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5th COSMIC STUDY
PREPARING FOR A 21st CENTURY PROGRAMME OF INTEGRATED,LUNAR AND MARTIAN EXPLORATION AND DEVELOPMENT

The International Academy of Astronautics (IAA) a non governmental organization recognized by the United Nations was founded in 1960. Since that time, IAA has brought together the world's foremost experts (1216) in the disciplines of astronautics on a regular basis to recognize the accomplishments of their peers, to explore and discuss cutting-edge issues in space research and technology, and to provide direction and guidance in the non-military uses of space and the ongoing exploration of the solar system. The purposes of the IAA, as stated in the Academy's statutes are to foster the development of astronautics for peaceful purposes, to recognize individuals who have distinguished themselves in a branch of science or technology related to astronautics, to provide a program through which the membership can contribute to international endeavors and cooperation in the advancement of aerospace science, in cooperation with national science or engineering academies. Prof. Ed. Stone is president of the International Academy of Astronautics.

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PREPARING FOR A 21st CENTURY PROGRAMME OF INTEGRATED,LUNAR AND MARTIAN EXPLORATION AND DEVELOPMENT

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Abstract

The twenty first century will see modern civilization reaching out to survey the Earth's wider environment. Generations of increasingly sophisticated robotic space probes will continue to chart the fields, plasmas and the larger bodies of the Solar System. For over a quarter of a century human beings have not risked leaving a low altitude orbit of the Earth, but in the coming millennium they will once again dare to take the trail blazed by humanity's electronic scouts and leave their footsteps on the Moon before exploring Mars. An expanded global spaceprogramme, focussed on crewed missions to the Moon and Mars, would be a dramatic corollary to the recent remarkable expansion in commercial activity in near Earth space. There is clearly an urgent need for extended studies to define the most productive interplanetary missions for a series of possible levels of support.

The exploration of the Moon and the planet Mars present similar challenges, and a cursory review might suggest that if the two programmes are combined the joint programme would be able to share a common pool of experience and systems. Only detailed studies, however, will identify the programme strategies that will both minimise costs and maximize the returns while still fulfilling an acceptable timetable. The final decision to return to the Moon or to send a crew to explore Mars will be political. Before responsible politicians approve a new thrust into space they will demand attractive, defensible, and detailed proposals that explain the WHEN, HOW and WHY of each stage of an expanded programme of twenty first century space research, development and exploration.

This report is an initial review of plans for a extensive programme to survey and develop the Moon and to explore the planet Mars during the coming century. It presents current plans for separate, associated and fully integrated programmes of Lunar and Martian research, exploration and development, and concludes in detail and subject to formal criticism and 'peer review', and in particular, the claims of daring, innovative, but untried systems must be compared with the known performance of existing technologies. The time has come to supersede the present haphazard

approach to strategic space studies with a formal international structure to plan for future advanced space missions under the aegis of the world's national space agencies, and supported by governments and the corporate sector.

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1.Introduction

1.1 Space and the Global Challenge

The knowledge painfully won during several millennia has today been harnessed as the technologies that transform the human and material resources of the Earth into goods and services that secure a healthy and satisfying life for some, at least, of its citizens. It is only too obvious, however, that our civilization's achievements fall far short of its lofty ideals. Only a privileged minority of the human race enjoyed the full benefits of a twentieth century that brought misery, poverty, suffering and death to billions. The world wide civilization of the third millennium must face a host of global challenges if it is just to sustain the present, unsatisfactory status quo.

Until recently the human race believed that the Earth was flat and it still largely acts as if its resources were unlimited. Today, we are becoming uncomfortably aware that the Earth is claustrophically spherical and its resources, though considerable, are distinctly limited. In many parts of the world the local ecosystem is crumbling under pressure from an expanding human population's demands for agricultural land, employment and mineral resources. The ultimate results of a denuded environment are poverty and disease that in turn foster illiteracy, ignorance and hopelessness; and without hope of improvement people readily turn to fanaticism, terrorism, drugs and war.

Increasingly, the decision makers and leaders of this planet will have to husband and allocate its limited resources to stabilize and improve the quality of life for both the present and future generations. National economies are increasingly interdependent, and the Earth's communications media are already global, and the global challenges of the next century will demand a supranational response.

Less than fifty years ago mankind finally reached beyond his own small planet and entered the unlimited environment of space. There is little doubt that research into and the development of the resources of space in the decades to come will play a prominent role in addressing the problems of a crowded world. Space technology is already a major component of the global economy, and has, through better communications, reliable positioning, improved weather observation and land management enriched the quality of life of almost everyone on Earth. As space technology improves it will enhance the quality of life on Earth in ways we can not yet imagine.

Twentieth century science and technology have offered the supreme vision of human beings and their powerful creations working, living and growing in space. It is an unchallengeable demonstration that humanity's options are not limited, and that, given the will, there is always hope for improvement. The Apollo programme of the nineteen sixties was spectacular proof that humans could journey to and work on other celestial bodies, and that if they so desired, or were forced to do so, human beings could inherit the Solar System.

While it is easy to predict that twenty first century space technologies will support a major extension of extraterrestrial human activity, it is, however, extremely difficult to predict the course and rate of that expansion. The unpredictable priorities of 21st century national and international politics and the condition the global economy will ultimately determine the resources allocated to space research and development. Nevertheless, as President Bush pointed out in 1989, the Moon and Mars will continue to spark the world's curiosity both as immediate founts of scientific knowledge and as eventual providers of material resources. The Earth's ecosystem, on which human life depends, exists only as part of a wider planetary and interplanetary environment, about which our understanding is still limited. In particular, the neighbouring celestial bodies, large and small, need to be fully surveyed, for the future well being, indeed the survival of the human race may depend on it.

Humankind stands at the threshold of infinite opportunities, and the next step must begin with plans for the exploration and development of the Moon and/or Mars. These plans that will hinge, on a critical analysis of the space technologies that will be needed for the voyage to either body. The technical similarities are so great that separate missions to the Moon or Mars could form part of an highly integrated programme to survey and perhaps ultimately exploit the resources of these two neighbouring bodies, and a joint programme promises to minimise the costs while enhancing the returns. Early in the new millennium the world's political leaders will be called upon to approve plans that will determine the course of 21st century space development. If they are to choose between detailed, realistic strategic plans that have been thoroughly tested and priced, then planning must begin NOW.

1.2 The Purpose of this Document

This document presents the most recent results of a continuing effort to predict and analyze the course, manner and ultimate aims of the twenty first century exploration and development of the Moon and the planet Mars. It assumes that a human presence on those bodies will be essential and emphasizes:

- The Rationale
- The Strategic Restraints
- The Programme Structure
- Stages in the Development of the Programme
- The Initial Organization

The goals and plans presented here are compatible with the strategic plan (HEDS) of the United States of America's National Aeronautics and Space Administration, the world's leading agency responsible for the exploration and development of space. Appendix A contains the relevant excerpts of HEDS.

The results reported here follow a three year concentrated effort by a team of international specialists working under the charter of the MOON - MARS Committee of the *International Academy of Astronautics* (IAA), as authorised by the Academy in April 1997. Two previously published IAA Cosmic Studies on Lunar and Martian exploration (8,15) form the foundation of this report which assesses current technologies before reviewing scenarios presenting possible courses of twenty first century Lunar and Martian research and development. The efforts leading to this documentation began in 1985 and hundreds of people from dozends of countries have contributed in various ways to the insights and information presented in this report. These contributions are acknowledged, but the number of contributors is too large to be listed here. Only those members of the task force have been listed on the title pages who have contributed frequently during the last three years leading to this final documentation.

1.3 Study Background

The challenges and opportunities offered by the exploration of the Moon and Mars can be defined with some confidence, thanks to almost half a century's experience with automatic space probes, crewed missions and theoretical analyses. The APOLLO Programme's manned lunar missions implied that a permanent lunar base is technically feasible. The President of the United States's proposal in 1989 to have people permanently return to the Moon, however, fell victim to the sudden shift in the geopolitical climate at the end of the Cold War.

Human beings will only walk on the surface of Mars, when the scientific, political and economic returns are seen to outweigh the risks and the considerable cost. These conditions will only be fulfilled after a further two decades of research with robot probes aimed at proving the technologies and gathering the planetary data required before a crewed expedition can be launched to the Red Planet.

The mining of Earth approaching asteroids is an intriguing and potentially rich field of endeavour; however, asteroidal studies are in the same condition as Martian studies were in the early 1970's. Even the total number of Earth approaching asteroids is not known with great certainty, and the majority of their orbits have not been accurately plotted. The NEAR mission has recently returned the first close images of an Earth approaching asteroid. This mission should be the precursor of many similar missions that must survey the mineral resources of near Earth space before any attempt is made to visit or exploit the asteroids, and therefore this report makes no further mention of missions to the smaller bodies of the inner Solar System.

To quote from a previous IAA study: "The rationale for an international context for a Mars Exploration Program is based on philosophical, technological, financial, scientific, and educational factors. All nations stand to gain from participation in the development of new technologies. One of the chief benefits of its existence would be the effect on world stability. Historically, programs which involve major international commitments have proved more resistant to adverse political pressures within the undertaking nations.

A Mars program may be the most ambitious single peacetime technical project ever undertaken by humanity. Quite apart from the technical challenges that must be solved, a Mars Exploration Program with many nations as participants, must nonetheless be managed as an integrated whole and in conjunction with the lunar development and other space programs. Such an pioneering enterprise will unite the nations of this planet." (15)

The management structure of any possible 21 st century space programme will have to be modelled and tested before the programme is approved. There are a number of models that could be candidates for setting up the required management structure. These are to be scrutinized for the best possible approach at the right time to optimize the benefits and reduce the cost. Only then will the responsible organization be able to adopt a regime that been shown to be capable of governing a programme that is both economical and has the greatest potential returns.

