100	1	30	600
workshop-laboratory module	30	250	100	200	1	30	300
surface habitat	30	350	2500	500	6	120	5500
physical /chem.life support system	3	10	500	100	4	12	900
thermal control system	2	10	200	100	4	8	600
water storage tank	1	10	10	10	2	2	30
EVA equipment	0.25	5	500	50	8	2	900
ISRU plant	1	5	500	50	6	6	800
10 kW solar power plant	2	10	200	20	5	10	300
3 kW PVA power	2	5	100	10	4	8	140
15 kW DIPS cart	2	10	100	50	3	6	250
160 kW nuclear power plant	12.5	100	2000	500	4	50	4000
PMAD and cables	3	10	150	30	3	9	240
communication system	1	1	50	10	3	3	80
plant growth facility	5	10	100	25	4	20	200
open rover for crew	0.5	10	50	10	8	5	140
pressurized rover for crew	6	50	100	25	4	24	200
science rover	0.5	1	50	10	8	4	130
science equipment	5	20	150	100	4	20	550
hand tools,machine tools	10	20	20	10	2	20	40
misc. and reserves	50	30	100	100	1	50	400
TOTAL	197	1117	7980	-	85	439	16300

In addition to the infrastructure facilities and equipment expenses accrue in connection with the operation of the Mars outpost. They are listed seperately, but exclude the cost of the space transportation system.

Table 5-4: Estimates of operational requirements for option 3

Equipment inventory and operational requirements:	ref mass (MT)	ref. vol (m3)	dev. cost (M$)	unit prod cost (M$)	no. units	total mass (MT)	tot. oper. cost (M$)
crew training and salaries	0	0	10	15	20yr	0	310
science support	0	0	100	100	20yr	0	2100
systems engng. & management	0	0	0	120	22yr	0	2640
consumables (food etc.)	10	20	10	20	6	120	130
clothes, hygenic materials	4	10	10	10	6	48	70
spares	4	20	50	50	6	24	350
hydrogen feedstock	5	30	0	5	6	30	30
Mars ascent vehicle partly fueled	12	300	0	0	6	72	0
totals	45	380	480	-	-	294	5630

Plotting these expenses for the Mars infrastructure acquisition and operation the floowing trend emerges:

Figure 5-1: Estimated distribution of budget requirements for the Mars infrastructure of option 3

The following space vehicles comprise the space transportation system supporting this program option logistically[14,15].

Table 5-4: Mass model and cost estimates for the space transportation system

	ELV+ TMI [[section]]	ERV	MLV	MAV #	CM *)	total
LC no.scheduled launches	15	6	15	6	6+6	
back-up launches	3	1	3	1	1+1	
launch mass (MT)	6000	120	110	30.5	36 + 6	
dry mass (MT)	752	6.5	6.5	6.2	30 + 6	
propellant mass(MT)	5174	63	22	24	0	
payload mass(MT)	110	30+6	89	3.0	0	
development cost(M$)	16430	1302	1895	2222	5285	27134
1st unit production (M$)	2872	163	131	250	696	0
total production cost(M$)	9155	1036	2140	1692	3708	17831
operating cost (M$)	1999	91	261	85	0	2166
total cost logistics(M$)	27585	2430	4296	3999	8993	47131
total cost per flight (M$)	1839	405	286	667	1499	-
direct cost for reuses (M$)	281	179	139	219	720	-

*) including a 30 MT flight habitat, and a 6 MT Earth entry capsules (ELV) ;
#) crew module integrated with ascent vehicle
[[section]]) including 12 units of the expendable TMI stage, stage 1 + 2 = reusable

The space transportation system has to provide as many flights as required to satisfy the logistic demand. The balance is summarized below.

Balance of logistic program:
Payload capacity of 18 scheduled launch vehicles planned:
6 crew vehicles x 65 MT 390
1 back-up to Mars orbit for return vehicle (110)
6 Earth return vehicles to Mars orbit (660)
5 cargo vehicles x 89 MT (max) 445
total Mars surface (MT) 835

The annual budget requirements have been estimated as follows:

Figure 5- 2: Annual cost of space transportation system vs.program life-cycle

The peaks showing up in this plott are due to the assumption that the cost of a newly purchased vehicle is paid fully in the year of delivery. This is a simplified assumption because in reality these cost are spread over three years. Thus it is possible to smooth this curve quite a bit.

Adding the infrastructure cost and the cost of the space transportation system the total cost picture is obtained. It is summarized below.

Cost Summary of program option :
Space transportation system 47,131 M $
Mars infrastructure acquisition and operation 21,930 M $
Total program cost 69,161 M $
Average annual cost during 22 year life-cycle 3,144 M $
Program effectiveness - 124 labor-years (M$/labor-year) 558 M $

The annual funding requirements for the entire program option show the following trend:

Figure 5 - 3: Estimated annual total cost of option 3 versus program life-cycle

In a more detailed study it is possible to smooth this trend. It also reflects the mission departure years which happen every two years during the respective launch window.

6. Mars Program Option 4 : Mars Laboratory

This option envisions a gradual growth of the outpost after a **7** year development phase to a full fledged Mars laboratory with nearly **50** people during a **30** year operational life-cycle. Total program duration: 37 years !

