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Return to the Moon to stay and going on to Mars -
A feasible scenario for the first half of the 21st Century

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Abstract

In July 1988, on the occasion of the 20th anniversary of the first landing of humans on the surface of the Moon, President Bush proposed *to return to the Moon to stay and going on to Mars* . Shortly thereafter the cold war ended with the dissolution of the USSR and the U.S. congress did not feel that this was the right time to start a new major enterprise in space. With the completion of the International Space Station, now planed for 2003, an answer is due on *what comes next ?* It appears advisable to have optional plans ready at that time to answer this question. This report outlines an integrated program for a Lunar Base combined with a Mars Laboratory for the first half of the 21st century. It would see about 230 people on the Moon and nearly 100 people on Mars by 2050. Representative base characteristics, benefit and cost data are derived, which indicate that such a program is feasible, desirable and affordable.

This report comprises 63 pages, 40 tables, 15 figures and 30 references.

Table of Contents

List of tables and figures

1.Introduction

1.1 Past planing efforts

The idea of building extraterrestial bases on the Moon and on Mars is not new. There is a long record of proposals in this direction, particularly after Wernher von Braun published his "Mars Project" in 1951/53[1]. After the APOLLO program was defined by the end of 1962 and the hardware development got underway, some NASA planers at headquarters and in the centers studied alternative programs for the time after APOLLO. Lunar outposts for the later seventies and a Mars expedition in the 1984-86 period were subjects of detailed planning[7].

With the end of the APOLLO project and the fiasco the United States suffered in Vietnam, it was difficult to motivate the Nixon Administration to undertake a new major space program. A NASA task group proposed an updated Lunar and Mars Program along with a space station and a reusable launch vehicle[4]. A Mars mission before the end of the century was proposed. However, only the Space Shuttle was approved as a new start 1972, all government sponsered studies of lunar and Mars missions came practically to an end in the following years.

In 1985 a National Commission on Space was mandated by the U.S.Congress and the President and charged with the task to recommend a civilian space program that was to advance the broader goals of American society in the next century. The Commission proposed in his report a future-oriented civilian space agenda with three mutually-supportive thrusts[5]:

Advancing our understanding of our planet, our Solar System, and the Universe;

Exploring, prospecting, and settling the Solar System;

Stimulating space enterprises for the direct benefit of the people on Earth.

To accomplish them economically, it was concluded, that the Nation must make a long range commitment to two additional thrusts:

Advancing technology across a broad spectrum to assure timely availability of critical capabilities; and

Creating and operating systems and institutions to provide low-cost access to the space frontier.

In its report the Commission outlined in broad terms a vision of the next 50 years as seen at that time. A lunar outpost was considered feasible by the year 2005, with propellant production to begin on the Moon about 2013. A first human outpost on Mars was expected by 2015 and a full base by 2028. Unfortunately, a short time later the loss of the Challeger Shuttle shocked the nation to the point that the appetite for more advantures in space was very limited. In spite of this disappointment, in 1985 the President of the United States - as a result of this nation wide effort - proposed an International Space Station as a first step in the direction proposed. This *ISS* is taking shape in these years and is supposed to be completed by 2003.

Several detailed studies followed this line of thinking during the eighties. The results of these studies prompted President Bush to propose at the ocasion of the 20th aniversary of the first Moon landing in July 1989 a *Space Exploration Initiative* (SEI). This had the goal "to return to the Moon to stay and go on to Mars". Again the timing selected was unfortunate, because only three month later the Berlin wall came down, the Soviet Union disintegrated and the cold war came to an end. The competition of two social systems was over and there was no reason to prove at that time to the world that the capitalist system is better than the communist system. Thus the U.S.Congress did not go along with the SEI proposal of the President.

The knowledge acquired in this period of planning was compiled by a *Synthesis Group* , appointed by the President, to document the potentials of future space activities as envisioned in the space exploration initiative[11]. This report was more detailed in the technical and programmatic area than past documents. Many guidelines for the development and operation of extraterrestrial facilities were developed. Among other conclusions, it was pointed out that heavy lift launch vehicles are the way to go and that on-orbit assembly requiring extravehicular activities should be eliminated or minimized. The Synthesis group expected a permanent lunar facility to be established between 2010 and 2015 and a first human mission to Mars by 2016. The report did not make an attempt to derive a cost estimate for such an enterprise. Consequently, these proposals were questioned by the public and there was the suspicion that this might add up to a 500 billion program. The media and the U.S.Congress were not willing to support such an ambitious space program at that time. It took almost a decade before NASA had the courage again to publish a *Mars Reference Mission* to reopen the discussion of long range space projects[14].

In addition to these national efforts, the International Academy of Astronautics took up the challenge of finding ways and means to develop extraterrestrial bases in the 21st century. It published two *COSMIC* studies in 1990 and 1997 to compile the state-of-the-art as seen from an international standpoint[9,16]. These studies on an *International Lunar Base* and the *International Exploration of Mars* were the basis for a third study. This attempts to show the way for an international effort to acquire and operate a Lunar Base and a Mars Laboratory within an integrated program[28]. To develop suitable program options at this time is considered importent, because a few years from now, probably before the ISS is completed, the question will come up again: *What is next?* Preparatory steps can be undertaken by groups outside the Space Agencies, but these have to join to develop a program that is acceptable to the public and the participating governments. Official steps towards a government sponsered international planning effort for a space program of the 21st century have yet to be undertaken.

In the meantime, additional system studies are made and should be continued to support such a future effort. This report is one of those. It is a case study of one particular solution to the problem, that is considered attractive and may be used as a point of departure for further analysis. The accuracy of performance and cost estimates is of a quality that is satisfactory to enter a debate of the pros and cons of such an enterprise.

1.2 Program structure

The purpose of this study is to define an integrated Moon-Mars Program for the 21st century that appears feasible, desirable and affordable from the viewpoint of the author, using fifty years of experience in the field. It will attempt to meet the following conditions, envisioned as political demands a few years hence:

1. The phased program must consider compatible facilities on the Moon and on Mars.

2. The program should be optimized on the basis of global benefit and risk criteria.

3. The program must allow authorization of stepwise funding from phase to phase.

4. The expenditures should reach the 1 billion dollar level not before the year 2007; the average annual expenditures should remain below 5 billion (1999) US dollars; the funding peak to be expected during the years of acquisition, should not exceed this limit by more than fifty percent.

5. The average annual expenditures for both extraterrestrial bases should be of the same order of magnitude and proportional to the expected benefits.

6. The program should employ a universal reusable space transportation system

unless expendable systems are more economical for individual legs.

7. The program should also consider use of lunar propellants for the Mars ferry vehicle if proven to be economical.

8. The program structure should be such that it encourages commercial participation at the earliest possible time.

1.3 General selection criteria

The program options have to be analysed and documented to a detail that potential investors would expect. The program to be selected eventually has to satisfy each of the following criteria to a high degree28:

a. Acceptable risks of the enterprise. -

These have to be spelled out explicitly and be taken into consideration in terms of probable mission success.

b. Minimum cost at comparable benefits. -

In this context, the program benefit is tentatively defined as the *sum of the cumulative degree of goal achievement of the partial programs.*

c. Smoothness of annual financing requirements. -

The program should minimize peaks of financial requirements during the life cycle with the preference of a constant share of the gross national products of the participating nations.

d. Ability to complete distinct program phases in a finite time.-

To the decisionmaker it must be clear, that he does not enter an indefinite program. Individual program phases, accompanied by respective benefits, must be accomplished within one or two decades. The program must be set up in such a way, that it can be reviewed periodically (i.e. every five years), and be upgraded or downgraded as the political and economical situation requires.

e. Growth potential

The inherent capability to expand the systems performance relatively fast and economically in case of need.

1.4 Master-schedule

The overall schedule should be developed in such a way, that the annual cost are below the established limits and the benefit optimized. To be able to start this optimization process, some kind of master schedule must be assumed as a point of departure. The following *milestones* are assumed:

2001

The newly elected President of the US invites interested countries to join a multi-year, multi-national planning effort for the human exploration of space during the 21st century, beyond the approved international space station program in near Earth orbit.

2002

Memorandum of agreement on establishing a planning office with participation of the interested countries.

2003

Initial plans are completed offering several program options for general discussion of goals, strategies and policies.

2004

Presentation of a first phase of an initial program plan to potential participants.

2005

Agreement of a coordinated pre-development phase on critical technologies within the national organizations without exchange of funds; development of system specifications by the planning office and participants.

2006

Refinement of program plans.

2007

Program selection and approval for first development phase including first phase financing, final agreement of distribution of work packages/subsystems among participants.

2010

Program approval for second development phase for all hardware projects required for the beneficial occupancy of a first extraterrestrial outpost; approval of management structure for joint development organization.

2011

Authorization of multi-year major funding by the program partners.

2015

First demonstration flight with cargo deliveries beginning to the first extraterrestrial outpost site.

2016

First human crew activates first extraterrestrial outpost.

2020

Authorization for development of all hardware elements for a second extraterrestrial facility.

2023

First equipment deliveries to the second extraterrestrial facility.

2026

First human crew activates second extraterrestrial facility.

2050

Arbitrary cut-off of program phases planned!

2. Infrastructure development of extraterrestrial installations

2.1 Initial technology program (2005 - 2007)

During the initial planning process technologies will be identified which are considered critical with respect to the timely feasibility of the next program phase.

Potential contributors will indicate to accelerate respective research and development activities in their own national facilities and commit themselves to do this in a coordinated fashion, but without exchange of funds. The next tables are a typical list of critical technologies. These are listed in two categories: infrastructure and equipment of extraterrestrial facilities and space transportation systems.

A group judgment was performed in 1998 with 15 people participating, to make an early *estimate on the state of the technologies* required for Moon and Mars base programs before final options are developed.

Legend :

1 = slight advances required ,

2 = considerable advances required,

3 = major advances required,

4 = entirely new development required ,

MY = effort in terms of labor-years required(cumulative no.of years)

Table 2-1: Base infrastructure and equipment pre-development

Improved technologies required	Moon	Mars	MY ROM
Space suits for surface operations	1.70	2.70	500
propellant production facility	2.40	2.90	350
food production facility	2.67	3.22	325
biological waste recycling equipment	2.56	2.56	300
energy beaming	3.20	3.40	450
remote exploration from secure positions	1.40	2.20	400
open personnel roving vehicles	1.60	1.90	100
closed personnel roving vehicles	2.18	2.64	120
multi-functional front loaders	2.12	2.25	80
photo-voltaic solar power farms	1.67	2.12	160
mineral analysis	1.10	1.44	20
beneficiation equipment	2.13	2.25	50
portable life support systems	2.00	2.40	180
robotic construction equipment	2.45	2.73	320
Total in the area of base infrastructure			3355

3,355 labor years are the equivalent of about 670 M $.

Present state of the relative availability of required technologies was estimated by a group judgement in 1998 as shown in the next table.

Table 2-2: Space transportation systems

Legend :

1 = slight advances required ,

2 = considerable advances required,

3 = major advances required,

4 = entirely new development required ,

MY = effort in terms of labor-years required(cumulative no.of years)

Improved technologies required	Moon	Mars	MY ROM
vehicle/personnel non-invasive monitoring	1.57	1.86	20
automated failure detection systems	1.90	2.40	300
spacecraft radiation protection	1.67	2.22	200
ruggedness of reusable space subsystems	2.25	2.50	200
space assembly procedures and equipment	1.78	2.44	250
highly autonomous space systems	1.90	2.60	500
on board crew health support equipment	1.50	2.38	20
high data rate communication systems	1.30	1.90	200
on board high energy storage devices	2.44	2.44	225
solar heated propulsion systems	2.00	2.38	290
high temperature materials	1.50	1.78	180
vehicle system control and management	1.25	1.50	150
data processing and valuation	1.30	1.60	150
low maintenance systems	2.00	2.50	220
superinsulation	1.57	1.71	40
subtotal of pre-development activities in the area of space transportation systems through the year 2006			2,945

2,945 direct labor-years are about 590 M $. It is assumed that most if not all of these technology deficits will be eliminated by the year 2007 by coordinated national efforts.

2.2 Combined infrastructure development

The initial goal of this part of the program is the development of an integrated extraterrestrial base infrastructure under long term aspects. Available technologies and subsystems will be used to reduce risk and cost. Such a multinational technology development program begins with designing a model typical, or even representative for the infrastructure required at a Moon base and a Mars laboratory. While these ROM (rough order of magnitude) estimates are crude, they have been derived by using analogy models. They can have to be improved in the process of developing individual specifications.

Table 2-3: Extraterrestrial base infrastructure development cost assumptions

Equipment requirements:	**general develop-ment cost (M$)**	**Moon specific add on (M$)**	**Mars specific add on (M$)**	**total program dev.cost (M$)**	**unit prod cost (M$)**
initial crew training infrastructure	**20**	30	10	60	0
science support cost on Earth infrastructure	**50**	50	30	130	0
initial pilot station	**100**	100	50	250	100
laboratory module	**500**	500	100	1100	150
central workshop	**100**	250	50	400	100
standard surface habitat module	**1500**	200	200	1900	300
phys./chem.life support system	**300**	100	100	500	100
thermal control system	**100**	50	50	200	50
EVA equipment	**300**	100	100	500	10
production equipment	**500**	700	300	1500	100
plant growth equipment	**500**	200	50	750	25
10 kW solar power plant	**150**	20	30	200	20
3 kW PVA power	**100**	10	10	120	10
15 kW DIPS cart	**0**	0	600	600	50
160 kW nuclear power plant	**750**	100	1550	2400	500
PMAD and cables	**100**	20	30	150	30
communication system	**50**	10	20	80	10
open rover for crew	**50**	10	10	70	5
pressurized rover for crew	**80**	10	10	100	10
science rover	**50**	10	10	70	10
science equipment	**100**	25	25	150	0
hand tools,machine tools	**20**	10	10	40	10
consumables (food etc.)	**30**	10	10	50	20
clothes, hygenic materials	**50**	20	20	90	20
spares	**10**	10	10	30	50
engineering support , upgrading & misc.	**1000**	250	1800	3050	0
TOTAL	**6510**	**2795**	**5185**	**14490**	**1680**
Lunar share	(50%)**3255**	2795	0	6050	
Mars share	(50%)**3255**	0	5185	8440	

A comparison of the options of an integrated program for the Moon and Mars

with estimates of stand-alone programs indicate a saving of about 20 percent. This tentative cost model should be replaced by a more refined mathematical model that is using a specific develop cost index, attempting to take into consideration relevant parameters such as : output rates, mass, relative complexity, relative maturity of the state-of-the art, past production numbers of same products etc. Such a model would lead to more accurate numbers.

These facilities, the equipment and the annual supplies required at extraterrestrial bases have to be transported to their destinations. Also local crews have to go to these locations in space and be rotated from time to time. Without a fairly safe and economic *space transportation system* extraterrestrial bases remain a dream. These are the prerequisite of the human exploration of space and deserve our primary attention. The present thinking on how the logistic problem of extraterrestrial bases can be solved, is summarized in the next chapter.