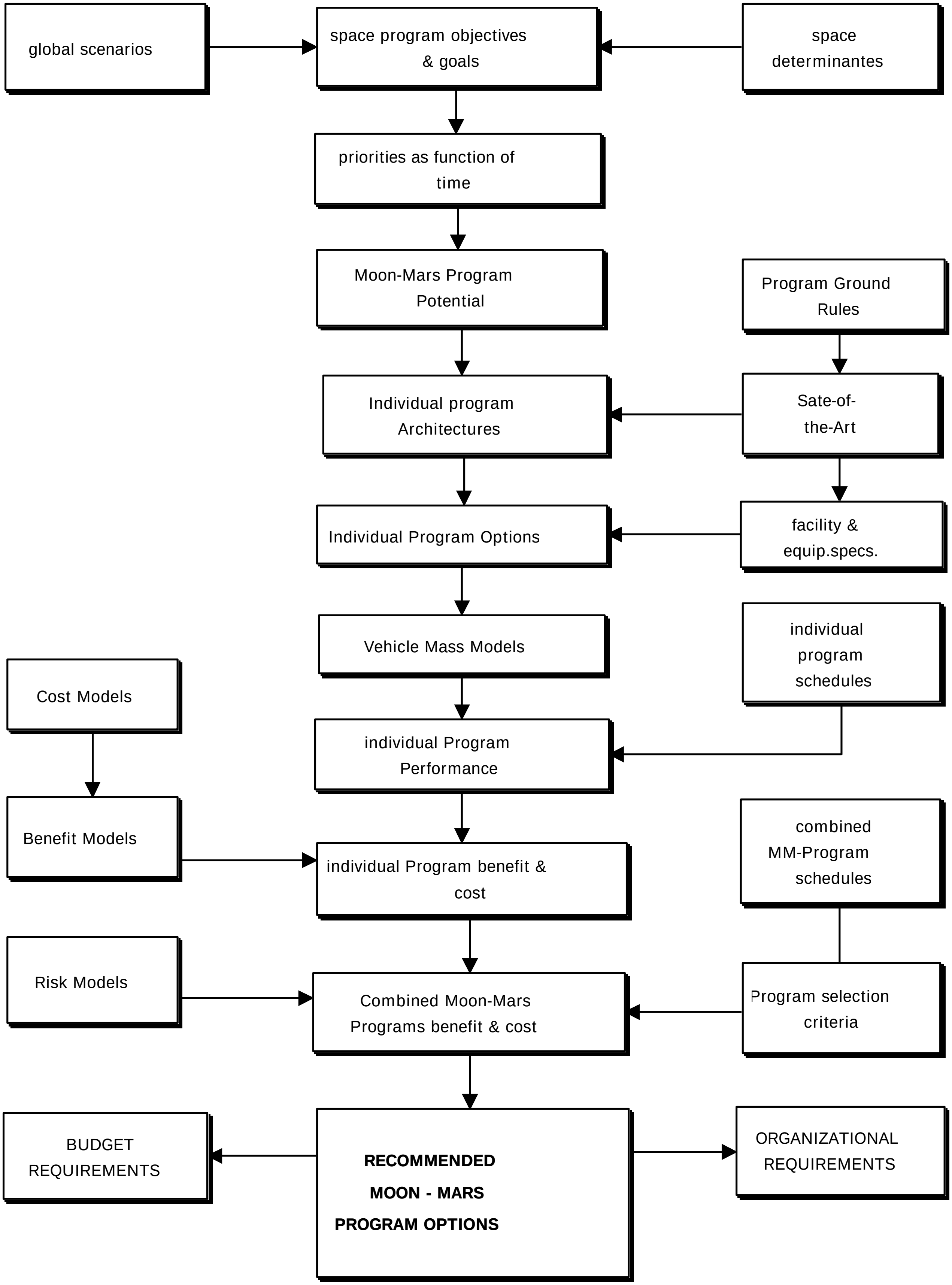
1.4 Study Approach

This report is intended to advise the executives responsible for a programme of twenty first century extraterrestrial exploration, and it is hoped that this compilation of the most advantageous strategies will be the precursor of a formal international planning effort, approved and supported by the spacefaring nations. The first part of this study extrapolates the current trends in space research and the development of space technology into a suite of probable global scenarios. These, in turn, are used to illuminate the goals that are likely to concern the executives of the next century, before presenting realistic models of the most attractive alternative programmes.

The simulations modelled the influences that may govern future political decisions leading to a major space programme, and, depending on the chosen goal, estimated the relative importance of the available technologies, the costs and possible rewards. The models also reflected much wider concerns, for any major international space programme will have to compete for limited resources with terrestrial activities. It is hoped that this document will be the basis of a thorough evaluation of the risks, costs and returns associated with a programme of Lunar and Martian exploration and development.

It should be emphasised that this is a preliminary study. It addresses the timing, course, manner and ultimate aims of the next major step in space exploration, and a flow chart (figure 1-1) presents the logical structure of the report in diagrammatic form. The overall effort was sub-divided into the work packages, here represented as boxes. The programme objectives were modelled first, for they will ultimately determine the success of the whole programme. Dynamic scenarios of the global economy and the political climate were then combined with the projected state of the world aerospace industry to create a simulated, but realistic context, for the proposed programme.

LOGIC OF MOON_MARS PROGRAM MODEL



2. The Rationale:

2.1 Basic Rationale

Noting

- the expansive evolution of life on this planet, and especially the recent evolution of our species; the result has been that
- the confines of this planet now must contain a rapidly growing human population, and that
- the members of that population harbour a natural desire for a higher quality of life. However,
- the expanding world economy will demand ever greater supplies of high quality industrial energy, that will lead to shortages during the next century; but at the same time
- advances in technology generate new economic opportunities; for
- as populations become richer they demand new and better products and services. In particular
- humans have a thirst for knowledge and adventure; so
- the highly educated global work force of the future will demand stimulating, rewarding careers, in spite of the
- challenges inherent in our global civilization's uncertain future,

and therefore:

Acknowledging

the debt we owe to our predecessors and

Recognizing

that we hold the well being of future generations in trust:

We Believe

that, seen by the light of experience, if the world is to surmount the challenges of the coming millennium, the time has come for responsible governments to seize the initiative and unequivocally support a broader international effort to explore and develop extraterrestrial resources. Consequently a new or an existing multi-national organization dedicated to space research and development should be given the responsibility, and allocated the resources needed, to plan for the permanent return of human beings to the Moon, there to exploit aggressively its resources for the benefit of humankind, while at the same time preparing for a continuing, aggressive programme to survey the planet Mars using both human explorers and remote systems.

2. 2 Social Forces

2.2.1 General trends

The space sector has become a significant and rapidly expanding component of the global social and fiscal economy. Artificial satellites monitor the condition of the Earth's ecosphere, observe the weather and track hurricanes. From orbit we measure changes in the Earth's crust and guide the geologist's search for new mineral resources, while transportation systems call upon the Global Positioning System(GPS) to direct the prompt and efficient delivery of freight and passengers. Communication satellites have spawned a multi-billion dollar a year industry, whose services are so all pervasive that the general public only becomes aware of their importance when a satellite occasionally fails unexpectedly. The space sector is the most flexible component of the communications network that has enriched and saved lives, carried our thoughts to every corner of this planet and will soon link even the remotest village into a seamless global web of information.

The application of space technology has enriched life on Earth in twentieth century and it will surely continue to do so in the 21st. Indeed, space technology enhances our civilization's chances of survival through the coming millennium and beyond. Any serious attempt to plan for a major space enterprise will first have construct a realistic frame of reference that recognises the factors that will ultimately determine the expansion rate of the global economy's space sector. The following representative model has expressed the goals of the space programme in a statistical form that can be balanced against the required financial and human investment.

2.2.2 Selected single trends

The next two tables are a reminder that history is in flux, and the future is uncertain, and the development of space technology will be moulded by chaotic global trends. Even so, if a plan is to be of value, current trends will have to be observed and extrapolated. Like a meteorologist forecasting the weather, a strategic planner reviews the best available, current information before making a series of structured value judgements to arrive at a range of likely future conditions. The two tables are not intended to be an absolute guide, rather, they should provide a convenient initial frame of reference for planners addressing a future Moon- Mars programme. These scenarios demonstrate that perceived influences are a factor in shaping opinions and valuations. These are important judgements, but not formal steps in a decision process of the nature under discussion.

Twenty people with backgrounds in space science, engineering and management participated in group judgements during 1997 and 1998 that identified and ranked the likelihood (in terms of percent probability) of the following significant global social and political trends to be expected during the coming century. The limited number of participants in these group judgements do not qualify them as representative, but may be used for further refinements.

Table 2-1 A Global Development Scenario

global developments during the 21st century	**%**	**rk**
privacy of individuals deteriorates	94	1.
the United States of America seeks to maintain lead in high-tech systems	88	2.
Global industrial enterprises grow in size and influence	87	3.
unemployment becomes a major problem requiring considerable public resources	83	4.
peace is maintained among the industrial nations	80	5.
developing nations continue to make progress but remain a problem of global concern	79	6.
international trade barriers are further reduced	78	7.
sporadic conflicts occur within and among developing nations during the first half of the 21st century	75	8.
effective international controls are established against threats of ballistic missiles and nuclear explosives	72	9.

Earth population increase reaches its peak by the middle of next century and strains use of Earth resources	71	10.
Japan and China compete to become the regional Asien leader straining their relationships	70	11.
"super strains" of bacteria develop	69	12.
in industrial nations age life expectancy reaches 100 years	65	13.
further deterioation of the Earth biosphere continues	64	14.
all people in all countries have access to modern communication systems	63	15.
productivity in the industrial nations continues at a slower pace and leads to a reduction of weekly workhours	62	16.
Terrorism becomes more sophisticated and an increasing burden to the public	60	17.
Europe develops as a regional leader with Russia becomming a member of the European Union	59	18.
conflicts in GUS states destabilize international relations	57	19.
expenditures for military activities continue to decline and become a smaller burden on public budgets	55	20.
decreasing natural resources lead to regional conflicts	54	21.
space based systems begin to deliver solar energy to users on the Earth	45	22.
many defaults on international debts substantially increase unemployment and destabilize the global economy	44	23.

In a second effort, eighteen people with backgrounds in space science, engineering and management participated in group judgements during 1997 and 1998 that also identified and ranked the importance of expected developments in the aerospace sector during the coming century.