The initial phase of logistic operations is close to option 3, it may even follow it (!), but in the middle of this 30 year life-cycle the Earth the Mars passenger transportation system and the local Mars vehicle will be modified to allow a fully reusable mode. During the first 15 year phase arrival and departure will be in an highly elliptic Mars orbit(HEMO), during the 2nd phase in a low Mars orbit(LMO).

With 12 crew arrivals and 6 crew departures per launch window in the second half of the operational phase, the Mars crew will increase by 6 persons per launch window. The average duty cycles of the people on Mars will increase accordingly. Five years is the minimum, many will have to stay longer. If is is not considered acceptable, the number of flights and thus the cost of the operation will increase.

Reusable trans-Mars ferry to low Mars orbit and reusable Mars ascent- and landing vehicle (Mars-Bus) for passengers using Mars propellants (LH2+LOX), will dominate the second half of the operational life-cycle. However, cargo will arrive on one way flights directly at the Mars laboratory site.

Table 6-1: Summary of program attributes and parameters of program option 4

```
program attributes and parameters
1. no assembly operation in Earth orbit
2. Earth departure orbit: LEO
3. E-M-E ferry vehicle : expendable  1st phase, reusable  during  second phase
4. Number of vehicles  during a specific launch window : 2-4
5.  Crew size per vehicle : initially 6, later 2x6 per mission
6. Propellant type for Earth - Mars ferry: LH2/LOX
```

7. Propellant source for EM-ferry : Earth only
8. Propellant source for Mars ascent vehicle : mostly Mars produced
9. Type of Mars ascent vehicle for crew : reusable to and from low Mars orbit in 2nd phase
10. Propellant of Mars orbit departure vehicle (LH2-LOX Earth) -(item 6.)
11. Earth capture maneuver direct entry during 1st pahse, crew pick-up in LEO during 2nd phase
12. Gravity provisions during transfer : 0.3 g E-M, none on return
13. Mars power plant type: solar & nuclear
14.Maximum crew size on Mars surface during life-cycle : 48
15. Duration of program: 7 development + 30 operational years = 37

The nominal operational life-cycle is 30 years, but at the end there would be 48 people on Mars! In case the program would be discontinued at that point, these 48 persons have to be returned to Earth requiring some 6 to 8 return flights. These are not included in the program cost shown below. It appears more likely that an other operational period would follow the program option discussed here. In priziple these options are: (a) a gradual phase out, (b) continuation at the present level, and (c) growth to a permanent Mars base.

This program can be summarized also by subsystems as follows:

Table 6-2: Program characteristics by subsystems

Mars infra-structure	mission profile	vehicle design	crew system
habitat solar power plants and nuclear power plants rovers propellant production plants	1st phase: see option 3, 2nd phase: refueling Earth prop. & departure in low Earth orbit, 0.3 g, aero-capture to low Mars orbit and slow descent, crew changes to Mars bus, ascent, depart from low Mars orbit, LEO capture and pick-up by shuttle	Lox/LH2 booster stage, reusable E-M-E ferry vehicle , 0.3 g Lox-LH2 Earth propellants for Mars orbit departure, reusable ascent & return vehicles, cargo flights direct expendable	6 per vehicle, 2 vehicles per fleet, initially 12people on Mars surface growing to 42, artificial gravity Earth-Mars leg after midcourse, none on return,

The acquisition of the Mars infrastructure is estimated as for the options before. The development cost of the individual subsystems remained the same as for option 3, but the production cost increases with the number of units manufactured. This number in turn is increasing with the number of the crew members.

Table 6-3: Estimate of infrastructure requirements option 4

Facility and Equipment	dev.	p.a. or cos (M$)	total mass	tot.dev.& (M$)	requi
pilot Mars station	500	100	60	700	
workshop-lab module	100	200	60	500	
surface habitat	2500	500	240	6500	
phys./chem.life support system	500	50	30	1000	
thermal control system	200	100	10	700	
storage tank s	10	10	5	60	
EVA equipment	500	20	3	740	
ISRU plant	500	50	6	800	
power plants	2550	400	215	6750	
communication system	50	10	5	100	
plant growth facility	100	10	50	200	
mobility systems	200	35	84	620	
science equipment	150	100	50	1150	
hand tools,machine tools	20	10	50	70	
sub-total	7880	-	868	19890	

The operational cost can be conveniently separated from the development and production cost. A first (ROM) estimate has lead to the following tentative figures which grow with the size of the facility and the number of crew members as compared to option 3.

Table 6-4 : Estimate of operational requirements for the 30 operational years of a Mars laboratory (option 4)

operational requirements	dev. cost (M$)	p.a. or unit prod. cost (M$)	mass (MT)	tot.oper.cost (M$)
crew training and salaries	20	50	0	1770
science support	100	100	0	3600
systems engng.&management	0	200	0	5000
hydrogen feedstock	0	5	150	150
consumables (food etc.)	10	10	300	160
clothes, hygenic materials	10	10	200	210
spares	50	20	120	650
Mars ascent vehicle partly fueled*)	0	0	120	0
misc. and reserves	100	20	300	400
sub-total	290	415	1190	11940

*) cost included in space transportation system

A first estimate of the distribution of cost versus time shows the following trend.