3. Logistic system development

3.1 Selecting Moon-Mars space transportation systems

Great care has to be taken upon selecting ground rules for the development of space transportation system(STS) to *enable fair comparisons* of competing concepts. Such a selection and/or comparison of STS has to begin with defining the parameters used. It is not very practical to include all theoretical possibilities which may exist in the next millenium in this analysis. The focus should be on the options available for the next generation of space transportation systems to satisfy the marklets of the first half of the 21st century.

The following list of selection criteria for ***future space transportation systems*** was developed by the "IAA Subcommittee of Lunar Development" in 1993, which appears to be aplicable for this purpose.

Table 3-1: Definitions of space transportation systems performance criteria20,27

01. Probability of mission succes.-

The initial, average and inherent probability that the transportation system will accomplish its assigned missions.

02. Human safety.-

The risk of loss of human life during the ground- or flight operations of the transportation system during its entire life cycle.

03. Schedule confidence.-

The confidence of the investors, developers and the potential customers in keeping the target dates for the initial operational readiness and planned annual flight rates.

04. Single flight payload capability.-

Size (mass, volume and dimensions) of payloads a single flight of the space transportation system can accomodate under optimum conditions to all destinations, including loading and unloading of cargo and passengers.

05. Annual payload capacity.-

The cumulative payload capability per year (= *transportation volume*) of the individual space transportation system and its growth rate from the initial annual operational capability during the entire life cycle, as an indicator for *overall systems performance* .

06. Operational flexibility (*resiliency)*

The capability of the space transportation system to adjust rapidly to unplanned events, such as mission-, payload- or organizational changes, technical problems, funding problems and major accidents.

07. System compatibility.-

The compatibility of the elements of the lunar transportation system in its passenger and cargo versions with other existing or planned space transportation systems for near Earth or planetary applications.

08. Development risk.-

The relative maturity of the technologies employed in the selected elements of the lunar transportation system, determining the confidence levels in cost-, schedule- and performance estimates.

09. Cost-effectiveness.-

The economic performance of the lunar space transportation system during its life-cycle, measured in terms of annual and cumulative system acquisition- and operation costs, divided by all payload masses and/or number of passengers delivered safely to their respective destinations.

10. Funding profile.-

The magnitude of the up-front investment for the individual space transportation system, the peak of the annual funding requirements as well as the life-cycle average annual funding requirements, measuring the relative acceptability by the investors.

11. System life expectancy.-

The duration of the acquisition cycle and even more so, the expected availability and utility of the lunar transportation system, in terms of operational life time, as a measure for the level of *return-on-investment* to be expected.

12. Environmental and social acceptability.-

This criteria is supposed to cover all other factors of the individual space transportation system, particularly environmental, but also other important social considerations of all relevant groups within the national and international bodies taking part in this selection process.

Two successive ratings of selection criteria for *Space Transportation Systems* during the year of 1993 have resulted in the following ranked priority list, indicating the relative importance of the defined selection criteria at the end of the 20th century:

Table 3-2 : Preliminary priorities of STS performance criteria

01. Human safety 14.0%

02. Probability of mission success 12.7

03. Cost-effectiveness 12.5

04. Annual payload capability 9.0

05. Environmental and social acceptability 8.0

06. Systems life expectancy 7.5

07. Single flight payload capability 7.0

08. Overall mission flexibility 6.7

09. Funding profile 6.6

10. Development risk 6.0

11. Schedule confidence 5.9

12. Sytem compatibility 4.1

Total 100.0%

The above list of selection criteria may be used be used for comparing alternative logistic concepts to serve an integrated Moon-Mars exploration program to select those which seem to satisfy these requirements best.

3.2 State-of-the-art5,10,11,14,19,24,25

The selection of a new space transportation system must take into consideration the experience available at the time of making a choice, and the state-of-the-art expected to be available at the time of system acquisition. The alternative concepts selected to be analysed for a deployment during the first half of the 21st century have been based on the following assumptions and insights available at the turn of the century:

01. The feasibility of safe and reliable transportation of people and cargo with rockets to and from the Moon has been proven in the 1968/72 period by the APOLLO program.

02. *Space Operation Centers* (SOC) are most probably be required in low Earth orbit (LEO) and/or lunar orbit (LUO) as transportation nodes and integral elements of the lunar STS in support of lunar and Mars ferry vehicles, primarily for refueling, transfer, and maintenance or repair operations, but also as a safe heaven in case of emergencies.

03. Automated rendevouz has been demonstrated frequently in the MIR program with the PROGRESS logistics vehicle in low Earth orbits, a technology now available to supply space operations centers (SOC).

04. Chemical propulsion systems are the most practical and the only available means to drive crewed space vehicles in cis-lunar and outer space for at least the first half of the 21st century.

05. Oxygen/hydrogen propulsion systems are the primary candidates for space transportation systems (STS) of the next generation, preferably derived from proven hardware.

06. Production of liquid rocket propellants on the Moon and on Mars are the best means to greatly improve the efficiency of space transportation systems and should be introduced as soon as possible.

07. The US *Space Shuttle* in its present configuration is not designed and not suitable for supporting lunar logistics operations and will probably be phased out before the first crew will arrive on the Moon in the next development phase. Consequently, it will most likely not be an element of the next lunar space transportation system (LSTS).

08. The *International Space Station* (ISS), to be operational in low Earth orbit early in the 21st century, will be a research station and not be available as a transportation node for human lunar or Mars missions. But it could be used for testing components and subsystems, as well as for crew training.

09. Automated soft landings on the lunar and Mars surface at pre-selected points have been demonstrated many times and are considered within the state of the art. Human pilots can support such landings and may have an override option in case of irregularities.

In this context, depending on objectives, timing and location, space trans-portation systems required for the logistic support of extraterrestrial facilities will have also a great number of commonalities. There will be differences, but they are not very great in most cases. They have to be taken into account after the program concept and the requirements are firmed up. They will lead to compromises in the design and operational concepts.

3.3 Earth launch vehicles 3,9,19,20

None of the presently available launch vehicles are suitable for the next phase of lunar and Mars exploration if human missions are included. During the last decades the following launch vehicle concepts have been considered for the extraterrestrial space transportation market:

1. Expendable launch vehicles, such as a re-engineered SATURN V or ENERGYA with Earth-to-orbit(ETO) payloads of about **100** metric tons(MT),

2. Expendable heavy lift launch vehicle using modified SATURN V and Shuttle hardware with payload capabilities up to about **200** MT,

3. Reusable single stage ballistic vehicle with ETO payloads of up to **20** MT,

4. Reusable Shuttle derived medium launch vehicle with ETO payloads of about **100** MT,

5. Reusable heavy lift launch vehicle of the POST-SATURN class with Earth to orbit payload capability of **300 to 400** MT.

The primary characteristics of these vehicle concepts are presented in table 3-3:

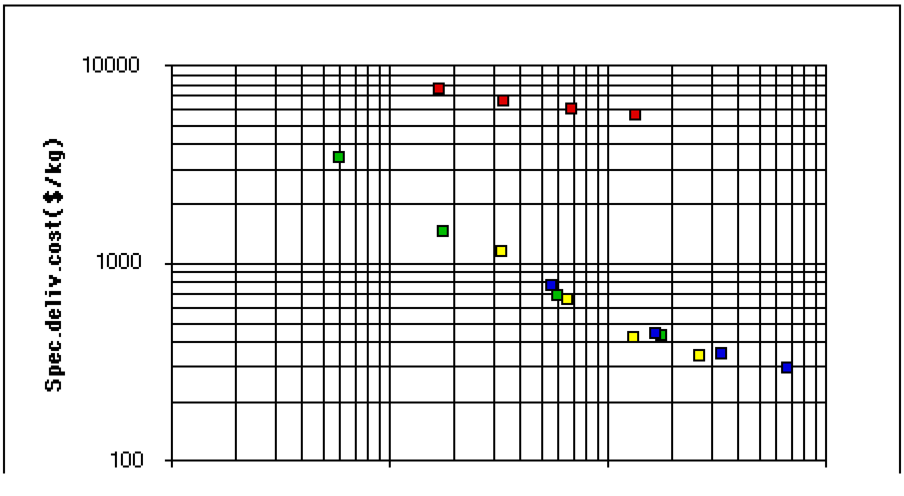
Table 3-3: Primary characteristics of future Earth launch vehicle concepts

Legend: Growth ratio= Launch mass/payload mass

concept:	**1.**	**2.**	**3.**	**4.**	**5.**
Number of stages to LEO	2	2	1	2	2
Launch mass(MT)	2837	4000	800	1940	6000
Payload mass to LEO (MT)	137	200	20	112	350
Growth ratio (MT/MT)	20.7	20.0	40	17.3	17.1
Development cost (M $)	8,260	10,500	9,538	11,059	19,635
First unit cost (M $)	1,859	2,500	576	1,302	3,445
Reference	(20)	(3)	(20,27)	(27)	(27)

The general trends of the specific delivery cost of expendable and reusable launch vehicles to low Earth orbit are depicted in the following double-logarithmic graph(figure 3-1). This shows clearly that expendable vehicles are not an economical solution for programs with life-cycle cumulative transport requirements of 4,000 MT and more.

Taking a closer look at the higher end and using linear scales (figure 3-2), the differences between the selected vehicles are somewhat more pronounced. If assembly and fueling operations are required in selected mission profiles, additional cost will occur, which increase with decreasing size of vehicle payload capability per mission.



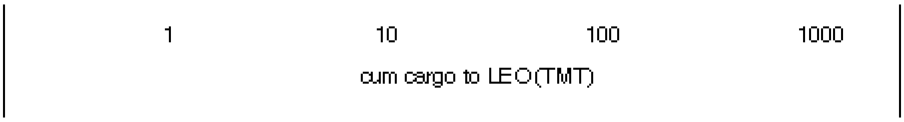


Figure 3-1: General trend of the specific delivery cost to low Earth orbit as function of transportation volume of expendable and reusable launch vehicle concepts (upper curve = expendable vehicles)

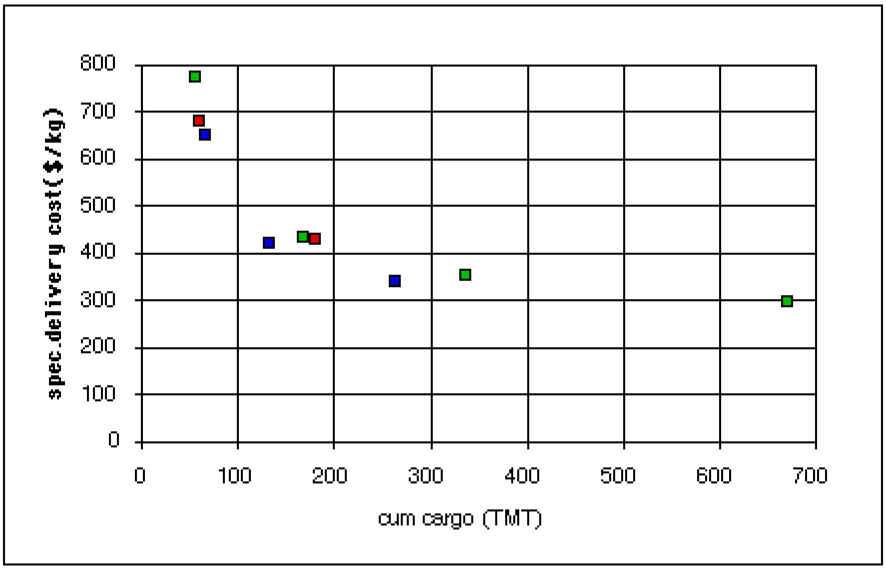


Figure 3-2: General trend of the specific delivery cost to low Earth orbit of reusable launch vehicle concepts as a function of life-cycle cumulative transportation volume (higher end, linear scale)

The graphs show only the cost trend of delivery **to** the orbit of destination. But *delivery cost to Low Earth Orbit(LEO) are not departure cost* ! If these are not individual direct flights, the payloads arriving in LEO have to be assembled into space vehicles going to the Moon or Mars, these have to be fueled and go through a checkout. These vehicles have to be parked in LEO for some time and take-off during the specified launch window. In doing so, they loose some propellants and the orbital crew needs supplies and housing. All this adds to the departure cost. Launch vehicles with small payload capability such as the SSTO with 10 to 20 MT per flight have much higher orbital operations cost than large launch vehicles. In case the entire space vehicle can be taken care off by the launch vehicle (i.e. such as a heavy lift launch vehicle with 350 MT payload), then there are practically no additional cost. It has been found that this *orbital burden rate* can double the specific delivery cost or more35.

Consequently, estimating mission cost should *not* be based on *LEO delivery cost* as is done quite often, but on the basis of *total cost of cargo delivery to the point of destination*. Human missions have also the return requirement, thus the total *cost per round trip* is the figure to derive and compare. This is the *most important figure* in space transportation system optimization, because it is the passenger transportation requirement in terms of total number of life-cycle roundtrips that is the program cost driver! The specific transportation cost for cargo and passengers can only be determined on a case to case basis within the frame of a reference mission and a specific space program scenario.

However, there is a good approximation available that can be used instead of using the delivery cost to LEO and the delivery cost to the point of destination. Moon-Mars missions have nearly the same velocity requirement, if the lunar orbit and transfer orbits to Mars are used as a reference. This is a value of about 4,100 m/s from a low Earth orbit. Using this delta v, one obtains a better basis for comparison of launch vehicles for an integrated Moon-Mars program.

There is no question that there is an interdependence between size of the space market and specific space transportation cost. The larger the market, the better the cost-effectiveness of transportation systems. Also, there is a relationship between vehicle size and specific space transportation cost. This raises the question of the relationship between vehicle size and market size. Small markets for small payloads and short life-cycles favour small expendable launch vehicles. On the other hand, large markets for big payloads and long program duration demand reusable heavy lift launch vehicles and high launch rates. Large markets of the 21st century, if they develop, will be the result of a demand of high energy missions, e.g. geostationary orbit, lunar orbit and planetary escape missions favouring heavy lift launch vehicles.

For this reason, an analysis was performed to attempt to develop a current answer to the question of the optimum size heavy lift launch vehicle(HLLV) as a function of the market volume. Two different reusable HLLV concepts were investigated, a Shuttle derived reusable launch vehicle of about 2,000 MT launch mass, and a sectionalized, modular HLLV based on the NEPTUNE concept, with launch masses between 3,000 and 6,000 MT.

A combined Moon-Mars program requires some 20,000 to 40,000 MT of LEO equivalent cargo on the Moon and Mars. This requirement approximately doubles, if the lunar orbit or injection to Mars transfer are taken as a reference mission20,22. If these markets would actual develop during the next century, then an answer must be found to the question: which concept and which size of a launch vehicle is to be developed for the expected market? The next table presents the overview of the cost-effectiveness of the vehicles investigated for comparison. Selecting the two best vehicles to determine the cross-over point the trend shown in figure 3-3 emerges. The differences in the range of 45,000 and 90,000 Mt of lunar orbit cargo are too small to be significant. A few percent is well within the inaccuracies of the assumptions made. Final answers can only be obtained in a detailed program analysis observing the influences of all critical parameters.