Table 2-2: Significant influences on the space programme
(ranked by importance)

space developments expected during the 21st century	**%**	**new rk**
Global high data rate space communication systems are in place	89	1.
the U.S.A.remains the leading spacefaring nation and plays the key role in an integrated international Moon-Mars program	81	2.
commercial space programs in near Earth space exceed public supported space projects	76	3.
developments in nano-technology revolutionize materials, structures, robotics & space transportation systems	75	4.
a small fully reusable orbital transport to serve low orbit operations becomes operational early in the 21st century	74	5.
Aerospace industries continue to merge	73	6.
a heavy lift launch vehicle becomes available during the first quarter of the 21st century for the logistic support of lunar and planetary human operations	72	7.
space tourism to space facilities in near Earth orbit will gradually develop to become a major market towards the middle of the 21st century	71	8.
non-chemical space propulsion systems become competitive in the second half of the 21st century	66	9.
international commercial consortia are formed for lunar base development including mining operations	64	10.
space based solar power systems in the Megawatt range become available for extraterrestrial use	63	11.
global space defense systems on Earth and on the Moon will be developed against extraterrestrial threats by asteroids and comets	62	12.
space qualified nuclear reactors become available for use as power plants on other celestial bodies	60	13.
evidence of extraterrestrial life is confirmed	58	14.

commercially operated space station in low Earth orbit will exceed the public supported International Space Station in the third decade of the 21st century	56	15.
artificial biological organs revolutionize space medicine	55	16.
performance and revenues of commercial space transportation enterprises exceed the performance of public supported space transportation systems	54	17.
Space becomes the military high ground	52	18.
Mars exploration continues with a human crew stationed permanently on the Mars surface	51	19.
Successful single piloted Mars mission leads to a discontinuation of piloted Mars program	42	20.

2.3 Market Forces

The space sector is a vital and rapidly growing component of the terrestrial economy. Today's satellites are built on Earth and from space return their services to the Earth. It seems likely that, during the next century, the space sector will create its own, self sustaining, market structure. The resources of space will be developed both to service and support existing satellites and to make extraterrestrial bases and large scale facilities possible and increasingly self-sufficient. Since both the customers and producers of this new market will be located outside the Earth, this market will develop when the on orbit price of extraterrestrial products falls below that of their competitors shipped from Earth. In particular, if consumables can be manufactured at a lower cost in space, that cost reduction will be reflected in lower operating costs for all space activities, and especially that of an extraterrestrial base.

Extraterrestrially produced products and services will have to compete successfully with Earth supplied products and services in both terrestrial and off Earth markets. A national or global security asset would not return a commercial profit, but its cost would have to be judged to be in proportion with its function. Space enterprises will have to have long term commercial yields commensurate with the risks and investments involved and adequate economic models of an extraterrestrial base will have to convince potential investors that the risks and returns would be acceptable.

The space economy will depend on its transportation infrastructure, and while in the long run, the space based economy will have to be commercially self sustaining, history shows that direct or indirect public funding almost always supports the development of any new transportation infrastructure. Therefore, it is assumed that the initial lunar base will be a joint corporate and government sector project. A Martian laboratory has limited foreseeable commercial potential and so will have to rely almost entirely on public funding

Recent studies have helped define both the needs and products of an extrater-restrial laboratory or outpost, and the following outlines the products and services that can be expected to flowfrom a lunar base of the next century.

Table 2-3: Relations of lunar base outputs and its potential users

products : buyers:	new knowledge	services	material goods and energy
lunar enterprises	new information relevant to lunar operations	maintenance and repair, social needs of lunar crew	construction material, propellants, consumables, el.& therm.energy
in-space enterprises	research results relevant to space operations	communication, maintenance and repair, recreation	propellants, construction material, energy, consumables,

Earth enterprises	research results relevant to life on Earth	environmental observation, entertainment, adventure	souvenirs, HELIUM-3, electrical energy

Clearly the space economy will develop many market sectors, each of which will expand at its own rate. The specific sectorial growth rates deserve special consideration for they act as controlling variables in any economic model of an extraterrestrial base and in turn determine the overall growth rate, the size, and define the performance criteria of a system of extraterrestrial bases at any time during its lifespan.

2.4 Programme Objectives

2.4.1 Improving the Quality of Life

"Man does not live by bread alone" and human beings are motivated by far more than a basal lust for money and material goods. The value of any human endeavour, and an extended space programme in particular, will not be judged solely by its fiscal accounts. A higher quality of life is easy to recognize and very difficult to quantify, but nonetheless the way people appreciate the quality of life has been studied extensively over the past three decades.

Not only theories have been developed, also quantitative models have been constructed to permit respective studies of the state of affairs at specific times and locations. One such model has been developed and tested in Germany(24,25). During the nineteen seventies nearly 500 people living in Europe contributed to a six year effort to develop a common, iterative model of what they judged important in their lives. The following table is derived from this model. The numbers show the relative importance in terms of a total of 1000 points of the various factors listed for the years 1950, 2000, 2050.

Table 2-4: A model of the Quality of Life

	Elements of the Quality of Life (QUOL)	1950	2000	2050
A	Improvement of the material QUOL	285	229	214
B	Improvement of the physical QUOL	230	263	272
C	Improvement of the mental QUOL	247	262	258
D	Improvement of the spiritual QUOL	238	246	256
	total	1000	1000	1000
A-1	Improvement of living conditions at home and surroundings	76	53	45
A-2	Improvement of the general market conditions & supply system	85	50	46
A-3	Better care and utilization of material things	56	51	50
A-4	Better utilization and extension of global resources	68	75	73
B-1	Improvement of the physical performance of the human species	52	51	50
B-2	Improvement of the natural environment	52	87	97
B-3	Maintaining the general state of health	61	72	69
B-4	Restoration of health in case of sickness	66	53	55
C-1	Improvement of the educational system	59	58	56

C-2	Better utilization of available knowledge	70	82	80
C-3	Extension of the knowledge base	65	70	72
C-4	Improvement of the cultural environment	52	52	50
D-1	Better utilization of the individual potential	55	60	63
D-2	Improved harmony in the family	54	53	53
D-3	Increased contributions to social groups	68	68	69
D-4	Improvement of ethics and morale	61	65	72
	total	1000	1000	1000

Crude though it is, this model is probably a valid reflection of the industrialized world's majority view of 'the quality of life'. The model assumes that an ideal state of affairs is unattainable, and people will always struggle to overcome life's
perceived deficiencies. Therefore, individuals and societies are continously engaged in improving the quality of their, or their children's, lives.
Ironically, experience often demonstrates that real satisfaction lies more in an honest effort than in winning for the sake of winning. In reality, a society's historical value systems change continually in response to changing material and political conditions, as will the relative priority of any given goal.

In 1993 a group of 30 graduate students living in Germany were asked to set priorities for the 20th and 21st centuries (25). The results may not reflect the attitudes of people living elsewhere. They may act, however, as an working reference and as a basis for further analysis. In the mean time, the model is sufficient to illustrate the forces driving investment levels in the space sector. Hopefully, future models will be based on more extensive group judgements. In this application, the model's 16 primary objectives were subdivided into 92 secondary objectives, which were then used to estimate the proportional contribution to improving the global quality of life of a hundred years hence by particular space sector activities. Then this group of 20 aerospace students subjected each secondary objective to the question: "Is it possible to effect this partial objective by the sum total of space projects conceivable, and if yes, how much in terms of percent of the total effort required?"

The resulting group judgement showed that, in 1993, space projects were expected by 2000 to contribute approximately 0.8% to an improved quality of life, 1.6% in 2050 and 2.4% in 2100. This is an encouraging result, considering the fact that the space faring nations currently invest only between 0.1% and 0.5% of their Gross Domestic Products in space activities!

Any quality-of-life model includes a fairly large number of parameters that might reflect how a person perceives their own quality of life, and the space sector holds little relevance for many of them. The model addressing all aspects of life is therefore a very coarse tool to use for planning an extended space programme. A refined space related model needs to be developed as a derivative of a Quality-of-Life model. This exclusive model will not include factors to which the space programme has no relevance, and by isolating and magnifying space relevant influences that change the all inclusive model by only a few percent, the new model will become a effective mission planning tool(26).

2.4.2 Extraterrestrial Programmes: General objectives

The overall aims of any generalized undertaking can be broken down into a series of specific objectives. Twenty first century extraterrestrial operations will be analyzed into a series of specific tasks whose results should justify the establishment of bases on the Moon and Mars. A logistical infrastructure will support these bases. There will be space operation centers in various orbits about the Earth and the bases on the surface of other celestial bodies will include their own laboratories and production facilities. - Commercial near Earth space activities are expanding rapidly, but so far there has been neither a definitive argument for the establishment of bases on the Moon or Mars, nor a

demonstration to show how such bases could improve the quality of life on Earth or contribute to our species' survival.
A refined model is needed to show that the overall aims of the space programme will be fulfilled by the services and products offered by an extraterrestrial base. The following table ranks, approximately in descending importance, the objectives of a Lunar or Martian facility.

Table 2-5 Objectives of an Extraterrestrial Base

Primary Objectives:

1. To support a science laboratory in the unique environments of other celeatial bodies or in deep space.
2. To expand our knowledge of the Moon and Mars.
3. To market space derived products and services.
4. To found the first extraterrestrial human settlement.
5. To supply the Earth with space generated energy and fuels.
6. To be a focus for the development of space technology.
7. To support reliable, low cost space transportation.
8. To be an isolated, observable, but accessible depository of long lived, high level, hazardous, wastes.
9. To demonstrate that economic and social growth is possible outside the Earth.
10. To stimulate the evolution of human culture
11. To preserve the best of human culture in the event of a global catastrophe.

Secondary Objectives in concert with terrestrial activities:

1. To advance our understanding of the Earth's biosphere and hence improve our management of this planet's ecosystem.
2. To stimulate the development of advanced technologies.
3. To be an opportunity for international co-operation.
4. To provide satisfying careers for highly educated personnel.
5. To stimulate the education system.
6. To sublimate social and political tensions on Earth.
7. To expand the global economic infrastructure.
8. To be the challenging frontier of human effort.
9. To be a non-military alternative customer for the products of the military-industrial complex.
10. To enhance the prestige of the participating nations.
11. To improve our understanding of the solar system.
12. To improve our understanding of the universe.

The exploration of Mars would offer the same benefits as the development of the Moon, however, the risks would be greater, while some of the benefits less. Mars is more remote and vastly more complex than the Moon, and currently we know considerably less about it, and the Red Planet certainly has a lot of surprises in store which makes this planet very facinating.

It is important to remember that all extraterrestrial activities will, to some extent, achieve many, if not all, the objectives listed above. Naturally, as time passes their relative values will change, as will the political and economic climate on Earth. Different programme strategies will result in a wide range of benefit to cost ratios and each strategy will have to be periodically re-examined in the light of the overall goals of an extended space programme.