Figure 6-1. Estimated annual funding requirements for the acquisition and operation of the Mars infrastructure for option 4: Mars Laboratory

Logistic system

Because this program envisions a change from expendable space vehicles to reusable vehicles (Mars ferry and Mars bus), modifications of the existing flight vehicles are required. These lead to the following specifications of a reusable interorbital ferry vehicle and a reusable Mars Bus for local transportation between the Mars surface and low Mars orbit:

Reusable Mars ferry:

The gross payload capability of standard 3-stage reusable NEPTUNE launch vehicle with launch mass = 6,000 MT to a 400 km LEO orbit remains 375 metric tons as discussed in option 2 and 3. It might be even higher due to the efforts within the product improvement program. The third stage of the standard HLLV will be modified to make a full round trip between low Earth orbit and low Mars orbit with a 600 day waiting time in Mars orbit before returning to LEO to be prepared for an other roundtrip to Mars. This is the same operational feature as the expendable ferry that returns to Earth orbit, but in this case no entry capsule would be required, because the crew will be picked-up by a shuttle and be brought back to the Earth surface!

Condiderable flexibility of performance and masses involved is available by changing departure mass, some refueling in Mars orbit and by accepting different flight times. In principle, either LH2/Lox or CH4/lox propellants could be used resulting in different launch masses.

Table 6-5: Characteristics of reusable MARS ferry vehicle

Ferry mass & performance :	
Earth Mars leg: launch mass : 375 (400) delta v = 4300 m/s injection + 200 m/s	Return flight: delta v return : 2500 m/s + 300 m/s maneuver in Earth orbit

maneuver c =4700 m/s u/c1 = 0.957 ; u/c2 =0.596 r1 = 2.604, r2 = 1.815 mass at Mars arrival LMO: 375 : 2.604 = 144 propellants used : 231 exchange of passengers and some cargo habitat with crew and supplies 40 dry stage 35 remaining propellants : 67

after aerobrake ; departure mass: 144 - 4 supplies = 140 cut-off after entry and orbit adjustment : 77 propellants used: 63, total propellants ferry : 231+63 = 294 reserves 2 dry stage and payload : 75

Reusable Mars Bus

The local Mars-Bus will now have a separate heat shield and be capabable to ascent to LMO, pick-up the arriving crews and return to the Mars surface. It will be stationed on the surface until the scheduled departure of a crew to Earth during the next launch window.

Table 6-6: Characteriatics of reusable Mars-Bus

Characteristics of the reusable Mars-Bus:
c = 4700 m/s; delta v up: 4200 m/s; delta v down: 500 m/s, total = 4700 m/s u/c = 1.00 , r = 2.718 crew module with crew : 5000 kg dry stage: 4000 kg (enlarged tanks for LH2/Lox propellants) residuals: 500 kg TPS : 1500 kg (added during manufacturing on Earth, reusable) cut-off : 11000 used propellants : 21 000 kg launch mass: 32 000

ascent maneuver: u/c =0.894, r = 2.445 mc = 32000: 2.445 = 13 088 m8= 18 912 landing maneuver with aerobrake: u/c = 500/4700 = 0.106 r=1.112 mc = 13 088 : 1.112 = 11 770 kg m8 = 1318, total m8 = 20 230 kg prop. reserves = 770 kg prop.fraction dry wo.TPS = 0.835 prop.fraction dry with TPS = 0.786

The anticipated flight plan can be summarized as follows:

Table 6-7: Number of scheduled flight missions

no,of launch window	crew flights to Mars	crew return flights	cargo flights direct	HLLV tanker flights	total HLLV flights	no of Mars-vehicle round-trips	size of Mars crew	av.no. labor years ##
1	0	0	3	0	4	0	0	0
2	2	1	1	0	4	1#	12/6**	14
3	1	1	1	0	3	1#	12/6	14
4	1	1	1	0	3	1#	12/6	14
5	1	1	1	0	3	1#	12/6	14
6	1	1	1	0	3	1#	12/6	14
7	1	1	1	0	3	1#	12/6	14
8	2*	1*	3	2	5	3*	18/12	22
9	2*	1*	3	1	4	3*	24/18	32
10	2*	1*	2	2	4	3*	30/24	40
11	2*	1*	2	1	3	3*	36/30	50
12	2*	1*	2	2	4	3*	42/36	59
13	2*	1*	2	1	3	3*	48/42	68
14	1*	1*	0	2	4	3*	48/42	68
Sum	20	13	23	11	50	27	av.20	423

*) reusable mode
**) one 6 person crew departs to Earth several month before the next crew arrives
#) ascent vehicle to HEMO only , expendable vehicles
##) with an average of 550 labor days per person per 760 day orbit cycle

The annual cost are estimated by simulation of the life-cycle with the TRASIM Code and show the trend depicted in figure 3.

Table 6-8: Cost summary space transportation option 4

vehicle	no.flights	1st unit cost	dev. cost	prod. cost	oper. cost	total
TMI stage	31.6	132	2351	3991	491	6834
cargo lander	7.4	168	1458	1377	91	2925
HLLV	53	2872	19204	9351	3493	32047
ferry	14.7	232	1269	520	103	1892
Mars bus	30.5	281	2733	2536	325	5595
sum vehicles			27015	17775	4503	49293
payloads			5285	5044	-	10329
total system			32299	22819	4503	59621

Preliminary estimates resulted in the following masses and cost during a 30 Earth year operational life-cycle using 14 launch windows.

The cost estimate for the space transportation system was optained by a simulation of the entire development and operational program as a function of time. The computer code used was the TRASIM program[10]. The total cost of nearly 60 B $ is plotted versus time in the following graph showing peaks in mission years and in years of vehicle replacements.