Table 3-4: Overview of cost-effectiveness of typical lunar orbit and Mars transfer orbit cargo vehicles

launch mass	6,000 MT	4,500	1,940
15,000 MT LC cumulative cargo	3,523 $/kg	3,317	**2,897**
45,000	1,695	1,723	**1,625**
90,000	**1,174**	1,286	1,312
180,000	**954**	1,016	1,105

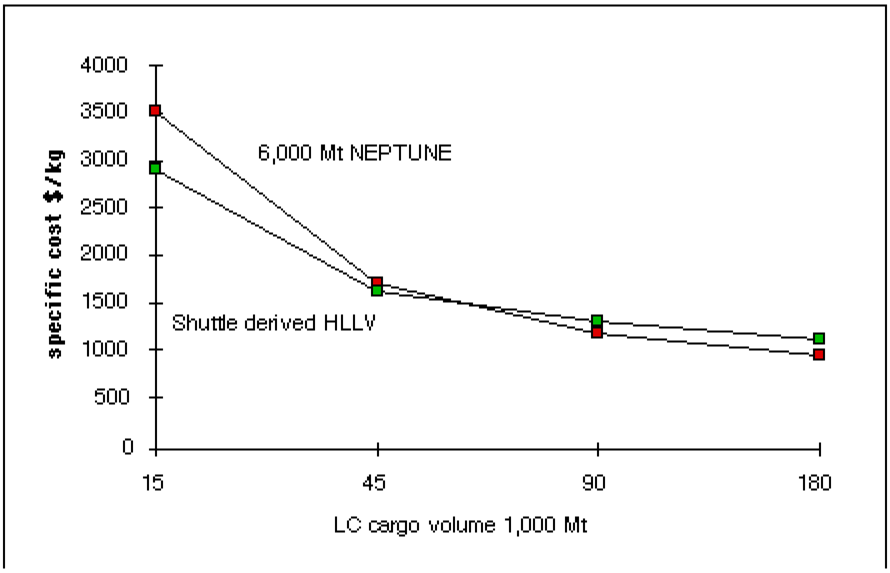


Figure 3-3: Comparison of the specific cost of cargo transportation to lunar orbit for a shuttle derived HLLV and a sectionalized modular NEPTUNE HLLV concept .

Note:

In case lunar surface cargo is of interest, these cost figures have to be multiplied by 2, if LEO missions are of interest, these figures have to be devided by 3.5!

Considering suitable launch vehicles for an integrated Moon-Mars program during the first half of the 21st century the following arguments should be taken into consideration:

Arguments in favour of vehicles with larger payload capabilities:

- reduced man-power requirements at destination for assembly operations,

- possibility of using the optimum launch window in case of lunar missions

launch rates up to one per month allow larger payload capability ,

- higher growth potential,

- reduced number of launch facilities,

- more efficient lunar landing- and launch vehicle.

Arguments in favour of vehicles with smaller payloads capabilities:

- better mission flexibility,

- reduced front-end cost,

- reduced noise at launch,

- better utilization of vehicle design lifetime.

The statements and trends discussed above are a general description of the alternatives available. However, looking at the problem a bit closer, it appears that the Heavy Lift Launch Vehicle (HLLV) has the edge because of the following arguments:

1. Nuclear and electric propulsion systems show some promise with respect to performance, and both of these propulsion technologies have matured to a relatively high state of readyness in the past. However, it must be concluded at this stage of development that neither has reached the level necessary to be used on human Mars Missions. They are no viable choice for lunar missions either.

2. Nuclear propusion is practically eliminated for an early human Mars mission, because there are neither the development facilities, nor flight hardware available or in sight. This is the case because of the high cost and long lead times involved. In addition, it must be observed that nuclear propulsion development and application will be resisted strongly by public opinion worldwide.

3. The hardware elements of human Mars missions require a launch vehicle large enough to place very large size modules bound for Mars into a suitable Earth parking orbit, minimizing extravehicular activities.

4. The best Earth orbit for Mars missions is different for each launch opportunity. Therefore, a permanent construction or propellant storage facility in a single Earth orbit is not an economically attractive solution. This tends to minimize assembly and refueling operations in low Earth orbit using a permanent space operations center.

5. All technologies must be proven prior to initiating production of the elements required for a human Mars mission.

6. A human Mars mission requires habitats and equipment, a return vehicle to Mars orbit and an Earth return vehicle from Mars orbit for each mission. Favouring the split mission concept, this requires a launch of several space vehicles during the same launch window. Based on past experience, it is inconceivable that this can be done, realizing the effort involved to get four sizable new *expendable* launch vehicles off the ground within the same launch window to Mars.

7. An *expendable* launch vehicle, as well as a nuclear injection stage, are of no commercial interest in contrast to a *reusable* vehicle. Only the latter one has the chance of distributing development cost over several users.

Some additional benefits of a chemical trans-Mars injection (TMI) stage must be taken into consideration[14]. After the injection maneuver into a Mars transfer orbit, this stage could:

serve as a counter-balance for the payload in case some artificial gravity is desired after the midcourse maneuver,

offer also additional meteorite and radiation protection during transfer,

make use of its propellant- and gas-residuals, which come very handy for various purposes during the transfer period,

use its heat shield for the aerobrake at Mars before releasing the landing stage,

benefit with respect to reliability and production cost because this TMI stage is practically identical with the lunar ferry stage,

solve the normal packaging problem associated with the use of small launch vehicles because of its large available payload volume.

serve as a potential resource of material on Mars, because it crashes near

the landing site after separating from the lander after entry, the impact

could be softened by air bags to reduce the damages.

All of these arguments and facts lead to the inescapable conclusion, that the launch vehicle required for a human Mars exploration program **must be a reusable vehicle** that can deliver a sizable payload of about **100** metric tons in a direct flight into a Mars transfer trajectory. Such a vehicle will have a launch mass of 4,000 to 6,000 metric tons. Its development cost are estimated to about $ 15 billion dollar during a six year development period, which may be shared with other space programs!

Consequently, a REUSABLE HEAVY LIFT EARTH LAUNCH VEHICLE (such as the *NEPTUNE* design concept of the Aerospace Institute of the Technical University Berlin) is a representative launch vehicle example for a Human Mars mission, and thus also for an integrated Moon-Mars Program. This vehicle has tentatively the following characteristics:

Figure3-4:

Longitudinal cross-section of

the NEPTUNE -2015

HEAVY LIFT LAUNCH VEHICLE

Technical University Berlin

Figure 3-5:

Horizontal cross section of the three stages of the

NEPTUNE -2015

heavy lift launch vehicle

This basic vehicle can be used as a tanker vehicle to low Earth orbit with about 350 MT of propellants to refuel the Mars ferry vehicle, or it can inject directly the Lunar Ferry vehicle in a transfer trajectory to lunar orbit, or it can inject directly a Mars cargo vehicle in a transfer trajectory for a direct landing on Mars. The payloads will change accordingly, a 375 MT to 426 MT injection payload of a tree stage NEPTUN can be used as probable range of performance, depending on the level of effort during the development phase.

Table 3-5: Primary characteristics of the NEPTUNE heavy lift launch vehicle (HLLV)

Masses : (t)	stage 1	stage 2	stage 3 (cargo)
launch mass	6000	1658	426
payload mass LEO	1658	426	372 gross/350 net
payload mass LUO	1648	416	108 gross/100net
payload shroud	-	-	2
instrumentation	9	4	2
structure	358	84	18
engines	80	25	8
recovery equipment	39	21	15 LEO /18 LUO
residuals	38	11	3
propellant reserves	56	16	3
propellant consumption	3762	1072	16 LEO/ 249 LUO
cut-off mass	2238	586 LEO/576 LUO	411 LEO/153 LUO
dry mass	486	133	36 LEO/ 40 LUO
net mass	580	160	39 LEO/ 45 LUO
Dimensions and mass ratios:			
width (m)	41	29	22.4
height (m)	38	21.2	33.4
cross-section (m2)	1 ,355	676	403
top structure(m2)	1 ,985	800	400
with shroud(m2)	-	-	1 ,165
bottom structure(m2)	3, 317	1 467	427
volume (m3)	40 ,327	11 977	4 742
ref.nose radius (m)	29	18	14
mass ratio r	2.680	2.828	1.036 LEO mission
prop.mass fraction	0.889	0.894	0.360
propellant ratio	0.626	0.646	0.038
payload ratio	0.277	0.258	0.878

growth factor	3.619	3.892	1.323
growth fact.vehicle			18.61
engine sea level thrust	1,845 kN	1,802 kN	-
vacuum thrust p.engine	2,082	2,167	200kN
number of engines	40SSME	9SSME	8 RL10A3
nozzle area ratio	20	120	200
sea level spec.imp. (s)	400	388	-
vacuum spec.imp.(s)	451	469	469
engine mass flow	470 kg/s	470	43.5
engine mass (kg)	2,000	2800	300
tot.prop.sys. mass(t)	80	25.2	2.5

3.4 Interorbital ferry vehicles

3.4.1 Lunar orbit ferry vehicle[8,20]

The standard cargo version of the lunar ferry vehicle is identical with the third stage of NEPTUNE as presented in table 3-5. Its actual payload capability varies between 85 and 100 metric tons, depending on the source of the return propellants from lunar orbit to the Earth. Initially these propellants will be brought along with the payload, and on the long run these will be lunar propellants, increasing the nominal payload to 100 MT or more. In the case of cargo flights between Earth and lunar orbit, 15 MT of propellants (12 Lox +3 LH2) are required for the return flight of the empty 3rd stage. If the LH_2 is taken out of the payload and Lox refueled in lunar orbit, then 100 - 3 = 97 MT remain for the actual payload and LH_2 propellants for the LUBUS. Alternatively the Lox can be taken out of the payload also, leaving room for 85 MT of cargo.

In a typical lunar base program, there will be more passenger flights than cargo flights. For passenger flights between Earth and lunar orbit, a 50 MT crew cabin (including the mass of the relieved crew and a few tons of cargo) is required. It is an integrated part of of the nominal 100 MT payload of the 3rd stage of the HLLV which is operating as a *space ferry.* It flies to the LUO-SOC and returns to the Earth spaceport requiring 30 MT propellants (25 MT Lox, 5 MT LH_2). On a standard mission profile the Lox propellant is lunar produced Lox, refueled in LUO at the space operations center. The LH_2 is taken out of the payload reducing it from 100 MT to 95 MT. This leaves a 20 MT margin for taking LH_2 along which is needed by the LUBUS for its roundtrip from the LUO-SOC to the lunar spaceport, leaving room for an additional 25 MT of cargo in a mixed passenger/cargo flight.

A typical mass breakdown of the crew module attached to the 3rd stage of the HLLV space ferry has been developed by J.Laßmann[15] as follows:

Table 3-6 : Mass model of the NEPTUNE lunar crew module

structural elements 26,590 kg

power supply 7,560

life support equipment 1,820

crew systems 3,030

instrumentation 1,000

basic vehicle dry for LEO missions 40,000 additonal heat protection equipment 5,000 (for GEO or lunar missions)

crew and luggage 5,000

total crew cabin loaded 50,000 kg

3.4.2 Mars orbit ferry vehicle[18]

The standard third stage of the NEPTUN launch vehicle requires some modifications if used as a reusable ferry vehicle between Earth orbit and Mars orbit.

The primary reason is the longer mission time, in this case about 1000 days instead of 10 days and a different propellant loading. These changes lead to the following specifications of a reusable interorbital ferry vehicle derived from the third stage of the HLLV:

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 has initially a nominal payload of 375 MT. It will increase with time due to the efforts within the product improvement program. It is designed for aerodynamic braking in the Mars atmosphere as well as in the Earth atmosphere upon return. The ferry returning a crew to Earth orbit, requires a habitat of about 40 MT. The crew will be picked-up in Earth orbit by a shuttle and be brought back to the Earth surface! Considerable flexibility excists with respect to performance by changing departure mass, some refueling in Mars orbit and by accepting different flight times. The assumed dry mass of the stage reflects the advances of the state-of-the-art through the first two decades of the 21st century.

Table 3-7: Characteristics of reusable MARS ferry vehicle (first flight 2025)

Ferry mass & performance : (all masses in metric tons)

Earth Mars leg:

launch mass : 375 (max 400)

delta v = 4,300 m/s injection

+ 200 m/s maneuver

c =4,700 m/s

u/c1 = 0.957 ; u/c2 =0.596

mass ratios : 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

Return flight:

delta v return : 2,500 m/s + 300 m/s maneuver

in Earth orbit 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,

mass of dry stage and payload : 75

to be refueled with about 300 tons of

propellants in LEO for next mission

Cargo vehicle:

In addition to the passenger round trips there will be one way cargo deliveries to Mars. In this case the space vehicle is an *expendable* stage with a one time aerobrake in the Mars atmosphere. The 3rd stage of the NEPTUNE vehicle needs also changes due to the longer mission time. The one-way trip can take up to eight months. The standard three stage reusable heavy lift launch vehicle (HLLV) is capabable (in a direct flight mode) to carry a nominal payload of at least 375 MT into a low Earth orbit at about 160 km altitude. This leads to 85 - 120 MT payloads to be sent by the 3rd stage (trans Mars injection stage) onto a Mars transfer trajectory, depending on the travel time and year of departure in the 15 year cycle. 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.

Table 3-8: Mass model of the nominal trans-Mars injection stage

(reference NEPTUNE max payload, reduced by about 10% if 375 MT launch mass is used)

instruments & el.equip.	1,760kg
structure	17,520
propulsion system	3,400
heat shield	15,500
dry mass	38,180
residuals & reserves	5,260
wet stage mass	43,440
propellants used	263,180
stage mass loaded	306,620
gross payload	109,380
cut-off mass	152,820
launch mass	416,000kg

propellant fraction (dry) = 0.875

propellant fraction(wet) = 0.858

eff.mass ratio = 2.722

eff.exhaust velocity = 4,600 m/s

delta V = 4,606 m/s

Gross payload capability of 3-stage reusable NEPTUNE launch vehicle concept of the TU Berlin with launch mass = 6,000 MT to 160 km LEO orbit is 416 MT maximum. If 10% are considered design reserve, the nominal initial mass of TMI stages is about **375** MT (10% design reserve) which is also the nominal payload capability for a 400 km orbit.