2.4.3 Goals for the end of the 21st century

Executive authority must set the goals that define success or failure. A major programme must begin by clearly stating the goals that will be its ultimate validation, and even if they are not immediately attainable, these goals must be endorsed by every major programme participant. NASA's goals and objectives were published as part of its long range strategy. They, however, do not fully apply to a possible integrated Moon-Mars programme, and since a more appropriate set of goals was not available, a preliminary working model of a Moon-Mars programme was developed(26,27,28,29). The following sections illustrate the type of analysis needed to select the best strategy from a large number of alternatives. Planning for an extended space programme will demand refined and detailed models that rank the programme's overall goals and objectives, and the overall value of a particular, individual Lunar, Martian and joint Moon-Mars programme will be judged against how well it achieved those goals.

Table 2-6 Objectives and Goals for the end of the 21st century

	Objective	**Goals for 2100**
A	**HUMANISTIC OBJECTIVES**	
a.1	enhance the protection of the Earth biosphere and the human species from extraterrestrial threats, in particular astroids, thus assisting in the preservation of our present habitat	activation of large scale high resolution asteroid and comet detection systems at the poles and a first astroid protection system on the farside of the Moon and / or in Earth orbit
a.2	enhance the evolution of the human culture in space by expanding human activities in our solar system and learn to live and work in isolated, extreme environments	permanent extraterrestrial population of 5,000
a.3	enhance the educational system and the motivation to learn	25% of the Earth population have access to higher education
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 more than 10,000
a.5	use space based systems to discourage use of nuclear ICBM's, to reduce tensions and conflicts, thus contributing to peace on Earth and thus enhancing social development	military & civilian extraterrestrial programs reach 0.1% global GNP
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	5 million people employed in the space program 0.1 million people take part in space tourism per annum
B	**POLITICAL OBJECTIVES**	
b.1	demonstrate the potential growth existing beyond the limits on Earth	10,000 mt of extraterrestrial products p.a. available ; the survey of lunar resources is 90 percent complete, 10,000 km traverses completed on Mars by human crews
b.2	provide more opportunities for international cooperation among nations	extraterrestrial programs to reach 0.1% global GNP
b.3	extend the infrastructure and experience for global commercial enterprises	extraterrestrial programs to reach 0.1% global GNP
b.4	provide a peaceful outlet for national, competitive high technology urges and a useful employment of the industrial-military complex	5 million people employed in the space program, extraterrestrial population of 5,000

b.5	enhance the self-esteem and prestige of participating nations	over 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 90 percent complete
c.3	improve our understanding of Planet Mars and other celestial bodies of the solar system beyond the Earth-Moon double planet	10,000 km traverses completed on Mars surface by human crews
c.4	improve our understanding of the universe beyond our own Solar System	large scale astrophysical research facilities operational on the lunar farside
c.5	provide a science laboratory in a unique environment for experiments and development activities in physics, chemistry, biology, geology, technology, physiology and sociology which can not be conducted on Earth	1,000 laboratory spaces 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	5 million people employed in the space program
d.2	stimulate the development of advanced technology on Earth	5 million people employed in the space program
d.3	produce in space marketable products for extraterrestrial use and for terrestrial consumption	10,000 mt p.a.of ertraterr.products available, sales of commercial extraterrestrial products reach 0.01 % 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 Earth	1,000 tonnes of high level waste exported into space
d.6	provide safe and 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 200 $/kg and 0.05 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 space transportation have annual sales of 0.05 %of the global GNP

2.5 Program Benefits

2.5.1 General approach

The value of a specific application of space technology is estimated by comparing the individual contribution of each component of a particular space programme to a set of previously defined, and relevant, objectives. Such an analysis must include contributions not only from the programme under evaluation, but also from other space activities and non-space based enterprises. In practice complex decisions are resolved intuitively, but the successful executive always first seeks the expert advise of experienced professionals who have insight into the underlying issues.

Shifting political priorities will constantly re-order the relative importance of any set of previously defined objectives. During a formal analysis each objective is assigned a numerical weight that reflects its current relative priority. The validity of an assigned set of weights is limited, and then only as a guide to a broader range of future expectations. Political prognostications are notoriously unreliable, nevertheless future social and political dynamics must be considered before developing a long range plan.

2.5.2 Relative potential returns from the Moon and Mars Programme

The case study begins by assuming that there are no funding limits and that the programmes of Lunar and Martian exploration are completely separate. Each programme's maximum possible contribution to the achievement of a series of predetermined objectives was then estimated. The lunar and Martian programmes would only help to achieve some of those objectives, and to those, it was found that space based and non-space activities contributed approximately equally.

Averaging the percentage contributions to the achievement of the space related objectives listed in table 2-7, showed the Lunar and Martian programmes could contribute up to 24 percent and 14 percent respectively to their attainment. When added, the contributions of Lunar and Martian base programmes could, by the year 2100, have contributed up to 38% to the achievement of those objectives, while a further additional 18% is contributed by Earth orbiting facilities and deep space probes, and the remainder of 44% by the non-space activities listed in table 2-10 further below. The actual results of any eventual Lunar and/or Martian programmes, will, of course, depend on their size and structure, and the value of individual programme elements that is assessed later.

The results of a separate study (26) to estimate varying political and economic priorities were used to determine the potential contributions of separate Lunar and Martian programmes to the improvement of the world's perceived quality of life. The respective shares (cumulative returns) of the selected programmes by the year 2100 were estimated with reference to the priorities assigned to the attainment of previously selected objectives.

Table 2-7 Global space related objectives for the year 2100:
Estimated contributions of separate Lunar and Martian programmes.

	Objective in year :	**Moon 2100**	**Mars 2100**
A	**HUMANISTIC OBJECTIVES**	**443**	**323**
a.1	enhance the evolution of the human culture (in space)	90	70
a.2	establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system and learn to live in isolated, extreme environments	155	84
a.3	enhance the educational system and motivation to learn	24	28
a.4	provide a survival shelter for artifacts,documents and some elements of the human race in case of a global catastrophe	93	58

a.5	assist in reducing tensions and conflicts, thus contributing to peace on Earth	22	24
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	59	59
B	**POLITICAL OBJECTIVES**	**343**	**262**
b.1	demonstrate the potential growth existing beyond the limits on Earth	140	77
b.2	provide more opportunities for international cooperation	43	47
b.3	extend the infrastructure and experience for global enterprises	43	20
b.4	provide a peaceful outlet for national, competitive high technology urges & a useful employment of existing industrial-military capabilities	58	47
b.5	enhance the national pride and prestige of participating nations	59	71
C	**SCIENTIFIC OBJECTIVES**	**604**	**445**
c.1	improve the understanding and control of our own planet	80	57
c.2	improve our knowledge of the Moon and its resources	150	113
c.3	improve our understanding of the solar system beyond the Earth-Moon double planet	63	95
c.4	improve our understanding of the universe beyond our own Solar System	110	67
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	201	113
D	**UTILITARIAN OBJECTIVES**	**1001**	**362**
d.1	provide rewarding job opportunities and thus stimulate the economy on Earth in general	30	23
d.2	stimulate the development of advanced technology on Earth	62	40
d.3	produce marketable products for extraterrestrial and for terrestrial use	202	55
d.4	contribute to the supply of space based energy to the Earth	254	6
d.5	provide an isolated extraterrestrial depository to store high level wastes	134	2
d.6	enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources	184	129
d.7	provide thrust and focus for continued development of space technology other than in the area of space transportation systems	135	107
	total potential (percent x 100)	**2391**	**1392**

The previous two tables may now be used to rank the objectives to which the Lunar or Martian space programmes would be best able to contribute. The resulting rankings, in terms of 1000 points, can then, in turn, identify the most promising programme options and indicate how to maximize their returns.

Table 2-8: Objectives, by rank, primarily benefiting from lunar activities during the 21st century (those greater than 100 points by 2100)

1. Contribute to the supply of space based energy to the Earth(254)
2. Produce marketable extraterrestrial products for extraterrestrial and terrestrial use (202)
3. 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(201)
4. Enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources (184)
5. Establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system and learn to live in isolated, extreme environments(155)
6. Improve our knowledge of the Moon and its resources (150)
7. Demonstrate the potential growth existing beyond the limits on Earth (140)
8. Provide thrust and focus for continued development of space technology other than in the area of space transportation systems (135)

9. Provide an isolated extraterrestrial depository to store high level wastes(134)
10. Improve our understanding of the universe beyond our own solar system(110)

Table 2-9: Objectives, by rank, primarily benefiting from Martian activities during the 21st century (greater than 60 points by 2100)

1. Enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources (129)
2. Provide thrust and focus for continued development of space technology other than in the area of space transportation systems(107)
3. 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(113)
4. Improve our knowledge of the Moon and its resources(113)
5. Improve our understanding of the solar system beyond the Earth-Moon double planet(95)
6. Establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system and learn to live in isolated, extreme environments(84)
7. Demonstrate the potential growth existing beyond the limits on Earth(77)
8. Enhance the national pride and prestige of participating nations(71)
9. Enhance the evolution of the human culture beyond Earth(70)
10. Improve our understanding of the universe beyond our own solar system(67)

Only a substantial socio-economic analysis would identify the most productive programme strategies. Although the above results naturally reflect the biases of the people making the initial assessments, nonetheless they indicate where and when substantial benefits could flow from extensive programmes of Lunar and Martian exploration and development, and hence they provide a strong justification for those programmes.

2.5.3 Overview of 21 st Century Programme Potential.

These results of a preliminary benefit analysis can now be summarized for all contributors and the selected points in time, taking into consideration also the Earth orbit programs and robotic interplanetary probes. The aggregate weights are presented in terms of relative relevance (the product of the objective weight with the sub-programme contribution to that the objective) as a percentage. (26,28) Objectives which are not directly influenced by space activities have not been included in this summary.

Table 2-10: Estimated potential contributions of the partial programs to the weighted space objectives as functions of expected changing priorities with time

Programs	**year 2000**	**year 2050**	**year 2100**
Earth orbit facilities	13.5	14.2	14.8
Lunar programs	21.6	23.4	**23.9**
Mars programs	14.8	14.5	**13.9**
Robotic spacecraft	4.1	3.9	3.6
TOTAL SPACE PROGRAMS	54.0	56.0	56.2
NON-SPACE PROGRAMS	46.0	44.0	43.8

totals	100%	100%	100%

The tables presented above will be used in this analysis as *yardsticks for measuring the potential benefits of defined individual and integrated Moon-Mars Program options* within the bounds of these potentials.