Figure 6-2: Cost trends for the logistic system of option 4

Adding the acquisition and operation of the Mars infrastructure cost and the development-, production and operation cost of all elements of the space transportation cost, the overall program cost can be determined. The turn out to bre below 100 B $ based of the assumption that there is no cost sharing with a lunar or other part of the space program. The average annual program cost remains below 3 B $!

Cost Summary Option 4:
Space transportation system 59,621 M $
Mars infrastructure 31,830 M $
Total program cost 91,451 M $
Average annual cost during 37 year life-cycle 2,472 M $
Program effectiveness - 423 labor-years (M$/labor-year) 216

The following plot versus time illustrates the financial requirements of such a program option.

Figure 6-3: Estimate of total annual program cost (logistics and infrastructure) of option 4

7. Mars Program Option 5 : Mars Base

This option envisions after a 10 year development phase a gradual growth of a permanent Mars Base during 12 launch windows and 25 (Earth) operational years, from the 1st year with 16 crew members arriving, and 8 crew members departing each launch window.

The passenger transportation system is comprised of reusable vehicles: (1) Earth launch vehicle to LEO, , (2) Mars ferry to and from MARS low orbit using Earth propellants, (3) MARS Bus for local transportation from LMO to Mars spaceport and back. The cargo transportation is a direct system using the reusable HLLV to LEO, an expendable trans -Mars injection stage (TMI) which provides also the aerobrake at LMO, and an expendable Mars lander. The Mars bus is now using only propellants locally produced.

Table 7-1: Architecture of a typical permanent Mars base

program attributes and parameters

1. Servicing of ferry vehicles in Earth orbit between two flights
2. Low Earth orbit is departure point for crew flights, cargo flights are one way direct from the Earth surface
3. Reusable Mars ferry vehicle
4. Number of vehicles during a specific launch window: 2crew, 4-2 cargo
5. Crew size per mission during transfer 2 x 8 = 16,
6. Propellant type for Mars ferry : LH2+LOX
7. Propellant source for ferry: Earth propellants
8. Propellant source for Mars Bus : Mars propellants
9. Reusable Mars -Bus
10. Propellant of Mars orbit departure vehicle (LH2-LOX Earth)
11. Earth capture maneuver to LEO
12. Gravity provisions during transfer 0.3 g both ways
13. Mars power plant type: solar & nuclear
14. Maximum crew size on Mars surface during life-cycle : 100
15. Duration of life-cycle: 10 development +25 operational years (years)= 35 LC

Table 7-2: Summary of program attributes and parameters of program option 5

Mars surface infrastructure	mission profile	vehicle design	crew system
initial habitat solar & nuclear power plants rovers propellant prod.plant	LEO departure after refueling Earth propellants, 0.3g,aero-capture to Mars orbit, pick up of crew by Mars-Bus, depart from low Mars orbit,aero-& rocket brake into LEO & pick-up of crew by shuttle, cargo flights direct	reusable HLLV to LEO, 3rd stage modified as TMI with heat shield, reusable crew version providing 0.3 g,, Mars propellants for reusable Mars Bus, expendable TMI and lander for caro delivery	8-per vehicle, 2 vehicles per mission, initially 16 people on Mars surface growing up to 100, artificial gravity on both transfer legs

Mars surface equipment and supplies during a 30 year operational life-cycle
can be estimated in somewhat more general terms due to the large capability of the transportation system and the uncertainties of this development scenario.
Equipment and operational requirements will be presented in different tables.

Table 7-3: Definition of infrastructure subsystems required for program option 5

Equipment inventory:	dev. cost (M$)	total prod. cost (M$)	total mass (MT)	tot.oper. cost (M$)
habitats ,workshops,-lab modules	3000	7000	560	10000
life support system	1200	2000	100	3200
ISRU plants	600	600	160	1200
power plants	2600	6000	300	8600
communication system	50	150	10	200
surface vehicles	200	400	200	600
hand tools,machine tools	50	50	100	100
spares	50	350	200	700
misc. and reserves	250	150	600	400
totals	8000	16700	2230	25000

Table 7-4: Operational requirements estimated for option 5 during 25 year life-cycle

operation	non-recurrent cost (M$)	annual cost (M$)	annual mass (MT)	cum life-cycle mass (MT)	life-cycle operation cost (M$)
crew training and salaries	200	100	0	0	2700
science support	200	160	0	0	4200
systems engng.& management	1000	240	0	0	7000
science equipment	500	100	4	100	3000
propellants	0	12	30	300	300

average consumables (food etc.)	100	8	16	600	300
av. clothes, hygenic materials	200	16	20	400	600
Mars -Bus hardware (cost below)	0	0	0	120	0
totals	2200	636	70	1520	18100

Operational requirements of option 5

Distributing these estimated cost over the 10 years of development and 25 years of operation the following trend for the expenditures or financial requirements respectively would have to be expected.

Figure 7-1: Estimated annual cost of infrastructure acquisition and operation

The total delivery requirement of cargo is of the order of **3,800** metric tons
which in turn require about 42 flights with 89 metric tons. Adding 2 flights
as a 5% reserve, this allows a total transportation volume of 3916 metric tons
or in round figures 4,000 MT. This figure is the basis for developing a flight schedule for cargo deliveries. In addition the passenger requirements must be satisfied. These can be handled by two flights with 2x8 people during each launch window. It should be noted, that the following table is arranged as function of launch windows and not of calender years on Earth.