Table 3-9: TMI Stage masses as a function of delta v with constant launch mass

(masses in metric tons, velocities in m/s)

m-launch	**375 000**	**375 000**	**375 000**	**375 000**	**375 000**
m-dry	38 200	36 600	35 200	32 300	29 500
m-prop	263 000	252 000	242 000	221 000	200 000

m - resid	5 300	5 100	4 900	4 500	4 000
m-stage	306 500	293 700	282 100	257 800	233 500
prop share	0.858	0.858	0.858	0.857	0.856
m- cargo	68 500	81 300	92 900	117 200	141 500
m-cutoff	112 000	123 000	133 000	154 000	175 000
m -ratio	3.348	3.049	2.820	2.435	2.143
ln r	1.208	1.115	1.037	0.8899	0.7622
delta v	5557	5130	4770	4094	3500

The higher speed missions are of interest only in case of emergencies, if the flight time must be reduced due to the unfavourable position of the target planet. Slow missions are carried out on Hohman type trajectories requiring about 3,500 to 3,600 m/s delta v. These performance data are the point of departure for space vehicles leaving the low Earth orbit in direct modes when developing alternative architectures of individual and/or integrated Moon-Mars programs. The 3rd stage with its heat shield will be used for the aerobrake maneuver at Mars and be dropped when reaching subsonic velocity, releasing the landing stage with the payload. Its impact on Mars will be softened by air bags and similar devices to enhance further uses.

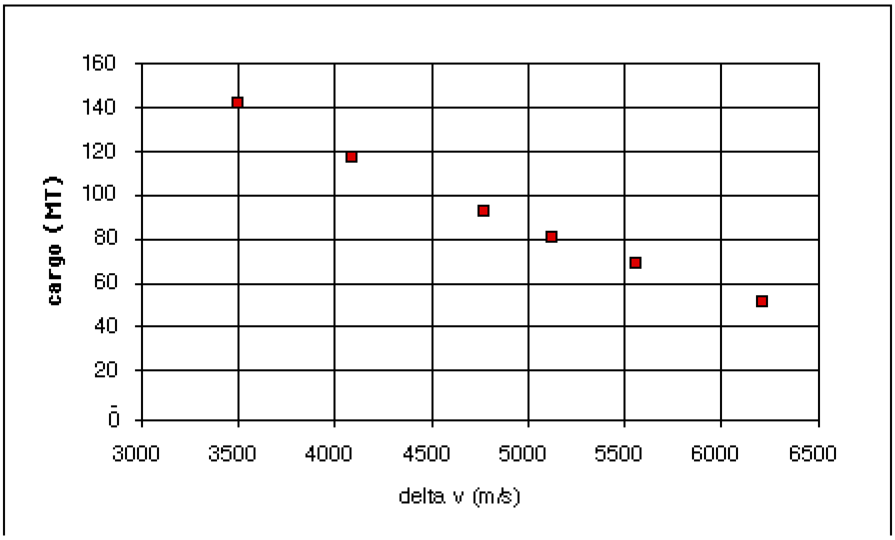


Figure 3-6: Reusable NEPTUNE cargo capability from low Earth orbit with 375 MT launch mass as a function of characteristic velocity

The landing stage is an expendable stage providing about 500 m/s delta v. With CH_4/LOX propellants the exhaust velocity is 3,700 m/s. The performance of this lander can be summarized as follows, assuming a nominal 120 MT mission payload arriving on a near Hohmann trajectory with the transfer stage in a Mars orbit. After the entry maneuver and stage separation about 110 MT are left for the lander with payload:

Table 3-10: Mass model of Mars landing stage for heavy cargo

$u/c = 0.135$, $r = 1.145$, cut-off mass = 96 MT, propellants used = 14 MT

with landing stage masses of :

structure & landing gear 4000kg

tanks 500

engines & attitude control 1500

el.& G&C equipment 500

total dry mass 6500kg

residuals 500

total stage mass 7000 kg

Deducting these 7 MT from the cut-off mass, a total cargo of 89 MT can be unloaded on the Mars surface. This can grow to about 100 MT depending on the actual delta v requirement of the launch window and the effects of product improvement efforts.

3.5 The lunar orbit service center[8,20]

A transportation node in lunar orbit is required as a propellant storage and payload transfer station. It is a modified version of the second stage of the Earth launch vehicle. a typical concept is sketched below.

Figure 3-7: Representative space operations center

The lunar orbit operations center (**LUO-SOC)** has an empty mass of about 250 t and it is a modified second stage of the HLLV. After modifications, refueling and checkout have been completed in low Earth orbit, it transports itself during the first operational year in an extra flight to the lunar orbit. Two secondary refueling flights to low Earth orbit (LEO) are required by the HLLV (this is a total of 3!) to make this transfer of the LUO-SOC facility into lunar orbit (using its own propulsion system) feasible.

These additional flights are calculated automatically by the program as secondary missions in the first operational year. About 180 MT of propellants remain onboard of the SOC after arrival in lunar orbit if completely fueled in LEO before departure. These propellants are needed for suplying the initial LUBUS flights due to a limited LULOX production capability on the Moon in the early years. This space facility is scheduled to be activated in lunar orbit, before the first lunar crew arrives. Under standard operational conditions, the LUO-SOC has a maintenance crew of 3-6 astronauts depending on the traffic. An average crew duty cycle of six months is assumed resulting in additional secondary missions.

Mass model:

The transfer of the LUO-SOC from the low Earth orbit to lunar orbit requires a velocity increment of 4,165 m/s, with an effective exhaust velocity of c = 4,500 m/s this results in a mass ratio of r = 2.523. The LUO-SOC with a dry mass of 250 t arrived in LEO with 300 t residual propellants to be modified for its lunar orbit mission. After refueling 2 x 300 t in LEO its take-off mass is about 250 + 900 = 1,150 t. The required mass ratio of 2.523 leads to a SOC mass at arrival in LUO of 1,150 : 2.523 = 456 t or 250 t hardware, some 26 t unusable residuals and about **180 t** of propellants for later use by the LUBUS.

3.6 Lunar bus[8,20]

The local transportation tasks between the lunar orbit space operations center and the lunar spaceport are taken performed by a lunar bus.

Figure 3-8:

The lunar launch and landing vehicle -

LUBUS

The lunar launch- and landing space vehicle is a single stage vehicle. It is a modified third stage of the heavy lift launch vehicle with a 7 meter loading plattform on top and other payload locations at the bottom. Using a charateristic velocity requirement for a single flight between the lunar orbit and the lunar spaceport of 2,000 m/s and an exhaust velocity of 4,500 m/s, the resulting minimum mass ratio becomes 1.56. These assumptions lead to the following mass- and performance characteristics on which the lunar landing- and launch vehicle (LUBUS) has to be designed. The masses specified are then used for estimating the additional development and manufacturing costs.

It has to be pointed out that the LUBUS propellant tanks have to be sized allowing the refueling of both propellants for the entire roundtrip. All

hydrogen is fueled in lunar orbit, all oxygen is fueled on the Moon! This explains the relatively large dry mass of this vehicle.

Table 3-11: Performance of LUBUS flights for passenger and cargo missions

DOWN LEG of the LUBUS from LUO-SOC for passenger missions

empty stage 20 t

crew cabin with crew 25 t (40 passengers for 1 hr flight time)

hydrogen for ascent 7 t

stage at cut-off 52 t

usable propellants required 30 t (5 t LH2 + 25 t Lulox)

take-off mass in LUO 82 t

ASCENT of the LUS to LUO

empty stage mass 20 t

cabin with crew 25 t (max.capacity 40 persons for 1 hr)

Lulox for down leg 25 t

cut-off mass 70 t

usable propellants required 40 t (7 t LH2 + 33 t Lulox)

Take-off mass on the Moon 110 t

DOWN LEG from LUO-SOC for cargo missions

empty stage mass 20 t

cargo incl.packaging 63 t

hydrogen for ascent 10 t

cut-off mass on the Moon 93 t

usable propellants required 52 t (7 t LH_2 + 45 t Lulox)

Take-off mass in LUO 145 t

ASCENT of cargo-LUBUS

empty stage mass 20 t

Lulox for down-leg 45 t

return cargo 50 t

cut-off mass 115 t

usable propellants required 64 t (9 t LH_2 + 55 t Lulox)

Take-off mass on the Moon 179 t

Mass-balance HLLV passenger flights with max. **40 Persons**: 50 t crew cabin + 30 t return propellants + 12 t hydrogen (without losses) = 92 t, propellant reserves or additional supplies 18 t. Total nominal life-cycle average HLLV payload capability = 110 tons delivered to LUO.

Mass-balance of HLLV cargo-flights : 30 t return propellants + 16 t + 1 t losses hydrogen for LUBUS,+ **60 t Cargo + 3 t container** = 110 t total payload delivered to LUO, used as *nominal* payload capability for this scenario.

Lunar LOX-requirements at the lunar spaceport:

Passenger flights : 25 + 33 + 2 losses = **60 t per flight**

Cargo flights: 55 + 45 = **90 t per flight**

3.7 Mars Bus

The local reusable Mars-Bus will have many commonalities with the Mars cargo landing stage. But is has larger tankage and in addition a separate heat shield. On the other hand, its basic structure and landing gear will be much lighter due to the small payload (5 MT instead of 89MT). It will also use hydrogen and oxygen propellants produced on Mars. In a standard mission it is capabable to ascent to LMO, pick-up the arriving crews with their luggage 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 3-12: Characteriatics of reusable Mars-Bus

Characteristics of the reusable
Mars-Bus:

c = 4,700 m/s; delta v up: 4,200 m/s;

delta v down: 500 m/s, total = 4,700 m/s

u/c = 1.00 , r = 2.718

crew module with crew : 5,000 kg

dry stage: 4,000 kg

(enlarged tanks for LH2/Lox propellants)

residuals: 500 kg

TPS : 1500 kg

(added during manufacturing on Earth, reusable)

cut-off : 11,000

used propellants : 21,000 kg

launch mass: 32,000

<u>ascent maneuver:</u>

u/c =0.894, r = 2.445

mc = 32,000: 2.445 = 13,088

m8= 18,912

<u>landing maneuver with aerobrake</u>:

u/c = 500/4,700 = 0.106

r=1.112

mc = 13,088 : 1.112 = 11,770 kg

m8 = 1,318, total m8 = 20 ,230 kg

propellant reserves = 770 kg

propellant fraction dry wo.TPS = 0.835

propellant fraction dry with TPS = 0.786

Two to four Mars busses will be stationed at the Mars spaceport. They could also be used for transporting people over longer distances on Mars, if the propellant productions is increased over the needs for arrivals and departures.

4. System acquisition cost

4.1 Acquisition cost of base infrastructure[23]

In this scenario the assumption is made that the first phase of the infrastructure development begins in year 2007 with the financing the long lead time items. The second phase begins about 2011. It is focussing on the development of the hardware required for the first extraterrestrial outpost, scheduled to be activated in 2016. The funding for the infrastructure development is streched by delaying items required only later during the operational phase and for the activation of the second outpost.

Table 4-1: Priority infrastructure developments (same as table 2-1)[14,25,26]

Equipment requirements:	general develop-ment cost (M$)	Moon specific add on (M$)	Mars specific add on (M$)	total program dev.cost (M$)	unit prod cost (M$)
initial crew training infrastructure	20	30	10	60	0
science support cost on Earth infrastructure	50	50	30	130	0
initial pilot station	100	100	50	250	100
laboratory module	500	500	100	1100	150
central workshop	100	250	50	400	100
standard surface habitat module	1500	200	200	1900	300

phys./chem.life support system	300	100	100	500	100
thermal control system	100	50	50	200	50
EVA equipment	300	100	100	500	10
production equipment	500	700	300	1500	100
plant growth equipment	500	200	50	750	25
10 kW solar power plant	150	20	30	200	20
3 kW PVA power	100	10	10	120	10
15 kW DIPS cart	0	0	600	600	50
160 kW nuclear power plant	750	100	1550	2400	500
PMAD and cables	100	20	30	150	30
communication system	50	10	20	80	10
open rover for crew	50	10	10	70	5
pressurized rover for crew	80	10	10	100	10
science rover	50	10	10	70	10
science equipment	100	25	25	150	0
hand tools,machine tools	20	10	10	40	10
consumables (food etc.)	30	10	10	50	20
clothes, hygenic materials	50	20	20	90	20
spares	10	10	10	30	50
engineering support , upgrading & misc.	1000	250	1800	3050	0
TOTAL	6510	2795	5185	14490	1680
Lunar share (50%)	3255	2795	0	6050	
Mars share (50%)	3255	0	5185	8440	

This is a tentative model and a point of departure for structuring the life-cycles of both extraterrestrial basis. This is an iterative planning process, implying that the estimates have to be refined from time to time to improve the accuracy of the results. If the above estimates are satisfactory for the beginning of the system analysis, we have to distribute the required funds over the years in which these development activities are planned to take place. In this scenario these are the years 2007 through 2024. The first outpost is supposed to be activated in 2016, the second in 2025.

Table 4-2: Distribution of infrastructure development funding in

program years 1 to 18

calender years: **Equipment requirements:**	**2007**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**
initial crew training infrastructure					10	10	10	10	10
science support cost on Earth infrastructure				4	6	10	20	30	30
initial pilot station				20	20	20	40	50	50
laboratory module			50	100	150	150	150	200	200
central workshop						50	100	100	100
standard surface habitat module			50	100	250	300	300	350	350
phys./chem.life support system						30	70	150	150
thermal control system							30	45	75

EVA equipment			20	30	50	50	50	100	100
production equipment				50	150	200	200	300	300
plant growth equipment			50	100	100	100	100	100	150
solar power plant							50	60	60
3 kW PVA power					10	25	25	25	25
160 kW nuclear power plant	50	100	100	100	100	100	100	100	100
PMAD and cables					20	20	20	30	30
communication system							20	20	20
open rover for crew							20	20	20
pressurized rover for crew						15	25	25	25
science rover							20	20	20
science equipment					25	25	25	25	25
hand tools,machine tools								10	20
consumables (food etc.)							10	10	20
clothes, hygenic materials							20	20	30
spares								10	10
engineering support , upgrading & misc.	10	40	100	150	150	200	200	200	200
TOTAL = 9305	**60**	**140**	**370**	**654**	**1041**	**1305**	**1605**	**2010**	**2120**

Equipment requirements:	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
initial crew training infrastructure								5	5
science support cost on Earth infrastructure							10	10	10
initial pilot station							10	20	20
laboratory module							20	30	50
central workshop							10	20	20
standard surface habitat module						50	50	50	50
phys./chem.life support system					20	20	20	20	20
thermal control system							10	20	20
EVA equipment					20	20	20	20	20
production equipment				50	50	50	50	50	50
plant growth equipment		5	5	5	5	5	5	10	10
solar power plant							10	10	10
3 kW PVA power								5	5
15 kW DIPS cart			50	50	100	100	100	100	100
160 kW nuclear power plant	200	200	200	200	200	200	120	120	110
PMAD and cables						5	5	10	10
communication system							5	5	10
open rover for crew							5	5	
pressurized rover for crew							5	5	
science rover	5	5							
science equipment			5	5	5	5	5		
hand tools,machine tools								5	5

consumables (food etc.)						5	5		
clothes, hygenic materials						5	5	5	5
spares							5		5
engineering support , upgrading & misc.	170	170	180	180	180	230	230	230	230
TOTAL = 5,185	**375**	**380**	**440**	**490**	**580**	**695**	**705**	**755**	**765**

In addition to the development effort, the cost of the first set of hardware is part of the acquisition cost. The first estimates of these are listed in table 4-3.