It is obvious that actual hardware programs, adequately financed, are required to realize the identified potentials. Without the realization of carefully designed programs there will be no benefits!

3. Strategic Restraints

3.1 Point of departure

The question still to be answered by future studies and programme analysis is *when and how* the next phase of human attended exploration of the Moon and Mars should be initiated and by *whom* ! Then and only then, the time comes to set up a competent organization based on the most recent experience in this field. To develop realistic models, one has to start out with a realistic assessment of the current planning environment in the real world.

The following statements attempt so describe the current situation which should be observed in planning human Moon / Mars programs.

- The point of departure is the recommendation of the National Space Commission of 1986 to return to the Moon to stay and going on to Mars, which was endorsed by President Bush in July 1989. The US Congress did not go along with this Space Exploration Initiative by President Bush, primarily because the end of the cold war changed drasticaly the geopolitical situation, but also because of the huge debt of the United States at that time.
- A valid frame of reference for all future planning activities in the human exploration of space has been defined in two official documents prepared at the national level:
  PIONEERING THE SPACE FRONTIER(1986) and
  AMERICA AT THE THRESHOLD(1991).
  The assessment of 1991 is considered to be a realistic point of departure for developing updated alternative program options in the years to come(9).

In doing so it is clear that:

- There won't be any return to the Moon and / or human exploration of Mars unless the United States decides to lead an international effort with this goal in mind. It is, however, unlikely that the United States will undertake such an ambitious endeavour on its own. Therefore it can succeed only if such a project is supported by other space faring nations. As a consequence the various national space agencies must endorse and support a bold and mind capturing long-range programme.
- The United States will not enter a new major effort in the human exploration of space beyond Earth orbit, unless there is a President proposing it, a Congress approving it and the taxpayer in the mood paying for it. This is unlikely to happen without a strong advocacy group in the USA lobbying the President, the Congress and the people.
- At the turn of the year 1998 the assembly operation of an international space station is in progress under the management of NASA. On the basis of the selected concept this operation will take about five years. It will be complex, difficult and risky. If this operation does not lead to the desired results with the resources available, then there won't be any human Moon / Mars project for decades to come, short of an emergency!
- If the assembly operation of the ISS will be successful, and if this facility promises or proves to be useful and cost-effective, which is still an uncertain propositon, the question will be asked "what is next"? - By then, a sound technology basis and a broad choice of viable program options must be available to be presented to the decision-makers, these are in the first place the US President and the relevant Congressional Committees. The mood of the general public must be supportive at this time, possibly enhanced by spectacular cosmic events or results of robotic space missions.
- Thus the efforts of the space program planners must be focussed on the situation expected after the election of the next President of the United States and the US Congress. The results of these planning efforts must be available in the 2000 to 2005 period, the earliest time a new debate of a human Moon / Mars program initiative can be expected.
- Observing the present trend towards more international cooperation, it will also be helpful to have, at that time, positive political and economical developments in Europe, Japan, Russia and China, who may be potential participants in such a program.
- Short of an planetary wide emergency, expected benefits and cost of a Moon / Mars Program will play a decisive role for or against a decision. Consequently, all options must be analysed to a

detail resulting in comparable and credible performance, risk, benefit and cost estimates. The quality of these estimates must be such, that they can be reviewed and veryfied by independent external specialists in a resonable period of time.

The present and near future extraterrestrial exploration phase is characterized by automatic probes. The next phase of Moon-Mars exploration and development is expected also to involve people in-situ. On the basis of the presently available insights the following *strategies and policies* are proposed as guidelines for the continued Moon-Mars exploration:

3.2 Strategies

S.1: All missions will be carried out in a cost effective manner with the ultimate goal of enhancing the quality of human life, while ensuring its enduring survival.

S.2: Living conditions on the Moon and Mars will, within the limits of practicality, resemble those on Earth, so that crew rotation cycles can be long, and hence personnel transportation costs minimised.

S.3: Low risk, proven technologies will be used when and where ever possible. Existing systems, those derived directly from existing systems and those using common sub-systems will be preferred. Frequent changes in technology must be avoided since they often lead to a waste of resources with only marginal gains in performance. All aspects of the programme will be managed with a view to having an extended, cost effective lifespan.

S.4: The assembly, maintenance and repair of the Lunar base and Martian facilities must not make heavy demands on the time of the crew. The cost of supporting a crew member will be high, and as far as possible the crew should be engaged in activities that are directly productive. During its initial stages, at least, the base should be assembled from large, prefabricated, fully equipped modules by robot assemblers when ever possible. On the Moon, but hardly on Mars, teleoperated systems controlled from the Earth could be used.

S.5: Crew safety, flexibility, and the long term cost will be the primary factors governing the logistics of any extraterrestrial operation. Marginal technologies and temporary systems must be avoided, and priority must be given to establishing a commercially viable, general purpose, space transportation system.

S.6: From the outset the Moon-Mars programme will encourage the development of associated commercial activities and the marketing of viable products and services.

3. 3 Policies

P.1: The support and management of the current generation of automatic space probes, together with all other current and planned activities related to an extended Lunar and Martian programme would remain the responsibility of existing national and international space agencies, and proven avenues of co- operation would remain unchanged. A limited multi-national effort to develop viable plans for lunar development and Martian exploration would expand as contemporary research results and available resources permit.

P.2: Current projections suggest the enabling stage of an integrated Moon-Mars space programme could be authorised following a period of detailed planning during the years 2004/05, and development of the key technologies would start in 2005/06.

P.3: The time line of a lunar or Martian programme will include milestones when progress is reviewed and resources can be reallocated accordingly. Long term commitments extending over several decades should be avoided.

P.4: The Moon-Mars programme must have a smooth financial requirement. Changes in programme funding must be gradual and as far as possible reflect changes in the global economy.

P.5: A Programme Office will direct the joint enterprise. Its management philosophy will reflect neither the crash programme 'cost no object' attitudes of the APOLLO programme, nor the current, hierarchical, business as usual, 'cost plus' military contracting culture of the Cold War business school graduate. At all times authority will be closely bound to responsibility, and frequently reviewed in the light of experience. The result should be a tight, compact, executive structure with a minimum of frills, that will direct the development of prototypes on time and in budget. Any needed new technologies will be developed by single purpose, high risk, low cost, 'X craft' test missions.

P.6: National efforts will be coordinated by the Programme Office that will be financed by the participating nations whose contributions will reflect the size of their Gross Domestic Products. Every effort should be made to broaden the base of support to as wide a constituency as possible. Currently non - spacefaring countries will be invited to contribute, and sponsorship in money and in kind will be sort from private corporations and interested individuals. The participants will have the right to influence the conduct of the programme in proportion to their contribution.

P.7: The resources to support the enabling phase of the integrated programme will be contributed annually from the national research and development budgets of the space faring nations. During the planning stage each nation will agree to take financial and technical responsibility for specific tasks.

Clearly, before the various individual or integrated Moon-Mars missions can be compared their architectures will have to be defined and their detailed performance analyzed. The individual Lunar and Martian programmes could select from a wide choice of technical and structural components and each component could also become part of an integrated programme of Lunar and Martian Exploration and Development. Consequently, possible separate programmes of exclusively Lunar or Martian exploration will now be considered before a possible joint programme.

4. Lunar Base Program Structures

4.1 Background of Lunar Exploration and Development

The forty year history of space based Lunar exploration that began in 1959 with the launch of the first space probe to pass the Moon now includes the following outstanding events:

Table 4-1: Milestones of lunar exploration

02.01.1959 LUNA 1, UdSSR, becomes the first spacecraft to achieve escape velocity and passes the Moon at a distance of 5600 km
12.09.1959 LUNA 2, UdSSR, first probe reaching the Moon, hard impact
04.10.1959 LUNA 3 returns the first pictures from the lunar far-side
25.05.1961 President Kennedy announces the the APOLLO Programme to land a man on the Moon
17.02.1965 RANGER 8, USA, takes 7000 pictures before hard impact on the lunar surface
31.01.1966 LUNA 9, UdSSR, **first soft landing** on the Moon and returns pictures from the surface
31.03.1966 LUNA 10 , UdSSR, becomes the **first lunar satellite**
02.07.1966 SURVEYOR 1, USA, first soft landing by an American probe, returns 11,150 pictures
10.08.1966 LUNAR ORBITER 1, USA, enters lunar orbit and returns 212 pictures
01.08.1967 LUNAR ORBITER 5, the last US orbiter enters lunar orbit
10.01.1968 SURVEYOR 7, USA, soft landing and conductssoil analysis
15.09.1968 ZOND 5, UdSSR, **unmanned lunar space probe returns to Earth**
10.11.1968 ZOND 6, UdSSR, circumnavigates the Moon and returns to Earth
24.12.1968 APOLLO 8, USA, **first manned circumnavigation of the Moon**
20.07.1969 APOLLO 11, USA, **first manned landing** (Mare Transquilitatis)
18.11.1969 APOLLO 12, USA, second manned landing
11.04.1970 APOLLO 13, USA, circles the moon and returns safely after accident
09.09.1970 LUNA 16, UdSSR, robotic lander returns 150 g of lunar soil to Earth
17.11.1970 LUNA17 lands softly **LUNOKHOD 1 rover that operats for several months**
09.02.1971 APOLLO 14, USA, third manned landing (Fra Mauro)
31.07.1971 APOLLO 15, USA, fourth manned landing (Mare Imbrium)
25.02.1972 LUNA 20, UdSSR, returns from the Moon to Earth with soil samle
20.04.1972 APOLLO 16, USA, fifth manned landing (Descartes)
11.12.1972 APOLLO 17, USA, sixth manned landing (Taurus-Littrow)
16.01.1973 LUNA21, UdSSR, lands the lunar rover Lunokhod II
22.08.1976 LUNA 24 ,UdSSR, returns from the Moon to Earth with soil samples
31.10.1984 First Conference on Lunar Bases concluded in Washington D.C.
07.04.1988 Second Conference on Lunar Bases concluded in Houston ,Texas
21.07.1989 President Bush announces the Space Exploration Initiative (SEI) proposing to return to the Moon and stay there, the US Congress declines to provide funds at this time
24.01.1990 MUSES A, Japan, launched successfully into elliptical lunar orbit
19.02.1994 Space probe CLEMENTINE I begins its lunar exploration phase
03.05.1994 CLEMENTINE I ends its lunar orbit exploration mision
03.06.1994 First International Lunar Workshop concluded in Switzerland
06.01.1998 Lunar Prospector is launched from Cape Canaveral and orbits the Moon on January 11. Hydrogen concentrations,probably indicating water ice deposits,are discovered at the poles.