Table 7-5: Typical flight schedule for program option 5

no,of launch window	crew flights to Mars	crew return flights	cargo flights direct	HLLV tanker flights	total HLLV flights	no of round-trips	size of Mars crew	av.no. labor years #
1	2	2	3	2	5	2	16/8	18
2	2	2	3	2	5	3	24/16	30
3	2	2	3	2	5	3	32/24	42
4	2	2	3	2	5	3	40/32	54
5	2	2	4	2	6	3	48/40	66
6	2	2	4	2	6	3	56/48	78
7	2	2	4	2	6	3	64/56	90
8	2	2	4	2	6	3	72/64	102
9	2	2	4	2	6	3	80/72	114
10	2	2	4	2	6	3	88/80	126
11	2	2	4	2	6	3	96/88	138
12	2	2	4	2	6	3	104/96	150
Sum	24	11	44	22	68	27	av.67	1008

Table 7-6: Total cost of space transportation system(M $)

vehicle	number of flights	1st unit cost	dev. cost	prod. cost	oper. cost	total cost
TMI stage	48	128	2226	6208	707	9196
cargo lander	48	267	1416	13090	173	14722
HLLV	62	2872	17234	9394	3804	30676
ferry	25	233	1677	745	205	2627
Mars bus	38	153	1013	1070	338	2421
sum			23596	30508	5227	59641
payloads			5024	2188	-	7212
total			28620	32697	5227	66543

Adding the cost of the infrastructure acquisition and development and the cost of space transportation system based on the flight schedule schown in table 3-29 the program cost are obtained.

Figure 7-2: Estimated annual logistic cost of option 5

Cost Summary Option 5:
Space transportation system 66,543 M $
Mars surface equipment 25,000 M $
Mars operation 18,100 M $
Total program cost 109,643 M $
Average annual cost over 35 years 3,133 M $
Program effectiveness - 1008 labor-years (M$/labor-year) 109

Figure 7-3: Estimated annual total program cost of option 5

This concludes the discussion of option 5. The prime characteristics of all Mars program options analysed can now be presented and compared to establish general trends of performance parameters versus size of the Mars facility.

8. Overview of individual Mars Programs

Considering the options:
1. Single Mars expedition
2. Multiple Mars expeditions
3. Mars outpost
4. Mars laboratory
5. Mars base

in some detail, the following preliminary estimates have been made for the mass and cost of the facilities and equipment required on the surface of Mars:

Table 8-1: Facilities and equipment mass requirements estimated for Mars program options 1 - 5 during their respective life-cycles (metric tons)

Equipment inventory:	option 1	option 2	option 3	option 4	option 5
habitats ,workshops,-lab modules	81	181	182	365	560
life support system	11	11	22	43	100
production plants	7	12	26	56	160
power plants	63	42	83	215	300
communication system	2	2	3	5	10
surface vehicles	14	16	33	84	200
hand tools,machine tools	10	10	20	50	100
spares	4	12	24	120	200
Mars -Bus hardware (cost below)	36	48	72	120	120
propellants	0	15	30	150	300
science equipment	3	10	20	50	100
consumables (food, etc.)	10	30	120	300	600
consumables (clothes etc.)	4	12	48	200	400
misc. and reserves	5	61	50	300	600
total	250	462	733	2058	3750

Table 8-2: Cost of facilities and equipment estimated for options 1 - 5 during their respective life-cycles

(million $)

Equipment inventory:	option 1	option 2	option 3	option 4	option 5
habitats ,workshops,-lab modules	4120	5420	6430	7760	10000
life support system	2100	1850	2400	2440	3200
production plants	710	740	1000	1000	1200
power plants	1140	3560	4930	6750	8600
communication system	120	70	80	100	200
surface vehicles	460	330	470	620	600
hand tools,machine tools	30	30	40	70	100
spares	100	200	350	650	700
misc. and reserves	50	400	400	400	400
TOTAL	8830	12800	16100	19790	25000

Table 8-3: Operational requirements estimated for options 1 - 5 during their respective life-cycles (million $)

operation	option 1	option 2	option 3	option 4	option 5	
crew training and salaries	120	130	310	1770	2700	scienc
systems engng.&management	1000	1200	2640	5000	7000	
science equipment	200	300	550	1150	3000	
propellants	0	15	10	150	300	
consumables (food etc.)	20	70	130	160	300	
clothes, hygenic materials	30	40	70	210	600	
totals	1970	2455	5810	12040	18100	

Table 8-4: Space transportation system cost estimated for options 1 - 5 during their respective life-cycles (million $)

operation	option 1	option 2	option 3	option 4	option 5
development cost	20789	25820	27134	32299	28620
production cost	11617	14954	17831	22819	32697
operation cost	1516	1151	2166	4503	5227
total space transportation cost	33922	41825	47131	59621	66543

What remains to be done is an estimate of the relative benefits of these program options with respect to their likely contribution to the quality of life on Earth.
A practical method has been developed that can be used as the frame of reference for this benefit assessment, because it has determined the benefit potential of Mars programs in general for the years 2050 and 2100. For an initial estimate,
the potentials determined for the middle of the 21st century will be used.