Table 4-3: First set of facilities and equipment for lunar outpost

lunar facility designation	**1st unit cost (M $)**	**x-3 years**	**x-2 years**	**x-1 year**	**delivery year**
01 .strip mine equipment	15	0	5	5	5
02 .beneficiation facility	18	0	6	6	6
03.chemical processing facility	54	9	9	16	20
04 .mechanical processing facility	18	0	6	6	6
05 .fabrication shop	0				
06 .assembly facility	0				
07 .laboratories and scientific equipment	35	5	10	10	10
08 . gas mine and equipment	0				
09 .gas prosessing and liquefaction facility	20	5	5	5	5
10.propellant storage for rocket propellants	0				
11. power plant system including power lines etc.	220	50	50	50	70
12 . dump	0				
13.spaceport and equipment	27		5	10	12
14 .central storage facility other than propellants	0				
15.central workshop for maintenance, repair and extensions	20	5	5	5	5
16 .central carpool & surface transportation facilities	18		6	6	6
17. control center	40	10	10	10	10
18 .housing facility and offices, incl. health & recreation facilities	160	40	40	40	40
19.biologcal facilities, incl. biol.waste recycling and food production	25		5	10	10
total 1,340	**670**	**124**	**162**	**179**	**205**

In a similar way, the first set of facilities and equipment for the Mars outpost are estimated and summarized in table 4-4.

Table 4-4 : First set of facilities and equipment of initial Mars outpost[26]

Equipment requirements:	**unit prod cost (M$)**	**x-3 years**	**x-2 years**	**x-1 year**	**year of de-livey**
initial pilot station	100	25	25	25	25
laboratory module	150	0	50	50	50
central workshop	100	10	30	30	30
standard surface habitat module	300	0	100	100	100
phys./chem.life support system	100	0	30	30	40
thermal control system	50	0	10	20	20
EVA equipment	10	0	0	5	5
production equipment	100	0	0	50	50
plant growth equipment	25	0	5	10	10
solar power plant	20	0	5	5	10
3 kW PVA power	10	0	0	5	5
15 kW DIPS cart	50	0	10	20	20
160 kW nuclear power plant	500	100	100	150	150
PMAD and cables	30	0	10	10	10
communication system	10	0	0	5	5
open rover for crew	5	0	0	0	5
pressurized rover for crew	10	0	0	5	5
science rover	10	5	5	0	0
hand tools,machine tools	10	0	0	5	5
consumables (food etc.)	20	0	0	10	10
clothes, hygenic materials	20	0	0	10	10
spares	50	0	10	20	20
TOTAL	**1680**	**140**	**390**	**565**	**585**

In addition to the development and first unit cost of the base infrastructure the development and first unit cost of the elements of the space transportation system are part of the system acquisition cost. These are estimated with the help of the TRASIM code and presented below.

4.2 Acquisition cost of space transportation system[20,22]

4.2.1 Development of Earth launch vehicle, lunar bus and space operations center

This cost estimate is limited to the non-recurring costs of the program to be carried out during an eight to ten year development and test phase, before the operational phase can be initiated. These costs are primarily the development costs, including first unit costs, derived by cost estimating relationships developed using relevant data on past experience during the last decades and entered into the TRASIM code[2,10]. In case pre-production of vehicles or modules are required due to the anticipated schedules prior to the first operational year, these are estimated at the level of first unit costs.

The following comments will help to understand the calculation procedure used for deriving the non-recurrent costs listed in the specified columns of table 4-5 :

(1) Development cost the heavy lift launch vehicle (HLLV) including prototype, ground facilities and flight testing, but excluding crew module and payload containers.

(2) Development cost the lunar lander (LUBUS), including prototype and flight testing, but excluding crew cabin and payload containers.

(3) Cost of development of crew modules and payload containers for HLLV and LUBUS including prototypes and flight tests, also including the development effort for the modification of the second stage as a space operation center.

(4) One pre-production unit - in addition to the prototypes - of all elements of the space transportation system (other than the SOC) as back-up vehicles in case of mishaps. - This has to be accounted for separately as this is not included in the standard cost estimating procedure!

(5) The production of the first complete unit of the space operation center (LUO-SOC).

(6) Total cost of the logistic system R&D phase, items (1) thru (4)

Table 4-5: Non-recurrent cost of initial lunar space transportation system

year (M $)	(1) HLLV dev.	(2) LUBUS dev	(3) payload modules dev.	(4) back-up units	(5) space ops center dev. +1st unit	(6) totals
-7	1205					1205
-6	1649	94	489			2232
-5	2070	133	691			2894
-4	2334	166	914	1100		4514
-3	2334	180	1020	1100		4634
-2	2070	166	949	1100	694	4979
-1	1649	133	774	1127	748	4431
0	1205	93	538		748	2584
totals	**14516**	**965**	**5375**	**4427**	**2190**	**27473**
Moon	11889	965	5375	4427	2190	24846
Mars	2627*)					2627

*) share of 18.1% propoprtional to the share of flights: 72/397

The second development phase begins after the HLLV plus LUBUS + SOC have become operational and focusses on those elements of the space transportation system required for the logistic support of the Mars facility.

Table 4-6: Non-recurrent cost of Mars elements of space transportation system

year M $	Mars lander	Mars-bus	Mars ferry	Trans-Mars injection stage	totals
-5		229	415		644
-4	157	334	607	203	1302
-3	237	411	747	308	1703
-2	276	411	747	357	1792
-1	237	334	607	308	1486
0	157	229	415	203	1004
totals	**1064**	**1949**	**3537**	**1380**	**7931**
product improvement	453	801	1212	413	**2879**
1st unit cost	89	298	993	393	

product improvement cost are integrated into the operation cost !

4.3 Total acquisition cost

Table 4-7: Total acquisition cost of outposts on the Moon and Mars[21,22,23]

calen-der year	infra-structure develop-ment	1st hard-ware sets for outposts	sub-total infra-structure	initial space trans-port. dev.	Mars vehicles addition to STS	sub-total STS (%)	total
2007	60		60			0	60
08	140		140	1205		81	1345
09	370		370	2232		86	2602
10	654		654	2894		82	3548
11	1041		1041	4514		81	5555
12	1305	124	1429	4634		76	6063
13	1605	162	1767	4979		74	6746
14	2010	179	2189	4431		67	6620
15	2120	205	2325	2584		53	4909
16	375		375			0	375
17	380		380			0	380
18	440		440			0	440
19	490		490			39	490
20	580		580		644	55	1224
21	695		695		1302	67	1997
22	705	140	845		1703	68	2548
23	755	390	1145		1792	63	2937
24	765	565	1330		1486	54	2816
25		585	585		1004	65	11589
totals	**14,490**	**2,350**		**27,473**	**7931**	**68%**	**52,244**

To these acquisition cost the operations cost have to be added! Before this can be done, the size and growth rates of the extraterrestrial facilities have to be determined, because they define the number of flights to be schedules for the space transportation system.

5.Characteristics of the Lunar base[21]

5.1 Performance

The performance and operations cost of an extraterrestrial base is primarily a function of the logistc support required. Launch rates are the most influential variable in that respect. They are a function of the mass of facilities and equipment, of the number of crew members, the length of their duty cycles, the production rates of manufactured propellants and goods and the resulting supplies in terms of consumables, spares and facility extensions. The following table describes the logistic requirements of the lunar base designed for the model analysed in this report.

An adequate sized lunar base providing commercial opportunities and permitting the support of optional Mars exploration programs, seems to be an affordable program for the first half of the 21st century. A detailed model of such a representative lunar base, that achieves a beneficial occupancy by 2016 and is operated through the calender year 2050, has the characteristics presented in the following tables.

To achieve a beneficial occupancy for an initial lunar base, facilities and equipment of about 360 metric tons will have to be available on the lunar surface no later than in the second operational year. A typical composition of the modules required is summarized below:

Table 5-1: Typical mass model of initial lunar	**outpost**
1. Habitat module no.1	15 metric tons
2. Habitat module no.2	15
3. Pilot production modules	40
4. Control center	15
5. Science laboratory	5
6. Workshop	15
7. Central storage	15
8. Airlocks	15
9. Rover vehicles	5
10.Multi-purpose trucks	15
11.Structural nodes	15
12.Connecting tunnels	15
13.Tools and minor equipment	10
14.Life support supplies	20
15.Road construction material	15
16.Spaceport equipment	10
17.Propellant tanker vehicle	15
18.Power plant	50
19.Spares and reserves	45
Total mass requirements other than personnel	360 metric tons

The primary operational characteristics during the assumed life-cycle are presented in the next table.

Table 5-2: Overview of Lunar base characteristics during a 35 year operational LC

year of operatio-nal life-cycle	number of total lunar crew	total mass of lunar	imported spares and facility extensions	imported consum-ables tons p.a.	propellants for local use tons p.a.	output of products of lunar

	members	facilities tons	tons			facilities tons p.a.
1	21	257	2	36	184	24
2	44	419	161	60	292	37
3	42	446	30	69	365	54
4	46	487	43	78	425	65
5	50	531	48	87	477	74
6	56	580	52	97	530	84
7	61	629	53	106	580	94
8	67	680	54	115	629	104
9	72	731	54	123	677	113
10	78	782	55	132	724	123
11	84	836	57	141	761	130
12	90	889	57	149	797	137
13	95	944	59	158	832	144
14	101	999	59	166	867	151
15	107	1055	60	174	901	158
16	115	1120	67	183	925	160
17	121	1178	61	193	947	166
18	128	1243	67	201	969	169
19	134	1303	63	209	991	175
20	142	1369	68	218	1012	177
21	155	1488	106	231	1033	168
22	160	1544	61	240	1054	187
23	168	1619	75	250	1074	185
24	176	1699	77	260	1094	187
25	185	1780	78	270	1114	190
26	187	1813	46	275	1129	208
27	192	1860	55	281	1142	206
28	197	1908	56	286	1156	208
29	201	1958	56	292	1169	210
30	206	2008	56	297	1183	212
31	211	2058	56	303	1196	214
32	216	2108	56	308	1208	216
33	221	2159	56	314	1221	218
34	226	2210	56	319	1233	220
35	230	2262	56	325	1246	222
totals	4585	2262	2116	6946	31137	5390
av	131	1283	60,4	198	890	154

Matching annual launch rates with the tentative requirements of the lunar base leads to the payload capacities and propellant requirements listed in table 5-3. The table shows that the system performance is determined nearly equally by the demands for crew rotation and cargo flights. With 4,585 labor-years on the Moon and a capacity of 139 x 40 = 5,560 seats, the average duty cycle will be about 10 months. If this can be increased, this will reduce the number of passenger flights and cost accordingly.

Table 5-3: Typical flight schedule for supporting the lunar base

(passenger flight = 40 persons, cargo flights = 60 MT, one-way = 50 MT + empty stage)

*) five flights tests, **) Lubus delivered partly fueled to LUO, # tanker flights

YEAR	no. of pass. flights	no of regularcargo flight	cargo capa-city reqrd.	total cargo capacity avail.	flights to LEO &SOC	total no. of HLLV lunar flights p.a.	Lulox reqrd	Lulox pro-duced	Lox brought from Earth
0	0	1	257	60	5*) + 1	0+6	0	0	0
1	1	5(2)	38	260	1**)+2	9	330	184	0
2	2	4(1#)	321	220	2**)	8	390	292	100
3	2	4(1)	99	220	1**)	7	390	365	25
4	2	3	122	180		5	390	425	
5	2	2	135	120		4	300	477	
6	2	2	149	120		4	300	530	
7	3	2	158	120		5	360	580	
8	3	3	169	180		6	450	629	
9	3	3	178	180		6	450	677	
10	3	3	187	180		6	450	724	
11	3	3	198	180		6	450	761	
12	3	4	206	240		7	540	797	
13	3	4	216	240		7	540	832	
14	3	4	224	240		7	540	867	
15	3	4	234	240		7	540	901	
16	4	4	250	240		8	600	925	
17	4	4	255	240		8	600	947	
18	4	4	268	240		8	600	969	
19	4	5	272	300		9	690	991	
20	4	5	285	300		9	690	1012	
21	4	5	336	300		9	690	1033	
22	4	5	300	300		9	690	1054	
23	5	5	325	300		10	750	1074	
24	5	6	338	360		11	840	1094	
25	5	6	348	360		11	840	1114	
26	5	6	320	360		11	840	1129	
27	5	6	335	360		11	840	1142	
28	6	6	342	360		12	900	1156	
29	6	6	350	360		12	900	1169	
30	6	6	354	360		12	900	1183	
31	6	6	359	360		12	900	1196	
32	6	6	364	360		12	900	1208	
33	6	6	370	360		12	900	1221	
34	6	6	375	360		12	900	1233	

35	6	6	380	360		12	900	1246	
sum	139	160	9417	9520		300+)	22290	31150	125
av	4.0	4.6	269	272		8.6	637	890	

+) including 6 development flights ,some 18 secondary flights have to be added

There is an excess production of lunar oxygen which is tolerated and accepted as a reserve. It may also compensate some optimistic assumptions. This is one of the possibilities for further optimization of the program.

5.2 Operational cost 22,23

Items of interest are the cost per flight between Earth and Moon spaceports as well as the cost of the operation of the unar base. The total logistic costs are given in the last column, but need to be split in lunar Mars shares.

Table 5-4: Cost per launch of HLLV and LUBUS (M$ p.f.) and base operations p.a.

YEAR	Cpf pass to LUO	Cpf cargo to LUO	Cpf LUO-LUS pass	Cpf LUO-LUS cargo	Cpf pass ES-LUS	Cpf cargo ES-LUS	Moon base oper. cost M $	logistics incl. Mars share
1	236	225	53	17	289	242	776	5365
2	162	150	21	10	183	160	1302	4051
3	156	145	20	10	176	155	871	3879
4	152	141	20	10	172	151	923	969
5	150	140	20	10	170	150	941	3234
6	148	137	19	10	167	147	959	507
7	145	135	19	9	164	144	966	1272
8	144	134	19	9	163	143	977	641
9	142	132	18	9	160	141	981	627
10	141	131	18,	9	159	140	990	647
11	140	130	18	9	158	139	1002	804
12	139	129	18	9	157	138	1007	864
13	137	128	18	9	155	137	1017	1515
14	131	121	17	9	148	130	1022	866
15	127	117	17	9	144	126	1031	834
16	124	114	17	9	141	123	1061	890
17	124	114	17	9	141	123	1048	930
18	121	112	16	8	137	120	1073	1069
19	119	110	16	8	135	118	1065	1764
20	119	110	16	8	135	118	1087	3605
21	118	109	16	8	134	117	1223	1096
22	118	108	16	8	134	116	1077	3546
23	115	106	15	7	130	113	1131	1187
24	114	105	15	7	129	112	1148	3608
25	112	104	15	7	127	111	1159	1832

26	112	104	15	7	127	111	1056	3546
27	111	102	15	7	126	109	1091	1008
28	110	101	15	7	125	108	1099	1100
29	109	100	15	7	124	107	1105	1058
30	109	100	14	7	123	107	1108	1073
31	108	100	14	7	122	107	1113	1661
32	105	97	14	7	119	104	1116	1200
33	105	96	14	7	119	103	1121	1074
34	103	94	14	7	117	101	1124	1291
35	105	96	14	7	119	103	1129	900
av	121	117	16	8	137	125	1054	1700
total							36,900	59,513

The declining cost per lunar mission for passengers and cargo versus time is illustrated in the next graph.