4.2 Lunar products and services

The long term growth of the commercial space sector will justify and promote a steady increase in extraterrestrial activities of all kinds. Initially public funding, however, will probably have to establish a lunar base and sustainfor some time its infrastructure, but, gradually the Moon will become a source of saleable services and products, of which the following are examples that have so far been identified:

Table 4-2: Services a lunar base can provide

- Knowledge derived from science *of* the Moon (selenology)
- Knowledge derived from science *on* the Moon (human studies)
- Knowledge derived from science *from* the Moon (Earth observation, space observation, astrophysics, astronomy)
- Engineering research into materials
- Engineering research into mineral and organic processing
- Technologydevelopment
- Launch services for space transportation systems
- Maintenance, repair and recycling services for space transportation systems
- Waste storage
- Administrative services
- Training services for other space projects
- Virtual education
- Virtual entertainment
- Tourism
- Health services

Table 4-3: Products a lunar base can provide

- Technical gases
- Liquid propellants
- Processed raw materials (water, cements, glass , metals)
- Feedstock (beneficiated minerals)
- Construction material (lunar bricks, glasses, fibers, foamed glass)
- Formed metals (ingots, sheets, plates, wires, cables, girders, pipes)
- Electric materials (solar cells)
- Food
- Pharmaceuticals
- Thermal and Electric power,
- Nuclear fuels (^{3}He)

Clearly the space economy will develop many market sectors, each of which will expand at its own rate. The specific sectorial growth rates deserve special consideration for they act as the significant variables in any economic model of a lunar base, and in turn they determine the overall growth rate, the size, and define the performance criteria of a lunar base system at any time during its lifespan. Lunar science, which includes studies of the Moon and scientific research that can take place on the Moon, has been given a very high priority in the foregoing lists. Ignorance is not bliss. It means poverty, fear, and powerlessness. Knowledge will be the basis of wealth in the coming century, just as land, labour and energy were in the three centuries that preceded it. The exploration of space, and of the Moon in particular, will pay high dividends, and lunar research is an activity that deserves particular attention. Despite the wealth of knowledge already gathered about the Moon, much remains to be discovered.

A lunar base will be expected to carry out a wide spectrum of scientific research. These activities could not all be concurrent and research tasks will have to ranked and planned in detail to make optimum use of the base's facilities. Highly qualified personnel and their equipment will have to be transported to the base, from where they will still be able to call upon advise and support from the

Earth. The overall research programme will have to be flexible and respond effectively to the results of strategic reviews while reacting quickly to unexpected situations.

A list of lunar research priorities drafted today will only illustrate that part of the planning process. Later, fully developed priority lists will form a important component of any systemic model of lunar development. - The Lunar Exploration Science Working Group (LESWG) of NASA summarized in July 1992 (JSC-25920) the current major themes of lunar science as follows:
1. Formation of the Earth-Moon System
2. Thermal and magnetic evolution of the Moon
3. Bombardment history of the Earth-Moon system and nature of impact process
4. Regolith formation and evolution of the Sun
5. Nature of lunar atmosphere
6. Planetary astronomy from the Moon.

A previous effort identified 18 fields of lunar research. These are listed in the following table where they are arranged into overall research groupings:

Table 4-4: Lunar research activities overview

LUNAR RESEARCH FLIELDS / Lunar science:	**of** the Moon	**from** the Moon	**on** the Moon
1. Global geographic, geochemical and geophysical mapping from lunar orbit	X		
2. Geological transverses	X		
3. Search for mineral occurrences	X		
4. Passive data collection, search for senelogic / geologic activities	X		
5. Astronomical interferometry		X	
6. Radio Astronomy		X	
7. Neutrino Astronomy		X	
8. Plasma and field observatory		X	
9. Optical Astronomy		X	
10.High-energy astrophysical observations		X	
11.Particle Physics			X
12.Sociology & psychology experiments and studies			X
13.Health & medicine, human functions and performance			X
14.Exobiology experiments			X
15.Biological experiments			X
16.Material science			X
17.Applied technology			X
18.Pilot production facilities and processes			X

Each field encompasses many possible experiments and procedures. and the research programme of a lunar base will have to justify a major scientific effort extending over several decades.

The Moon is of vital importance to Solar System studies because:

1. The primordial crust of the Moon has survived unchanged since immediately following its accretion, and therefore provides an excellent opportunity to study the early evolution of a terrestrial planet.

2. The Moon's surface has retained a record of its, and therefore the inner Solar System's, the early post accretional impact history.

3. The origin of the Moon is inextricably linked with, and therefore offers insights into, the earliest history of the Earth.

4. The Moon is small and has no atmosphere and therefore resembles the smaller bodies of the inner solar system. Its surface may contain traces of meteoritic impacts occurring during the past three billion years.

4.3 Overview of individual Lunar programme activities

The exploration of the Moon by robot probes will continue sporadically during the first decade of the 21st century, with hopefully, a more concerted effort leading to a crewed mission to the Moon before the fiftieth anniversary of the end of the Apollo programme. The next stage of lunar exploration has been the subject of a plethora of studies and reports and a thorough and authoritative review of the most productive lunar mission profiles is badly needed.

Lunar programmes can be conveniently classified into 5 stages:

a. Temporary Lunar Outpost

b. Permanent Lunar Outpost

c. Lunar Laboratory

d. Lunar Factory

e. Lunar Settlement

The stages partially overlap and each stage would provide a foundation of experience and technology for the evolution of subsequent stages. The following working specifications are derived from a recent effort to model lunar exploration and development(16,19).

TEMPORARY LUNAR OUTPOST

Crew Size: 12
Developmental Status: 10 years
Operational Status: 15 years
Logistical Support: Reusable single stage Earth surface to Low Earth orbit (SSTO) + Reusable lunar ferry, propellant reloaded in LEO at a space operations centre (SOC) with Earth produced liquid hydrogen and oxygen from SSTO tanker. Partial propellant reloading on the Moon with lunar derived liquid oxygen (LULOX). - Lunar LOX production limited to 100 tonnes per annum.

PERMANENT LUNAR OUTPOST

Crew Size: 24
Developmental Status: 10 years
Operational Status: 50 years
Logistical Support: As for stage I, but with lunar oxygen production steadily increasing during the life of the outpost.

LUNAR LABORATORY

Crew Size: Approximately 100
Developmental Status: 10 years
Operational Status: 30 years
Logistical Support: Reusable heavy lift space transportation system (HLLV) with Saturn-Plus performance operating between the Earth spaceport and a space operations centre in lunar orbit

(LUO-SOC). Refuelling is with Earth produced liquid hydrogen both on the Earth and in Lunar orbit. A Lunar bus (LUBUS) ferries freight and personnel between LUO-SOC and the lunar laboratory. LULOX is provided on the Moon and at the LUO-SOC.

LUNAR FACTORY

Crew Size: Growing to 2,500
Developmental Status: 30 years
Operational Status: Permanent, based on major mining operations and the heavy manufacture of lunar products for use and sale on the Moon and export to other extraterrestrial installations.
Logistical Support: As for stage III but both lunar liquid oxygen and hydrogen are available as propellant on the Moon and at the LUO-SOC on a cost recovery basis.

LUNAR SETTLEMENT

Population: Growing from 50 to 2,500 residents
Developmental Status: 10 years (following 10 as a laboratory, 50 years of growth and 25 years of consolidation)
Operational Status: Permanent based on a lunar economy supplying a wide range of products and services to extraterrestrial and terrestrial clients.
Logistical Support: As for stage IV.

The costs, returns and overall performance corresponding to these five stages of lunar development have been modeled using a common set of strategic restraints and a common data base. The result is a compatible range of possible lunar programmes spanning the next century(19).

Table 4-6: A Representative Lunar Base: Programme Alternatives

	OPTION: PARAMETER (cost in billion and million $)	**tempor. lunar outpost**	**permanent lunar outpost**	**lunar labora-tory**	**lunar factory**	**lunar settle-ment**
1	Duration of life-cycle (years)	10+15	10+50	10+30	10+40	10+85
2	LC lunar labor years	140	1,205	2,170	31,437	82,000
3	labor-years for lease	40	225	523	6,598	39,819
4	size of lunar crew	12 max	24 av	120	2500	2,000
5	average crew duty cycle (months)	6	6	6	20	22
6	total facility mass at EOL	330	537	1,167	36,728	44,450
7	number of lunar missions	54	201	180	1,125	2,071
8	no.passenger roundtrips	282	2,376	4,340	19,920	45,240
9	total imports	1,095	5,400	15,210	58,500	103,000
10	LC base system cost (B $)	55	117	94	287	387
11	**average annual lunar base system cost (B $ p.a.)**	**2.20**	**1.95**	**2.34**	**5.74**	**4.11**

12	average specific annual system cost (M $/lab.-year)	393	97	42.0	9.14	4.71
13	relative specific total cost to Option 1 (%)	100	25	10.7	2.3	1.2
14	**specific transportation cost (M $/passenger)**	**53**	**15**	**3.71**	**3.0**	**2.60**
15	**specific transportation cost ($/kg cargo)**	**27,000**	**7,700**	**1,688**	**1,500**	**1,060**
16	benefit expected with respect to QUAL at end of life	679	916	1023	2094	2005
17	benefit / average annual cost	309	470	437*)	365*)	488*)

*) not including any commercial investments

The trend of facility size versus selected performance parameter has been plotted. Figure 4.1 follows immediately and other graph will be included after the returns are analyzed.