Table 8-5: Preliminary assessment of benefits to be expected by the programs selected by the year 2100

	OPTION	2100 Max	single expedition	mul-tiple expe-ditions	Mars out-post	Mars labo-ratory	Mars base
A	HUMANISTIC OBJECTIVES	732	53	115	210	402	616
a.1	enhance the evolution of the human culture beyond Earth	520	20	50	100	250	400
a.2	establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system and learn to live in isolated, extreme environments	60	5	10	20	30	60
a.3	enhance the educational system and motivation to learn	16	3	5	10	12	16
a.4	provide a survival shelter for	90	10	30	50	70	90

	artifacts, documents and some elements of the human race in case of a global catastrophe						
a.5	assist in reducing tensions +conflicts, thus contributing to peace on Earth	10	10	10	10	10	10
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	40	5	10	20	30	40
B	POLITICAL OBJECTIVES	205	60	70	115	155	190
b.1	demonstrate the potential growth existing beyond the limits on Earth	40	10	10	20	30	40
b.2	provide more opportunities for international cooperation	30	10	10	15	25	30
b.3	extend the infrastructure and experience for global enterprises	30	10	15	20	25	30
b.4	provide a peaceful outlet for national, competitive high technology urges and a useful employment of existing industrial-military capabilities	45	10	20	30	35	40
b.5	enhance the national pride and prestige of participating nations	60	20	25	30	40	50
C	SCIENTIFIC OBJECTIVES	585	80	140	205	315	420
c.1	improve the understanding and control of our own planet	45	5	10	15	35	40
c.2	improve our knowledge of the Moon and its resources	90	10	20	30	50	70
c.3	improve our understanding of the solar system beyond the Earth-Moon double planet	240	50	75	100	140	200
c.4	improve our understanding of the universe beyond our own Solar System	150	10	20	30	40	50
c.5	provide a science laboratory in a unique environment for experiments in physics, chemistry, biology, geology, physiology and sociology which can not be conducted on Earth	60	5	15	30	50	60
D	UTILITARIAN OBJECTIVES	321	84	115	148	212	267
d.1	provide rewarding job opportunities and thus stimulate the economy on Earth in general	15	4	5	7	10	12
d.2	stimulate the development of the educational system and advanced technology on Earth	60	10	20	30	40	50
d.3	produce marketable products for extraterrestrial and for terrestrial use	6	0	0	1	2	5
d.4	contribute to the supply of space based energy to the the Earth	0	0	0	0	0	0
d.5	provide an isolated extraterrestrial depository to store high level wastes	0	0	0	0	0	0
d.6	enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources	120	40	50	60	80	100
d.7	provide thrust and focus for continued development of space technology other than in the area of space transportation systems	120	30	40	50	80	100
	total benefits expected	1843	277	440	878	1084	1493
	percent of maximum		15	24	48	59	81
	total program cost		42.4	56.6	70.2	91.5	109
	benefit/cost		6.5	7.8	12.5	11.8	13.7

The information listed above is needed for the comparison of individual Mars mission programs. This will be done in a first step under the assumption that there are no interrelationships to other space programs.

Now it is possible to compare the primary characteristics of all five options analysed.

Table 8-6: Overview of Mars Program Options

	1	2	3	4	5

Option

Mars facility:	single expedtion	multiple expedition	Mars outpost	Mars laboratory	Mars base
program duration (years)	11/14	15	22	37	35
operational period(years)	4/7	8	15	30	25
total labor years on Mars	7(14)	20(30)	124	423	1008
total mass imported (MT)	250	462	733	2058	3750
tot.production on Mars (MT)	0	120	600	2500	5000
max.no. of crew members	6	6	12	48	100
no. of passenger roundtrips	6	18	36	120/78	192/88
av.space duty cycle of crews	3 years	3 years	5 years	5 years	10 years
reserve transp. capacity (%)	50	33	10	5	15
cost of Mars GSE & supplies	10.800	14.755	21.930	31.830	43.100
cost of space transportation	33.922	41.825	47.131	59.621	66.543
total program cost (B$)	44.722	57.080	69.161	91.451	109.643
cost per Mars labor-year (M$)	6 390	2854	558	216	109
average annual program cost /calender year over life-cycle	3.195	3.805	3.144	2.472	3.133
total benefits expected	277	440	878	1084	1493
benefit/cost	6.5	7.8	12.5	11.8	13.7

The trend of systems effectiveness which drops by almost two orders of magnitude by going from a single expedition to a permanent Mars base comes out more clearly in the following graph, illustrating the specific cost per Mars labor year as a function of total labor years performed on Mars during the anticipated life-cycle. However, the fact must be observed that these program options do *not yet* take into consideration the cost savings obtainable by cost sharing with other partial space programs, such a a lunar program.