Figure 5-1: Trend of mission cost for lunar passengers (upper curve) and cargo (lower curve) as function of operational year

Comparing these trends to the present cost of shuttle flights indicates that quite some progress can be made in terms of cost-effectiveness of space transportation systems. These improvements can be realized for chemical propulsion systems. It remains to be shown that other propulksion systems are offering lowwer cost than shown here.

This concludes the discussion of the characteristics of the lunar base envisioned for the scenario presented in this case study. The next chapter is attempting to do the same for a Mars base.

6. Characteristics of the Mars laboratory[14,24,26,28]

6.1 Performance

This option envisions a ten year development phase, and thereafter a gradual growth of a permanent Mars Base during 12 launch windows and 25 (Earth) operational years. The population will grow to nearly 100 persons.

Table 6-1: Architecture of a typical permanent Mars laboratory

program attributes and parameters

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

Table 6-2: Summary of program attributes and parameters

Mars surface infrastructure	*mission profile*	*vehicle design*	*crew system*
initial habitat solar & nuclear power plants rovers propellant production 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, 3 vehicles per mission, initially 24 people on Mars surface growing up to 96, artificial gravity on both transfer legs

The simulation of the operational life-cycle will be based on Earth years, because the annual supply rates are using 365 days per year. The LUBSIM model results in the following data with the present assumptions, which have to be confirmed.

Table 6-3: Overview of the characteristics of a Mars laboratory with a

25 Earth-year operational lifecycle

year of operatio-nal lifecycle	number of total Mars crew members	total mass of Mars facilities MT p.a.	imported spares and facility extensions MT p.a.	imported consum-ables MT p.a.	propellants for local use MT p.a.	other products output of Mars facilities MT p.a.
1	11	148	150	19	97	32
2	17	217	70	29	117	41
3	21	240	27	35	120	56
4	25	272	36	41	123	69
5	29	306	37	48	125	82
6	30	318	18	50	126	90
7	32	334	22	54	127	95
8	34	351	23	57	128	100
9	36	368	23	60	129	105
10	39	385	24	64	130	111
11	40	396	18	66	130	113
12	42	408	20	68	130	114
13	43	420	20	71	130	116
14	45	432	20	73	130	117
15	47	444	21	76	130	118
16	50	471	34	81	130	118
17	53	492	29	86	130	119
18	56	515	31	90	130	120
19	60	538	31	95	130	121
20	63	560	32	100	130	122
21	71	686	119	111	129	110
22	76	717	41	119	129	122
23	82	756	49	127	129	122
24	88	799	52	136	128	122
25	94	842	53	146	128	122
totals	1183	842	861	1902	3168	2557
av	**47**	**455**	**34**	**76**	**127**	**102**

The anticipated flight plan can be summarized as follows, neglecting the fact that the delta time between two launch windows is not 2 but 2.16 Earth years. This leads to conservative estimates. The passenger transportation system is comprised of reusable vehicles:

(1) Earth launch vehicle tanker and shuttle to departure orbit in 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 using only propellants locally produced, with some reserves arriving from Earth if needed.

Table 6-4: Number of scheduled flight missions

year of operational life-cycle	crew flights with ferry to Mars fast	crew arrivals/ de-partures flights	cargo flights direct	HLLV tanker flights	total HLLV flights	no of local passenger Mars bus flights	number of shuttle support flights ES-LEO
1			3		3	0	
2	3	24/12		3	3	3	8
3		12	3		3	2	8
4	3	24/12		3	3	3	8
5		24	3		3	2	8
6	3	24/16		3	3	3	8
7		32	3		3	2	8
8	3	24/16		3	3	3	8
9		40	3		3	2	8
10	3	24/16		3	3	3	8
11		48	3		3	2	8
12	3	24/16		3	3	3	8
13		56	3		3	2	8
14	3	24/16		3	3	3	8
15		64	3		3	2	8
16	3	24/16		3	3	3	8
17		72	3		3	2	8
18	3	24/16		3	3	3	8
19		80	3		3	2	8
20	3	24/16		3	3	3	8
21		88	3		3	2	8
22	3	24/16		3	3	3	8
23		96	3		3	2	8
24	3	24/24		3	3	3	8
25		96				2	8
totals	36		36	36	72	60	200

The capacity of 36 cargo flights assuming an average payload of 80 MT results in a capacity of 2,880 MT, which is above the estimated requirement of 2,763 MT.

12 missions with three passenger vehicles each (with 3x8 crew members) have a capacity of 288 people. If a crew of 96 remains after 25 years, 192 will have returned. This results in an average duty cycle of about 6 years.

This logistic schedule is the basis for an initial cost estimate of the operational phase. Other than of the cargo vehicles from LEO to Mars surface, only 3 to 4 vehicles will have to be built because they are reusable. This is reflected in the next two tables. The production cost are estimated with the help of the TRASIM code, on the basis if their mass models with adequate consideration of existing commonalities. An overview of the vehicles employed in this Mars logistic concept and their costs are presented in table 6-5.

Table 6-5: Cost summary of space vehicles employed for the logistic support of a permanent Mars facility -

	Mars lander	Mars bus + cabin	Mars ferry +habitat	TMI stage	all vehicles
development without p.imp.	1064	1949	3537	1380	7930
with product improvement	1517	2750	4749	1793	10809
production	2460	1462	9802	10102	23826
mission operations	398	437	552	363	1750
total including product imp.	4376	4649	15103	12278	36406
first unit cost	89	298	993	393	N.A.

A certain number of support people for flight control and as trouble shooters as well as training personnel are resulting in the operations cost, are included with the initial development cost above, but in the next table these are summarized with mission operations in column 5.

6.2 Operational cost

Table 6-6: Partial operational cost of Mars logistics operation (M $)

(not including the cost of the HLLV or development cost) - *) tooling

calen-der year	production exp.TMI stages & cargo landers	production of reusable ferry and Mars bus	production of ferry habitat & bus cabin	prod.imp.+mission operations	shuttle flights ES-LEO-ES M $	Mars space vehicle operations LEO-Mars
26	1068+257	212+171	154	170	120	2152
27		197+171	435	244	120	1167
28	928+227	188+171	120*)	201	120	1955
29				240	120	360
30	879+216			198	120	1413
31				237	120	357
32	847+209		426+151	195	120	1948
33				234	120	354
34	824+204			193	120	1341
35				231	120	351
36	808+200			191	120	1319
37		182	419	228	120	949
38	802+197	178	148	189	120	1634

39		174+171		226	120	691
40	797+194	171		187	120	1471
41		171		224	120	515
42	792+192			185	120	1289
43			413	221	120	754
44	789+190		146	183	120	1428
45				219	120	339
46	786+188			181	120	1275
47				217	120	337
48	783+186			179	120	1268
49			408	214	120	742
50			145	113	120	378
total	12565	2157	2965	5100	3000	25787

7. Steps of program development and execution [29]

The following steps of an integrated *Moon-Mars Exploration and Development Program* are presently envisioned:

1. Program Preparatory Phase (at less than $ 100 million)

2. Program Enabling Phase (at an expenditure rate of about $ 1 billion p.a.)

2.1 Extraterrestrial facilities and equipment

2.2 Logistic system infrastructure

3. Hardware Development Phase (at about $ 6 billion p.a.)

4. Initial System Core Aquisition Phase

5. Initial Operational Phase

6. Long range operational alternatives

The following sequence of development steps is envisioned:

7.1 Program Preparatory Phase (PPP) -

Three types of activities should take place during a multi-year preparatory phase to establish a data base to enable future program decisions :

a. Establishment of an *International MM - Planning Office.-* This has the task to document alternative scenarios and program options of an integrated Moon-Mars Program for the first half of the 21st century. Objectives have to be veryfied. The present knowledge of the past and current Moon-Mars programs has to be compiled as the point of departure. Lunar options, Mars options, combined options have to be defined. Schedules, benefits, cost and risks of all promising alternatives have to be estimated with a high degree of confidence. Organizational models have to be developed for each of the program phases. This information must be available as a basis for further program decisions.

b. Establishment of an international technical planning team to assess the state-of-the-art in the field of *space facilities*. Long lead time elements of extraterrestrial facilities and equipment for all program options have to be defined, detailed specifications, development effort required and tentative schedules must be deliniated. This activity is in support of the MM-Planning Office.

c. Establishment of an international technical planning team to assess the state-of-the-art of *space transportation systems*. Long lead time elements for the logistic infrastructure, launch vehicles, space vehicles and space facilities considered essential for the most promising program options along with tentative schedules and funding requirements must be defined. This activity is in support of the MM-Planning Office.

A draft of the proposed program and/or next step respectively, is to be submitted to the representatives of the participating Governments for consideration by the potential contributors some 18 months after activation of the planning team, and a final report after two years.

7. 2 Program Enabling Phase

If the findings of the first phase and the global political environment justify the continuation of the first phase effort, then the initiation of the development of relevant technologies and infrastructure must be approved with respect to goals, level of effort and schedule of a second phase of an integrated MM-Program. This phase will also be coordinated and supervised by the International MM- Planning Office. In addition to these duties, this office will also prepare all organizational steps required to set up an International organization required to manage the next phases.

7.2.1 Extraterrestrial facilities and equipment

Development of key technologies and elements of the infrastructure - not available from existing or near term national programs - are initiated and executed for the duration of up to four years to demonstrate technical and financial feasibility of the next Moon-Mars development phase. Also alternative detailed plans for the logistic requirements of a lunar base and human exploration of Mars are to be developed in this period, particularly for the acquisition and operation of an initial lunar base and a Mars laboratory are to be developed in this period. This is a step *short of* a commitment to proceed with the acquisition of an initial lunar base or crewed flights to Mars.

7.2.2 Logistic infrastructure

Development of key technologies and elements of the logistic infrastructure - not available from existing or near term national programs - are initiated and executed for the duration of up to four years to demonstrate technical and financial feasibility of required space transportation systems. Also this is a step *short of* a commitment to proceed with the acquisition of an logistic system to support Lunar and Mars ground facilities.

7.3 Hardware Development Phase

Only if after several years of planning and pre-development activities prove that the technical and financial concepts are viable and promising, then a new *International organization* will be established to manage the development of the essential elements for the next program phase.

The development of all system elements are to be completed as the schedule requires, employing the "rapid prototyping" concept. All necessary steps for the acquisition of an initial lunar outpost and/or a first crewd Mars expedition are to be initiated and approved for about a five year period if not specified otherwise. Also the further course of action is to be decided upon. For the purpose of illustration only a typical development program might be structured as follows.

To illustrate the requirements for hardware development the following tentative list of subsystems is included:

Table 7-1 : Major hardware subsystems to be developed during the first decade of an integrated Moon-Mars program

1. Reusable heavy lift Earth launch vehicle (HLLV) for cargo and passenger transportation to and from LEO, lunar orbit or other destinations;

2. Reusable lunar launch and landing vehicle for cargo and passenger transportation from lunar orbit to the lunar spaceport and back;

3. Space operations center in lunar orbit and/or planetary departure orbit;

4. Habitat module including all life support systems;

5. Power module providing thermal and electrical energy;

6. Production plant module for LOX and construction material;

7. Workshop module for maintenance, repair and extensions;

8. Laboratory module for research and development activities;

9. Ground support equipment, transportation, launch services etc.;

10. Control center module for systems control activities & communication.

All modules have to be designed to be used on the Moon and/or on the Mars surface if so specified by the program.

Illustrative steps of development, if so adopted as part of the MM-program, may have the following structure and sequence:

7.4 Acquisition and operational phases

7.4.1. Acquisition and beneficial occupancy of first outpost

The first step of the acquisition shall be the establishment of a nucleus lunar facility to ensure the survival and safety of the first lunar crew for a minimum of six months. All essential functions must be provided for an initial beneficial occupancy by a small crew scheduled to arrive after at least one year of flight testing during the end of the first operational year. Priority science tasks will be taken up. This is the smallest possible program that should be persued during the acquisition phase.

7.4.2. Activation of lunar laboratories

The establishment of lunar research and development laboratories shall gradually be pursued after beneficial occupancy is achieved, in conjunction with a reasonable extension of the lunar infrastructure. The immediate goal is to lease research and development laboratory spaces at an affordable rate to interested parties on Earth at an early time to contribute to the financing of the project.-

This phase of development shall last several years up to one decade, or be broken off, if its benefits are not in line with the investments and/or are far below expectations.

7.4.3. Activatian of lunar production facilities

An oxygen plant shall be activated on the lunar surface at the earliest possible time to support the needs of the lunar crew and to contribute to a reduction of the logistic costs of the lunar base. Other products to be used for the extension of the lunar infrastructure and the consumption of the lunar crew shall follow as economically justified and resources permit. Most of these production facilities shall be transported from

Earth to the lunar base site in complete modules, checked out and be ready for operation.

The goal of this development step is to reduce import requirements to the lunar base and achieve an increasing degree of self-sustenance on a fast track bases.

The development of a broad spectrum of production facilities on the lunar surface will require at least one, probably two decades.

7.4.4. Execution of first crewed Mars landing

This step should be initiated at the time enough experience is available from the operation of the first extraterrestrial outpost. This experience will certainly have to be integrated into the hardware. This will take some time. Thus a ten year period seems to be a good choice between the beneficial occupancy of the first and the second outpost. But this development step might be initiated at any time of the program. It is designed to open the door to human tended exploration of Planet Mars. It should be approved only if robotic missions have demonstrated that manned activities on Mars are desirable and can be expected to be accomplished with acceptable risk and cost.

The steps sketched above would probably cover the first three decades of the 21st century, both bases would be in a gradual operational growth phase as described above in the chapters 5 (Lunar base) and 6 (Mars laboratory).

8. Total benefits of the integrated program 5,6,11,12,13,17,18,24,25,30

8.1 Objectives and goals

The human mind is not capabable to project or even predict the discoveries that will be made on other celestial bodies in the centuries to come, even less to estimate their value to humanity as a whole. Our imagination is simply not good enough. But it is certain that valuable discoveries will be made in establishing and operating facilities on the Moon and on Mars during the next century. On the other hand it is not sufficient to insist that we have to go there to find out.