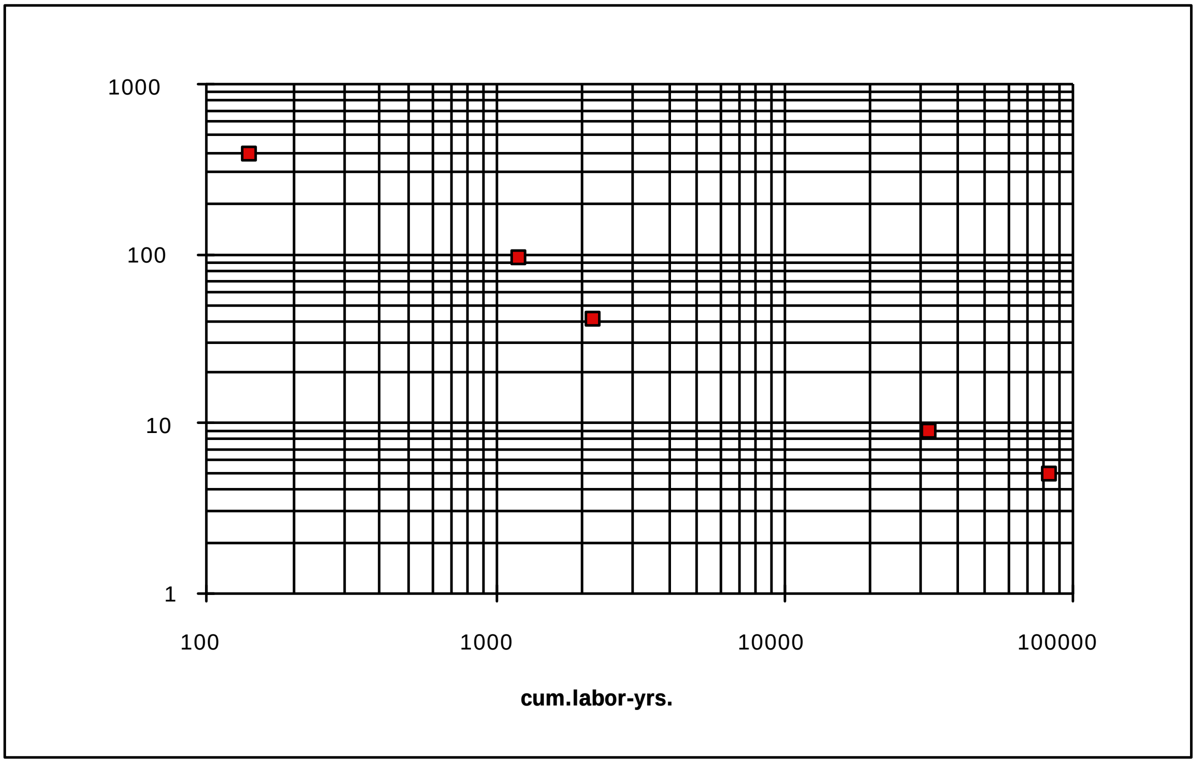


Figure 4-1: Specific lunar labour cost as a function of cumulative lifespan labour-years. (M$ 1999)

The estimated relative benefits of the various lunar programmes that were listed at the end of the foregoing table are of particular interest. Perhaps a space planner's most controversial task is estimating a programme's overall returns. If these estimates are to be generally accepted then the method used to calculate them must transparent and open to review. Chapter 2 presented the method used for the preparation of this report.

Recapping briefly:

Chapter 2 discussed in some detail the problems involved in estimating a space programme's returns. A frame of reference was constructed so that the relative benefits of individual programmes could be compared provided their performance, costs and overall schedules are known. The characteristics of five typical lunar programmes were presented in tables 4-5 and 4-6.

The relative benefits were estimated with reference to Table 2-7. These benefits are defined as the estimated proportional contribution of a specific lunar programme towards the achievement of the modelled optimum increase in global quality-of-life at the end of the 21 st century. The largest lunar facility considered would make the fullest contribution to the quality-of-life. More modest programmes would contribute less. The relative contribution made by each programme has been estimated with respect to a set of relevance indicators and their relationships used to estimate benefits. The contributions are expressed as percentages with respect to each of the listed objectives. The relative priority given to each objective is represented as a time dependent numerical weight. Therefore it is important at the outset to limit the duration of each programme. In this report the following milestones representing programme approval, initial deployment, and completion of operations have been assumed:

1. Temporary Lunar Outpost: 2006-2016-2030

2. Permanent Lunar Outpost : 2006-2016-2066

3. Lunar Laboratory : 2006-2016-2035

4. Lunar Factory: 2026-2036-2065

5. Lunar Settlement: 2006-2016-2100

Table 4-7: Benefits resulting from the selected programmes at the end of the 21 st century (Preliminary Assessment)

	Options	**temporary lunar outpost**	**permanent lunar outpost**	**lunar laboratory**	**lunar factory**	**lunar settlement**
A	**HUMANISTIC OBJECTIVES**	**131**	**201**	**218**	**341**	**414**
a.1	enhance the evolution of the human culture in space	6	25	39	65	89
a.2	establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system and learn to live in isolated, extreme environments	62	84	84	117	146
a.3	enhance the educational system and motivation to learn	10	12	10	13	14
a.4	provide a survival shelter for artifacts,documents and some elements of the human race in case of a global catastrophe	32	59	57	78	99
a.5	assist in reducing tensions and conflicts, thus contributing to peace on Earth	9	8	11	23	20
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	12	13	17	45	46
B	**POLITICAL OBJECTIVES**	**140**	**138**	**177**	**335**	**270**

b.1	demonstrate the potential growth existing beyond the limits on Earth	41	52	72	153	128
b.2	provide more opportunities for international cooperation	25	17	22	52	32
b.3	extend the infrastructure and experience for global enterprises	29	27	22	27	22
b.4	provide a peaceful outlet for national, competitive high technology urges and a useful employment of existing industrial-military capabilities	26	22	30	38	37
b.5	enhance the national pride and prestige of participating nations	18	20	31	65	51
C	**SCIENTIFIC OBJECTIVES**	**160**	**315**	**343**	**870**	**836**
c.1	improve the understanding and control of our own planet	2	3	26	85	61
c.2	improve our knowledge of the Moon and its resources	37	42	69	143	126
c.3	improve our understanding of the solar system beyond the Earth-Moon double planet	32	28	32	60	53
c.4	improve our understanding of the universe beyond our own Solar System	49	46	41	83	106
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	128	143	117	177	139
D	**UTILITARIAN OBJECTIVES**	**160**	**315**	**343**	**870**	**836**
d.1	provide rewarding job opportunities and thus stimulate the economy on Earth in general	14	12	12	22	20
d.2	stimulate the development of the educational system and of advanced technology on Earth	20	25	30	59	59
d.3	produce marketable products for extraterrestrial and for terrestrial use	1	3	16	172	140
d.4	contribute to the supply of space based energy to the the Earth	34	66	68	195	232
d.5	provide an isolated extraterrestrial depository to store high level wastes	27	74	72	120	111
d.6	enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources	43	102	95	169	142
d.7	provide thrust and focus for continued development of space technology other than in the area of space transportation systems	41	33	50	133	132
	total benefit expected with respect to QUAL	**679**	**916**	**1023**	**2094**	**2005**
	Percent of maximum potential theoretical achievable	**28%**	**38%**	**43%**	**88%**	**84%**

The inherent trends of the lunar base models discussed are illustrated in the following graphs:

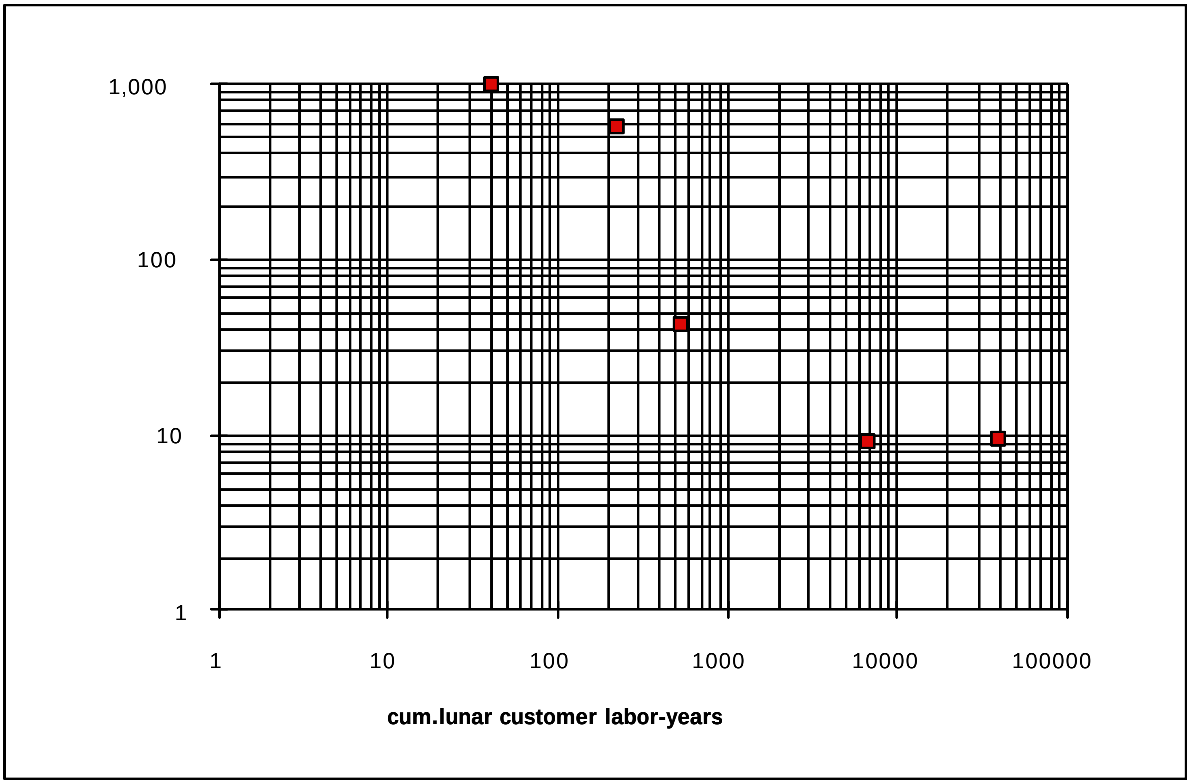


Figure 4-2: Specific cost of lunar labor years performed in leased lunar laboratories for commercial customers as a function of cumulative customer labour-years during the life-cycle (M 1999 $)