9. Outlook on future work

9.1 Resolving Remaining Issues

While representative program options have been analysed it must be admitted that many issues require further study and must be resolved before a final choice of a mission concept and program architecture can be made. The major known issues in this area are the following:

(a) Mars surface system:

1. What information on Mars has to be provided by the present class of small robotic systems, before the next phase of Mars exploration with heavy robotic equipment can be initiated?
2. How many unmanned cargo flights with a heavy lift launch vehicle transporting heavy equipment and supplies to Mars and on what kind of a schedule will have to preceed the first crewed flight?
3. What are the minimum or allowable rates of facilities, equipment and supplies per person and per unit time as function of operational life-time?
4. Do we need to demonstrate the production of extraterrestrial propellants on the Moon first before we send people to Mars?
5. Do we need to demonstrate the know-how of extraterrestrial construction/life-support systems and manufacturing techniques on the Moon before dispatching people to Mars?
6. Do we need nuclear power plants on Mars and can they be ready on time considering all the technical, financial and political risks connected with nuclear systems?
7. How many people on a Mars expedition and/or regular supply flight are acceptable as the bare minimum for survival?
8. What duty cycles are acceptable for Mars crew members as a function of time and facility size?
9. Should a Mars crew eventually be trained on the Moon, depart from there and return to the Moon before getting back to Earth?

(b) Space transportation system:

1. Do we first have to demonstrate that Mars propellants can be produced for the return trip before we commit a Mars crew?
2. How much redundancy is required with respect to passenger flights? Do we send two ships capable to transport all passengers on either ship at each opportunity?
3. Do we have to provide artifical gravity for passengers during the transfer flight to and from Mars?
4. Which options are available for the crew to return safely to Earth in case of mishaps?
5. When and how do mission profiles change, e.g. departures from a high elliptic Earth orbit instead from a low Earth orbit, which may be desirable in case lunar oxygen can be provided.
6. Under which circumstances is it justified to develop a propulsion system other than chemical (e.g.nuclear) and thereby postpone crewed flights?

(c)Programmatics:

1. Which is politically and economically the best time(year) to initiate the crewed Mars exploration program?
2. Will the Mars moons have a place in the human exploration program?
3. What kind of financing arrangement is the minimum requirement for a stable program?
4. What must be done to enable an international organization to manage such an undertaking effectively?
5. How can be assured that experienced and competent managers are selected for the program and that they stay on the program for a reasonable time?

9.2 Planning efforts to improve credibility and accuracy

The database of Mars exploration opportunities and program concepts is far from satisfactory. The data presented in this and other reports allow a good understanding of the basic problems, technical requirements, even the cost and benefit structure, however, more accuracy is needed. The cost estimates in this report appear to be more accurate than they are, they are produced by mathematical models. At least a ten percent margin is to be expected, particularly because the management structure and the relevant experience of the key personnel to head this effort are unknown. To improve the accuracy of this early model requires more effort and takes longer time. The accuracy of the available planning information can be improved by the following activities:

I. Provide more accurate data of Lunar and Mars facility concepts, such as
* including the cost reductions achievable by maximizing commonalities with other partial space programs,
* the effectiveness of a crew with number of crew members,
* specific time lines of crew activities.

II. Extend the method of benefit estimates to the next level of complexity by:
* assigning relevant one-dimensional and two-dimensional performance parameters as indicators of benefit to each of the defined objectives,
* assigning specific values of these indicators as goals for the year 2100 or any other year,
* assigning a utility function to each of these indicators,
* integrating all of this into a mathematical benefit model.

III. Attach this refined benefit model to an existing program that can simulate on an annual basis the performance of individual or combined extraterrestrial base programs.

IV. Develop a suitable risk model that allows to differenciate between subsystems with a long reliability record and others newly developed. The subsystem reliability should also take into consideration the relative complexity, redundancy provided and number of units manufactured as well the frequency of application. The influence of funding should not be overlooked.
This risk model should then be integrated into the benefit model.
This would allow to optimize the best possible combination of Moon / Mars exploration and utilization programs at any desired cost level, while keeping the peack funding during the acquisition period as flat as possible. Many trade-offs could than be made depending on the preferences of the potential investors.

9.3 Methodical improvements on measuring program performance

In many cases simple evaluation models will suffice using only a few *representative indicators* . Such simple intuitive indicators of performance using one parameter only, either on the basis of
(a) Cumulative values over a given period of time, or
(b) annual averages during the system life-cycle. Examples are:
* total number of spaces at extraterrestrial facilities,
* number of scientists in situ,
* number of people with actual space experience at the end of life-cycle,
* number of people employed in the extraterrestrial space program,
* tons of extraterrestrial products available for local use,
* tons of extraterrestrial products available for commercial sale.

The next level of complexity are *performance ratios* using two or more parameters. These again could be
(a) cumulative or
(b) on an annual basis.

Examples are:
(1) Systems life-cycle cost per lunar/Mars labor-year (M $/labor-year)
(2) Systems life-cycle cost p. lunar/Mars science year (M $/laboratory workplace)
(3) Systems life-cycle cost per unit mass produced on the Moon/Mars (M $ /t)
(4) Base facility mass percrew member (t/ person)
(5) Imports per crew member (t p.a./ person)
(6) Extraterrestrial products manufactured per crew member (t p.a./person)
(7) Share of import mass per unit mass of extraterrestrial products (%)
(8) Mass of extraterrestrial products per unit mass of facilities (t p.a./t)
(9) Installed power per unit mass of extraterrestrial products (kW/ t p.a.)

Of particular interest are the composition and effectiveness of the crew as function of time during the anticipated life-cycle, such as:
a. Share of total crew required for housekeeping, maintenance & repair as functions of total crew (percent).
b. Relative effectiveness of crew as function to total crew size.
c. Annual number of labor-hours as function of crew size.
d. Annual number of labor-hours as function of facility life duration.

These functions should be taken into consideration when it comes to a final choice between options of nearly similar performance.