A program of this magnitude has to be justified in some fashion to be approved. This is difficult, particularly if it is a long range program that obviously does not satisfy pressing needs of society. But it is generally accepted, that there is clear evidence of benefits from space activities available. There are quite a few space applications already producing benefits, such as communication satellites, navigation satellites, observation satellites and weather satellites. These programs can be justified economically and they are realized an expanded on that basis. They are also producing taxes already today. Research satellites and robotic space probes are justified as part of the basic research activities, and even that is not easy because most people do not care about basic research. In case of space projects with human participation the justifications are even more difficult, because they are perceived as fairly expensive. The lunar expeditions in the years 1969 to 1972, costing 22 billion dollars, were justified and accepted by the American tax payers primarily for political reasons.

Such a political motivation is unlikely to be repeated for extraterrestrial bases, short of some global catastrophe. Thus to prove sufficiant benefits of such enterprises are a real challenge. There are two approaches to this problem:

1. If it is generally agreed that the exploration of space and the utilization of its resources is an essential step of the evolution of humankind which can not be questioned and not be stoped. In this case there would be no need of a detailed benefit analysis. It would simply be a matter of priorities when and at what speed the human civilization would expand into space. However, the majority of the Earth population does not accept this argumentation at this time.

2. Consequently, in the current situation a different way must be found to convince the general public that

the cost of exploring space by humans is justified by the likely benefits resulting from it, and are contributing to the enhancement of the quality-of-life on Earth. This calls for a benefit model that is transparent enough to be transmitted to the educated taxpayer. It is obvious that are are many aspects which only together will produce benefits in the amount needed to justify the costs, this means we have to consider the details.

This can be done with with a *model* representing our present knowledge of the complexities involved. A model can demonstrate that the likely benefits of extraterrestrial bases on the Moon and on Mars for humanity are manifold and sufficiant to justify the expenditures. A model that is a practical step in this direction was recently developed and can be used as a departure for the analysis30.

The process of developing a detailed benefit model begins with a listing of all aspects of the *quality-of-life-on Earth*, that can be affected by activities on the Moon and on Mars with people in situ. These aspects are defined in terms of *objectives* and *goals* for a specific point in time. The goals can be set for an entire century and must be re-evaluated from time to time. Table 8-1 is such a list of objectives broken down in:

A. Humanistic objectives

B. Political objectives

C. Scientific objectives and

D. Utilitarian objectives.

The goals listed for the year 2100 are selected for the purpose of illustrating the possible choice of typical benchmarks of what can be expected by the end of the 21st century. Such benchmarks may be used in the benefit analysis.

Table 8-1: General scale of measurement and goals based on the reference year 2100 for estimating the benefit of extraterrestrial space programs

	Objective	**Goals for 2100**
A	**HUMANISTIC OBJECTIVES**	
a.1	enhance the protection of the Earth biosphere and the human species, especially from extraterrestrial threats, thus assisting in the preservation of our present habitat	activation of a first defense system on the farside of the Moon
a.2	enhance the evolution of the human culture in the dimension of space by expanding human activities in our solar system and learn to live and work in isolated,extreme environments	permanent extraterrestrial population of 1,000
a.3	enhance the educational system and the motivation to learn	university degrees for 25% of the population
a.4	provide survival shelters for remnants of the human race and its civilization in case of a global catastrophe	develop the basic infra-structure for an extraterrestrial population of 5,000
a.5	assist in reducing tensions & conflicts,thus contributing to peace on Earth	extraterrestrial programs to reach 1% global GNP
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	1 million people participating in the space program
B	**POLITICAL OBJECTIVES**	

b.1	demonstrate the potential growth existing beyond the limits on Earth	10,000 metric tons of extraterrestrial products p.a.
b.2	provide more opportunities for international cooperation	extraterrestrial programs to reach 1% global GNP
b.3	extend the infrastructure and experience for global enterprises	extraterrestrial programs to reach 1% global GNP
b.4	provide a peaceful outlet for national, competitive high technology urges and a useful employment of the industrial-military complex	1 million people employed in the space program
b.5	enhance the self-esteem and prestige of participating nations	50% of all UN members participate in space programs
C	**SCIENTIFIC OBJECTIVES**	
c.1	improve the understanding and control of our homeplanet	quality of Earth biosphere is better than in year 2000
c.2	improve our knowledge of the Moon and its resources	the survey of lunar resources is 100 percent complete
c.3	improve our understanding of Planet Mars and other celestial bodies of the solar system beyond the Earth-Moon double planet	25% of the Mars surface explored by human crews on traverses
c.4	improve our understanding of the universe beyond our own Solar System	large scale astrophysical research facilities have been installed on the lunar farside
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	100 laboratory spaces are available to government & commercial users in extraterrestrial facilities
D	**UTILITARIAN OBJECTIVES**	
d.1	provide rewarding job opportunities and thus stimulate the economy on Earth in general	1 million people employed in the space program
d.2	stimulate the development of advanced technology on Earth	1 million people employed in the space program
d.3	produce in space marketable products for extraterrestrial use and for terrestrial consumption (other than space solar energy)	sales of extraterrestrial products reach 0.2 % of global GNP
d.4	increase the flow of space based energy to users on Earth	100 GW of space generated energy is delivered to Earth
d.5	provide isolated extraterrestrial depositories to store high level wastes outside the gravity well of the Eart	1000 tonnes of high level waste are exported into space
d.6	provide safe & economical space transportation systems as a mandatory step for the exploration and utilization of space resources in general	spec.transportation cost to LEO has been reduced to 500 $/kg and 0.1 M $ per passenger
d.7	provide thrust and focus for continued development of space technology other than in the area of space transportation systems	space projects other than transportation have annual sales of 0.5 of the global

	GNP

8.2 Intuitive judgements

A model of this kind can not be used without attaching numbers to it. In a simple model these individual or group judgements are global and intuitive. In a more complex model some of the judgments can be replaced by mathematical models describing functional relationships. Using this frame of reference, the percentage of goal achievement by operating extraterrestrial facilities on the Moon and on Mars in the year 2050 is to be estimated using past experience and the results of the system simulations. The first judgement required is the *potential share of contributions* extraterrestrial bases are able to make regardless of their size. This is done with considering also contributions by other space projects and Earth based activities. Columns 4 and 7 of the following table are such estimates taken from a previous study30. They represent the upper limits of their potentials to contribute to the achievement of objectives defined.

The next judgement required is an estimate of the *percentage actually realized* by the individual Moon and Mars bases designed and analysed to these potentials at a particular time. These percentages are listed in columns 3 and 6. By multiplication of columns 3 &4 and 6&7, relevant figures are obtained which are a measure of the achievable gains in these space related aspects of the quality-of-life. A sizable facility established early in the century will obviously result in a higher percentage than a small base at a later time.

Table 8-2: Estimated benefits produced by the defined Moon and Mars Bases in the year 2050 as shares of the maximum benefits achievable by the year 2100

	Options	**2050 Moon base %**	2100 max	**2050 Moon base abs.**	**Mars base %**	2100 Max	**2050 Mars base abs**
A	**HUMANISTIC OBJECTIVES**	**52%**	916	**474**	**38%**	732	**229**
a.1	enhance the protection of the Earth biosphere and the human species,especially from extraterrestrial threats, thus assisting in the preservation of our present habitat	30%	210	70	10%	60	6
a.2	enhance the evolution of the human culture in the dimension of space by expanding human activities in our solar system and learn to live and work in isolated,extreme environments	50%	520	260	25%	520	130
a.3	enhance the educational system and the motivation to learn	50%	16	8	50%	16	8
a.4	provide survival shelters for remnants of the human race and its civilization in case of a global catastrophe	80%	105	84	50%	90	45
a.5	assist in reducing tensions & conflicts,thus contributing to peace on Earth	80%	15	12	80%	10	8
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	80%	50	40	80%	40	32
B	**POLITICAL OBJECTIVES**	**67**	275	**183**	**67**	205	**137**

b.1	demonstrate the potential growth existing beyond the limits on Earth	90%	50	45	80%	40	32
b.2	provide more opportunities for international cooperation	80%	45	36	80%	30	24
b.3	extend the infrastructure and experience for global enterprises	50%	45	23	50%	30	15
b.4	provide a peaceful outlet for national, competitive high technology urges and a useful employment of existing industrial-military capabilities	50%	75	37	40%	45	18
b.5	enhance the national pride and prestige of participating nations	70%	60	42	80%	60	48
C	**SCIENTIFIC OBJECTIVES**	**64**	700	**448**	**55**	585	**321**
c.1	improve the understanding and control of our own planet	80%	60	48	80%	45	27
c.2	improve our knowledge of the Moon and its resources	80%	120	96	60%	90	54
c.3	improve our understanding of the solar system beyond the Earth-Moon double planet	50%	240	120	60%	240	144
c.4	improve our understanding of the universe beyond our own Solar System	60%	200	120	40%	150	60
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	80%	80	64	60%	60	36
D	**UTILITARIAN OBJECTIVES**	**39**	1049	**405**	**79**	321	**253**
d.1	provide rewarding job opportunities and thus stimulate the economy on Earth in general	50%	25	13	40%	15	6
d.2	stimulate the development of advanced technology on Earth	50%	90	45	50%	60	30
d.3	produce marketable products for extraterrestrial and for terrestrial use	25%	54	13	10%	6	1
d.4	contribute to the supply of space based energy to the the Earth	10%	420	42	0	0	0
d.5	provide an isolated extraterrestrial depository to store high level wastes	10%	100	10	0	0	0
d.6	enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources	80%	240	192	90%	120	108
d.7	provide thrust and focus for continued development of space technology other than in the area of space transportation systems	75%	120	90	90%	120	108
	total benefit expected with respect to the quality-of-life		2940	**1510**		1843	**940**
	percent of maximum achievable	**51%**	**100**		**51%**	**100**	

total program cost (B $)	**121**	**74**
benefit/cost (M $/point benefit)	**12.5**	**12.7**

These not untypical estimates (which will differ from person to person!) suggest that theparticular Moon base described in this model will achieve about 51 percent, and the Mars base as described above will achieve also about 51 percent of the goals set for the end of the 21st century.

In absolut terms, however, their benefits amount to 1510 and 940 points on the scale of measurement. The difference is about proportional to the costs as illustrated by calculating the ratio of benefit/cost. These are very close with 12.5 and 12.7 respectively. -

These are the type of results a fairly simple benefit model will produce.

8.3 Mathematical Model

It is easy to recognize that the benefits of an extraterrestrial facility will increase with increasing performance of the facility, such as labor-hours available, or products manufactured. Thus we recognize that there must be a functional relationship between the performance of a base and the benefits it produces. These relatinships can be modeled. These socalled *utility functions* will partially be linear and non-linear. In doing so, the benefits can be calculated by this model without further judgments. The judgments to be made are entered, and in a way burried in the model, in terms of constants and exponents of benefit estimating relationships(BER's). They remain estimates, but make sure that the results are consistent. The quality of the results, however, are only as good as the assumptions of people entering the model.

The first task to be solved in developing a practical model, is to find performance parameters that can be used as indicators of benefit. Here are the candidates of performance parameters characteristic for extraterrestrial bases.

Table 8-3: List of base performance parameters

01.Total base population (people)

02. new crew members arriving p.a.

03. crew members departing p.a.

04. average duration of residence at the base of departing residents (years)

05. annual death rate (%)

06. annual birth rate(%)

07. annual growth rate of base population (%)

08. share of population under 20 years of age(%)

09. share of female population (%)

10. share of working population (%)

11. average annual work hours of working population (hours per person)

12. total annual workhours available (hours)

13. share of workhours available for maintenance, repair & housekeeping (%)

14. share of workhours available for research and development (%)

15. share of workhours available for manufacturing and production(%)

16. hours available for maintenance, repair & housekeeping (%)

17. hours available for research and development (%)

18. hours available for manufacturing and production(%)

19. total mass of base facilities and equipment (MT)

20. total base mass/ population (MT/person)

21. annual growth rate of base facility and equipment masses (%)

22. average annual spare rate of facilities and equipment (%)

23. number of permanent outposts outside the main facility

24. number of non-permanent occupied rescue stations outside the main facility

25. total mass of imports per annum (MT)

26. annually imported mass/population (MT/person)

27. annually imported mass of spares and facility components (MT)

28. annually imported mass of consumables (MT)

29. annually imported mass of propellants (MT)

30. annually locally produced mass of spares and facility components (MT)

31. annually locally produced mass of consumables(MT)

32. annually locally produced mass of propellants(MT)

33. mass of products manufactured per annum for the commercial market (MT)

34. mass of all products manufactured per annum (MT)

35. annual selfsufficiency rate - consumables (%)

36. annual selfsufficiency rate - facility components and spares(%)

37. annual selfsufficiency rate - propellants (%)

38. mass of all products manufactured p.a./production workhours p.a. (kg/hour)

39. mass of all products manufactured p.a./mass of production facilities(MT/MT)

40. annual imports/total mass of all products manufactured(%)

41. annual capacity of electric power plants(kW)

42. specific mass of electric power plants (kg/kW)

43. annual electric power produced (kWh)

44. annual equivalent thermal power generated(kWh)

44. anual imported electric power (kWh)

45. annual energy capacities available /total population (kW/person)

46. annual power consumption/mass of all products manufactures (kWh/kg)

47. annual number of landings and launches of space vehicles

48. length of dirt roads (km)

49. length of paved roads (km)

50. total annual land transportation of cargo (MTxkm/population)

51. total annual passenger transportation (persons x km/population)

52. number of missiles available for space defense operations

53. payload capability of missiles at 1 1/3 times of the local escape speed (MT)

54. annual cost of base operations without logistics (M $)

55. annual cost of base logistics (M $)

56. annual total cost of base operations including logistics (M $)

57. annual total cost/population (M $/person)

58. annual total cost/ workhour ($/hour)

59. annual sales of commercial services (M $)

60. annual sales of commercial products (M $)

61. share of total commercial sales of total cost (%)

62. specific cargo transportation cost from Earth ($/MT)

63. specific passenger transportation cost from Earth(M $/roundtrip)

64. total annual cost/ global defense expenditures (%)

65. equivalent number of full time support people on Earth/

base population(person/person)

Not all of these performance parameter apply to a small base or are not easily estimated, thus a choice has to be made which ones should be used for the benefit model. The user of the model must select one or more performance parameters for each of the objectives listed. He has to assign relative weights to them if there are more than one for each objective. Next, the type of utility function has to be selected, before their constants and/or exponents can be calculated on the basis of goals set for the end of the century. This is a personal choice of the user, but a group of experts will probably be needed to design a model that is widely accepted.

The further development of the benefit model for this particular application is a task for the near future. Similar efforts of the past have shown the methodological way[6,13,17,30] to do this.

9. Performance and cost of the integrated program

9.1 Performance and cost of extraterrestrial facilities on the Moon and on Mars

The size of the crew and the annual output of products are typical performance data suitable for the comparison of extraterrestrial facilities. These parameters are depicted in the next tables and diagrams. The totals of both, the lunar base and that of the Mars laboratory are shown in figure 9-1 and 9-2 to illustrate the overall performance of the scenario offered here for the first half of the 21st century. They are basic inputs for estimating the program benefit.

While the planning for this program is assumed to be initiated in the year 2001, the actual development begins in 2007. The first year of the operational period falls in the year 2016 with the beneficial occupancy of the initial lunar outpost. The operational period in this scenario lasts till 2050, where it ends arbitrarily. Thus the data is plotted for the operational years 1 through 35, which may be the calender years 2016 through 2050. This sudden end of the program is unlikely, but a satisfactury assumption for this analysis. The beneficial occupancy of the initial Mars outpost begins around the year 2026, about ten years after returning to the Moon. It appears possible to advance this date by one or two years from the budgetary viewpoint. On the other hand, it is desirable to collect the lunar experience and integrate it into the Mars hardware and operation which make it desirable to leave this time span of ten years between these two milestones.

After estimating the acquisition and operations cost of both the lunar base and the Mars laboratory, the total cost of such a program can be calculated. The partial costs presented in the tables above are now compiled in table 9-1 for the years 2007 through 2050. In this context it should be noted, that the space vehicles and their payloads, as well as the propellants needed to refuel the Mars ferry vehicles, require 72 launches of the HLLV to low Earth orbit. This flight operation alone amounts to about 72 x 100 = 7,200 M $.

By adding the figures of columns 6,7 and 8 of table 9-1, the total logistics cost are obtained. The share of logistics cost is about 64 percent of the program cost, but not constant. The trend of these annual expenditures are shown in figure 9-3, it can be smoothed by planning the procurement funds in a different way. Drawing this diagram it was assumed that the hardware would be paid in full in the year of delivery. Normally the procurement cost are spread over three years. That would reduce the peaks and valleys in this trend curve.

Adding the operational costs of the two extraterrestrial bases analysed to these logistic costs, the trend shown in figure 9-4 for the total annual program expenditures emerges.

Figure 9-1: Growth of extraterrestrial population as function of time

Figure 9-2:

Growth of the output of extraterrestrail facilities in terms of mass of all products

Table 9-1: Annual and total program cost

YEAR	base infra-structure develop-ment	1st hard-ware set for outposts	lunar base opera-tion	Mars base opera-tion	trans-porta-tion develop-ment	HLLV +LUBUS operation	Mars space vehicle operation	total
2007	60				0			60
08	140				1205			1345
09	370				2232			2602
10	654				2894			3548
11	1041				4514			5555
12	1305	124			4634			6063
13	1605	162			4979			6746
14	2010	179			4431			6620
15	2120	205			2584			4909
16	375		776			5365		6516
17	380		1302			4051		5733
18	440		871			3879		5190
19	490		923		100	969		2482
20	580		941		544	3234		5299
21	695		959		1302	507		3463
22	705	140	966		1703	1272		4786
23	755	390	977		1792	641		4555
24	765	565	981		1486	627		4424
25		585	990		1004	647		3326
26			1002	288		804	2651	4745

27			1007	943		864	2776	5590
28			1017	546		1515	3003	6081
29			1022	634		866	868	3390
30			1031	654		834	1292	3811
31			1061	476		890	185	2612
32			1048	517		930	1252	3747
33			1073	526		1069	184	2852
34			1065	535		1764	1224	4588
35			1087	541		3605	1519	6752
36			1223	499		1096	1204	4022
37			1077	517		3546	1479	6619
38			1131	521		1187	1194	4033
39			1148	527		3608	1685	6968
40			1159	532		1832	1416	4939
41			1056	677		3546	1026	6305
42			1091	645		1008	1179	3923
43			1099	665		1100	179	3043
44			1105	674		1058	1173	4010
45			1108	683		1073	179	3043
46			1113	1555		1661	1168	5497
47			1116	830		1200	179	3325
48			1121	910		1074	1163	4268
49			1124	954		1291	178	3547
50			1128	970		900	130	3128
total	14490	2350	36898	16819	35404	59513	28486	194 060
%	7.3	1.2	19.0	9.0	18.2	30.7	14.7	100

Figure 9-3: Annual cost of the development and operation of the integrated space transportation system for the logistic support of a Moon and a Mars base

(beginning the the first year of hardware development)

Figure 9-4: Overview of annual cost versus year of total program life-cycle

Considering the total 50 year program period, the following totals and annual averages for the Moon base and Mars laboratory respectively, are obtained:

Table 9-2: Overview of cost split for Lunar and Mars base (M $)

cost element:	***Lunar base***	***Mars laboratory***
share of infrastructure development	6,050	8,440
production of initial base hardware	670	1,680
initial space transportation development	24,846	2,627
additional development Mars STS	0	7,931
HLLV+ LUBUS operation share Moon	52,313	0
HLLV operation share Mars	0	7,200
Mars space vehicle operation	0	28,486
base operation	36,899 (35 years)	17,492 (25 years)
base infrastructure dev.& operation total	**43,619**	**27,612**
annual average base cost	1,014 (43 years)	837 (33 years)
logistics (development & operation) total	**77,159**	**46,244**
annual average logistics cost	1,794 (43 years)	1,401 (33 years)
total cost sub-program	**120,778 (43 years)**	**73,856 (33 years)**
cost per annum	2,808	2,238
percent of total program cost	62.2%	37.8%

There are at least two ways of reducing the program cost:

1. In this 50 year program, there are about 1,000 labor-years available in the extraterrestrial laboratories which can be leased to commercial customers. The present price of a month long stay at the MIR space station in low Earth orbit is about $ 20 million. It is conceivable that a laboratory space on the Moon or on Mars may be worth $ 50 M to customers, such as companies, media or even a few tourists. These

spaces in extraterrestrial laboratories may lead to commercial sales on the order of $ 50 B. These are nearly 25% of the program cost.

2. A few decades hence, it will become quite clear that this planet will have a shortage of energy in the second half of the 21st century. At this time, utilities might be interested to develop and test a prototype of a space solar power plant(SSPS), either on the Moon or in geostationary orbit. This would add at least 100 flights to the joint schedule, reducing the specific transportation cost of all partial programs. This in turn would also reduce logistic costs of extraterrestrial bases. Moreover, mining companies might want to get into the business of mining minerals on the Moon for people interested in the construction of extraterrestrial solar power plants. This could lead to sizable investments in the lunar infrastructure.

9.2 Cost of extraterrestrial propellants

This model allows also a preliminary analysis of the relative cost of propellants produced on the Moon and Mars. These can be compared with the cost of imported propellants. Such a cost comparison will help to decide the alternatives of selecting Earth produced or extraterrestrial propellants for the elements of the logistic system.

Present indications are that the cost of propellants produced on the Moon are less than the transportation of Earth produced propellants to the lunar surface. However, the picture is different, if the point of destination is not the lunar surface, but the lunar orbit or the L2 point. These are the orbits where a Mars ferry would have to be refueled and loaded before its next trip to Mars. The cost of propellant production and its transport cost to lunar orbit would have to be added. On the other hand, the cost of transporting Earth propellants from lunar orbit down to the lunar surface are saved.

This difference in concept indicates that the cost of lunar LOX in LUO would-, within the assumptions of this development scenario, be in the range of 4,000 to 2,000 $/kg in comparison of Earth LOX in lunar orbit. This is expected to cost between 2,400 and 1,000 $/kg. The general trend versus operational year is shown in figure 9-6 . It should be noted, that in this case the logistic cost of the lunar base is prorated over all lunar products and services. Thus the lunar LOX cost are real cost with the exception of the upfront cost. This analysis also takes into consideration the fact that there is a firm relationship between the logistic cost and the propellant cost, which in turn influemces the cost of lunar products. This required an iterative calculation process.

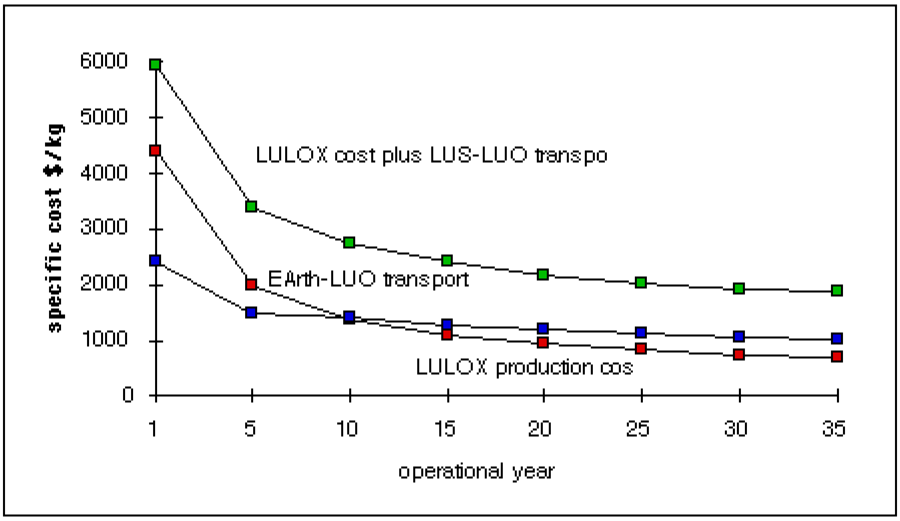


Figure 9-5. Cost of lunar LOX production on the Moon and transportation to lunar orbit compared with Earth LOX and transportation to lunar orbit

The cost of Mars produced propellants are more difficult to estimate. These are quite sensitive to the scenario selected. The specific transportation cost of cargo from the Earth to the surface of Mars are on the order of 7,000 $/kg. This mission mode assumes a reusable heavy lift Earth launcher to LEO, and from there an expendable trans-Mars-injection-stage and an expendable Mars lander. This combination is capable of transporting a cargo of about 90 MT per mission. The passenger roundtrip cost to Mars are close to 100 M $ per seat in this scenario, a factor of ten higher than a roundtrip to the Moon.

The specific cost of producing propellants on Mars, including the respective share of the logistic cost, seem to be on the order of 2,000 $/kg, indicating a clear advantage over imported propellants. This may not hold true for the very early missions, that needs to be analysed a bit closer, looking at the total systems cost and risks involved. It should be pointed out that this difference in propellant cost will only be a few percent considering the total program cost.

9.3 General cost trends of extraterrestrial bases

With a total of 12 case studies, six each for lunar and Mars installations, we can now establish a general trend of specific cost versus base size or total labor volume respectively. This is a pretty clear trend curve, however, the double logarithmic scales obscure the fact, that specific cost of a Mars base is about twice as high as an equally sized lunar base. Also the effects of program integration do not come out very clearly, they are about one third cheaper than seperate programs. This difference would even be greater if the same length of the duty cycle is assumed. It is less than one year for the lunar base and six years for the Mars laboratory due to the nature of the planetary orbits and the desire to have a permanent occupation of the Mars laboratory.

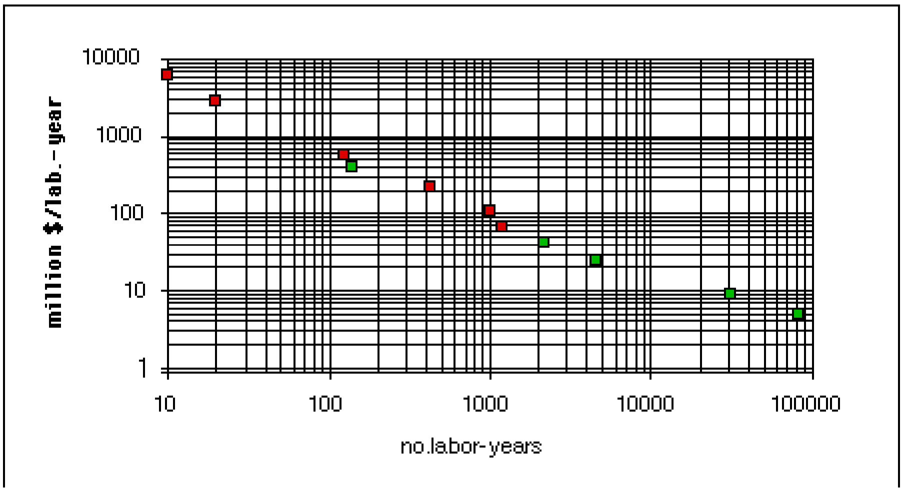


Figure 9-6: Average specific cost per labor year on the Moon (lower end of the curve) and on Mars (higher end of the curve) as function of base size (product of number of people * number of years = labor years available)

10. Summary and Conclusions

A fifty year scenario of developing and operating extraterrestrial bases on the Moon and on Mars in the 21st century was analysed in detail. Performance and cost data were derived with the help of simulation models for the base operation and the logistic system. At the end of the 50 year planning period this scenario leads to a lunar base with a crew of about 230 people and a Mars base with a crew of 96 people.

The results of this study are considered to be representative, but estimates with a limited accuracy. The cost estimates could probably be off by ten percent or more depending primarily on the program management concept selected.

Table 10-1: Summary of a program to establish and operate Bases on the Moon and on Mars in the first half of the 21st century -

SUMMARY:	***Lunar Base***	***Mars Base***
total program cost (M $)	**120,778**	**73,856**

average annual expenses (50 yr LC)-(M$)	**2,415**	**1,477**
cumulative labor years	**4,585**	**1,183**
total cost per cumulative labor year (M $)	**26.3**	**62.4**
average crew duty cycle in space	**10 months**	**6 years**
benefit/cost ratio	**12.5**	**12.7**

This analysis indicates that both base programs together require expenditures of about **195 billion US dollar during a 50 year life-cycle** or an annual average of 3,9 M $, or using a 43 year period the average is estimated to be 4.5 billion US dollar per annum. The individual cost of the two base programs are comensurate with the benefits expected, the benefit/cost ratios are nearly identical.The average specific cost of a labor year on the Moon is estimated to be about 25 M $ and on Mars 68 M $. Potential commercial customers might get involved and reduce the cost to the taxpayer considerably.

The ***conclusion*** is that the outlined 50 year - 195 billion U.S. dollar extraterrestrial development program appears feasible, desirable and affordable with an annual average expenditure of about 4 billion dollar, if one consideres the fact that about 40 billion dollar are currently spent annually on space programs, and 750 billion dollar are spent every year on this planet on military programs.

A first glimpse of possible developments in the 22nd century can be obtained by extrapolating the average specific cost of extraterrestrial bases as depicted in figure 9-7. This trend indicates that an extraterrestrial settlement of 10,000 people with a life-cycle of 100 years could possibly lead to average specific cost of 1 M $ per labor-year using current technologies and partial self-sufficiency! Consequently, the search is on for better ways of doing this. There is some hope, that advanced technologies and operational procedures will probably be available to half these specific cost by the end of the 21st century.

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