The method presented and used for estimating the benefits of extraterrestrial bases is neither the only one nor the best one. There is room for improvement.

10. SUMMARY AND CONCLUSIONS

10.1 Summary of the report

The human exploration of Mars remains an issue of interest to the space enthusiast and the general public as well. NASA has developed a Mars Reference Mission which is supposed to serve as a basis for detailed discussions among the specialists.

To complement this NASA reference mission, an analysis has been performed of five different program options from a single mission to a permanent Mars Base with about 100 people and life-cycles from seven to 37 years:
1. Single Mars Expedition
2. Multiple Mars Expedition
3. Mars Outpost
4.Mars Laboratory
5. Mars Base

These are based as "stand alone" concepts which do not take into consideration the savings that can be achieved by cost sharing with other programs, such as a lunar base program. Such savings are about 20 to 30 percent! The primary characteristics of these facilities including performance and cost data are presented. One good indicator of program performance is the specific cost per man-year (labor-year) available on Mars for science, production and housekeeping. The trend obtained in this analysis is shown in figure 10-1.

Figure 10-1: Trend of specific cost per 365 day labor-year on Mars as a function of life-cycle labor years without cost sharing by other programs

An other interesting parameter often discussed are the specific transportation cost per passenger seat for roundtrips between Earth and Mars. These are independend of the duty cycle of these crew members on Mars. The trend estimated is illustrated in the next plot.

**Figure 10-2: Average cost per passenger seat for Earth-Mars roundtrips
without cost sharing by other programs**

It should not be overlooked, however, that this is a very simplified model. In reality, one has to take into consideration that a very small crew on Mars would have to struggle to survive, and little time will be left to explore a planet with a land surface comparable to that of the Earth. In a more refined assessment one would have to take into consideration, that the percentage of available labor-hours for research, external services and production will increase with size of the crew! In other words the overhead burden will decrease. This will move the optimum effectiveness in the direction of larger crew numbers.

In addition to a classical performance analysis, an attempt has been made to determine the relative benefits expected to be derived from these mission concepts in a more general frame of reference. A "Quality-of-life" model is the basis for deriving a special model for extraterrestrial bases. Preliminary benefit/cost ratios indicate which program options are the most promising ones to be recommended for further study. The expected relative benefits of these typical programs have been estimated and are presented in figure 10-3. Interpreting these as a measure of goal achievement, they can be plotted versus total cost. The result is shown in figure 10-4.

`Figure 10-3: Relative  benefits of Mars program options`

`Figure 10-4: Goal achievement vs cost of Mars options`

Additional refinements of the proposed concepts and improved tools for program analysis are proposed. As far as the timing of a human Mars program is concerned, this is a very open question. The key is funding. But there is an estimate on possible and likely milestones available, it was obtained by a group judgment of 18 people made in December 1997.

Table 10-1: Estimated range of milestones on future Mars exploration

Some Governments, represented by their Space Agencies are **entering a formal agreement** to make a multi-year joint planning effort with the objective to prepare feasible options for a piloted MARS exploration program:
the earliest possible year the most likely year

2001	2005	2010	2006	2010	2020

Assuming that the event listed under 4. above is producing the desired results and the interested governments

come to an agreement to proceed with crewed Mars exploration **the first allocation of funds to** enable the beginning of the development of long lead time items could be available by :
the earliest possible year the most likely year

2004 2006 2012 2010 2012 2022

Assuming that the development phase of crewed Mars program (incl.the facilities, equipment and space transportation system) is proceeding without major technical, financial or political hitches, **the first crew could arrive on the Mars surface** :
the earliest possible year the most likely year

2013 2017 2025 2018 2025 2032

10.2 Conclusions

1. A separate program for human exploration of Mars appears technically feasible, although it remains to be a very risky endeavor. The cost of the smallest Mars program are close to 50 billion $. It would require a development and operational phase lasting about 17 years. The benefits of a marginal low cost program might not be worthwhile an investment of this size. If the Mars program would follow a lunar base program its risks and costs would be greatly reduced, and the benefits would thus be enhanced.

2. Of the five options analysed and presented in this report, option 3 a *Mars Outpost* operating for about fifteen years, looks presently most attractive as an initial program. It is the cheapeast program in absolute terms of those alternatives achieving nearly the same benefit to cost ratio. Mars programs with a limitation of the crew size to six are not recommended in case the exploration of Mars is the primary mission objective. It must be expected that very little spare time for Mars science will be available of the six people, even if they are healthy. Most of their time will be used for essential activities such as housekeeping, maintenance and repair activities.

3. It is also of no surprise, that in general the largest Mars facility, option 5 a*Mars Base* has the best benefit/cost ratio, but also the highest absolut cost. This shows in a modest way the plausibility of the model used for this system analysis.

RECOMMENDATION:

It appears desirable to develop - by additional planning efforts - an integrated Moon-Mars program that keeps the expenses below an annual rate of 10 B $ (2 percent of the then expected annual global defense expenditures). It has to begin with the development of a universal space transportation system and lunar infrastructure to be extended and modified for use on Mars. The growth rates of the lunar and Mars base should be governed by a ceiling of 10 B $ p.a. and about equal budgets for both partial programs after the initial acquisition. Such a program can be optimized with respect to joint benefits and may be considered as adequate, attractive, and affordable by the responsible decision-makers and the general public involved in such a program decision some time during the first decade of the 21st century.

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