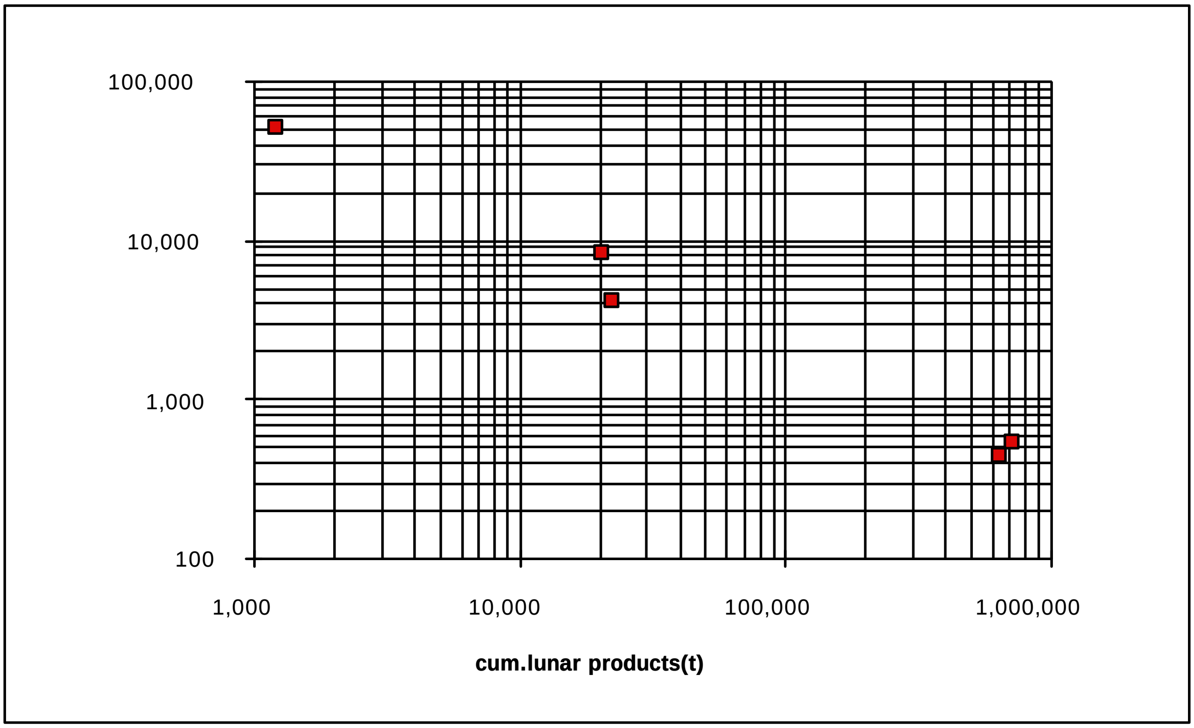


Figure 4-3. Average specific cost of all lunar products manufactured during the life-cycle as a function of cumulative mass of products (1999 $/kg)

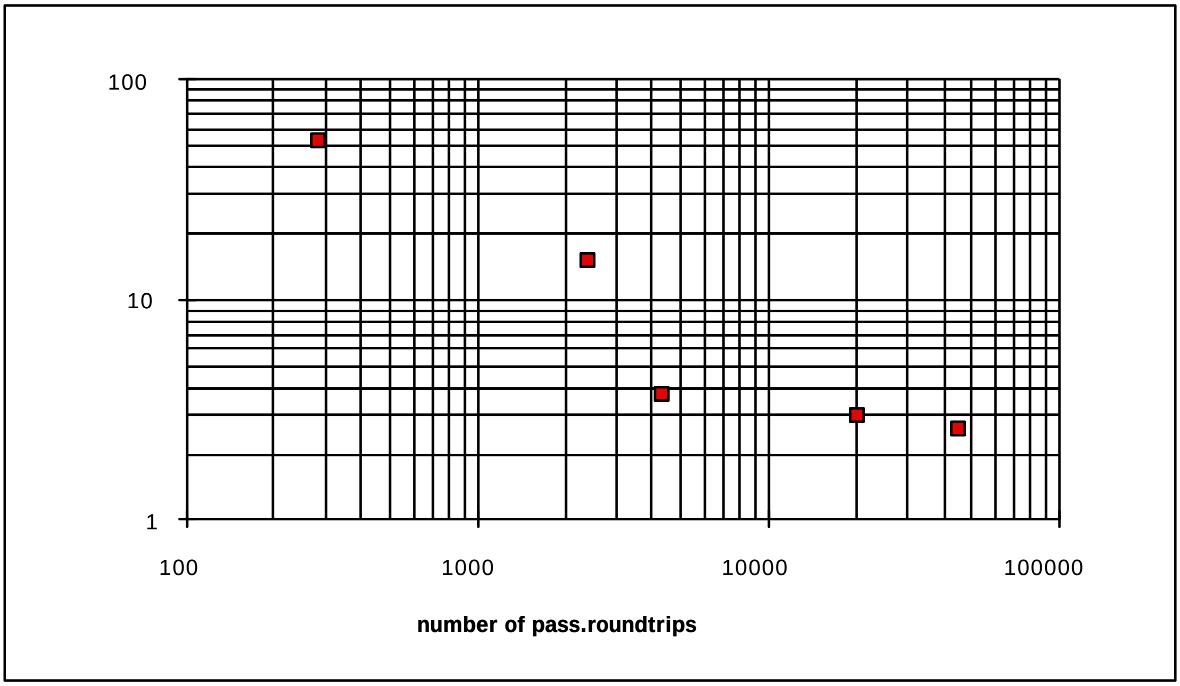


Figure 4-4: Average specific passenger roundtrip cost (million 1999 $) during the lunar base life-cycle as a function of cumulative number of passenger roundtrips

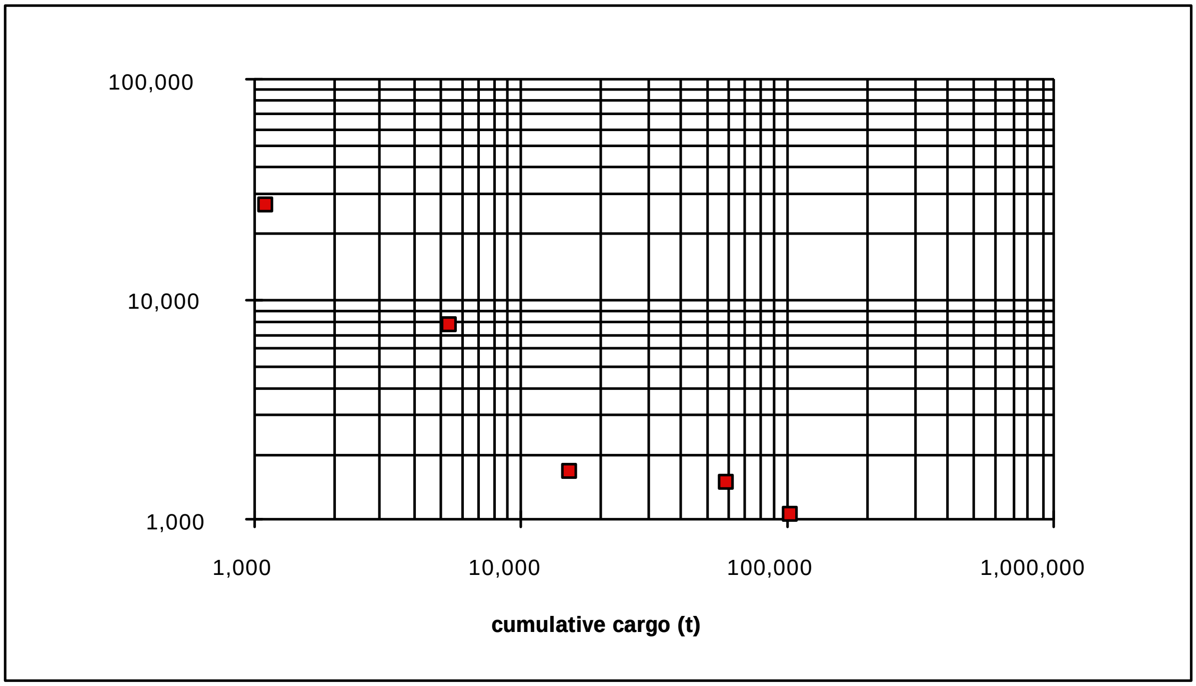


Figure 4-5: Average life-cycle specific cost of cargo transportation between the Earth and the lunar base as a function of total import mass (1999$/ kg cargo)

The previous graphs illustrated trends that identified the most feasible alternative lunar programmes, but only further analysis can define a representative programme in more detail. Of those analyzed, Option 3 currently seems to represent the most attractive approach among those considered feasible, and is now used by way of illustration.

4.4 A Lunar Laboratory

A medium sized lunar base built during the first half of the twenty first century would offer opportunities for commercial exploitation while supporting possible programmes of Martian exploration. The following is a detailed model of such a laboratory:

Table 4-8: A Lunar Laboratory with a 30 year Lifespan

year of operational life-cycle	number of total lunar crew members	total mass of lunar facilities mt p.a.	total mass of projected imports mt p.a.	total output mass of lunar facilities mt p.a.	total no. of lunar missions p.a.
1	40	361	73	335	10
3	43	459	97	514	7
6	44	488	97	568	4
10	56	580	114	666	5
15	68	688	122	748	5
20	79	796	129	812	6
25	100	982	150	882	7
30	**120**	**1,167**	173	948	8
30 yr.total	2,170	1,167	**3,813**	**21,900**	**180**
average pa.	72.3	700	127	730	6

360 metric tonnes will have to be shipped early to the lunar surface to provide the facilities and equipment for an initial lunar base. The base will consist of the following modules:

Table 4-9: 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 next table summarizes the cost breakdown of a publicly funded lunar laboratory.

Table 4-10: Lunar Laboratory costing summary, covering 10 years of development and 30 years in full operation (U.S. $ 1999)

COST ELEMENT	Life cycle billion $	million $ p.a.	% of LC total
Development & test of lunar facilities-10 year	11.2	1,120	12.3

Dev.& test of space transportation system-10year	28.6	2,859	31.4
Subtotal development & test - 10 year	**39.8**	**3,979**	**43.7**
Sustained engineering STS - 30 year	5.0	167	5.5
Production of space transportation system(STS)	17.1	571	18.8
Operation of space transportation system(STS)	17.6	587	19.3
Operation lunar facilities	11.6	388	12.8
Subtotal operations - 30 years operational LC	**51.4**	**1,712**	**56.3**
Total Lunar Laboratory System - 40 year life-cycle	**91.2**	**2,280**	**100**

These data can be represented graphically to show the expected improvement in cost-effectiveness as the crew size increases.

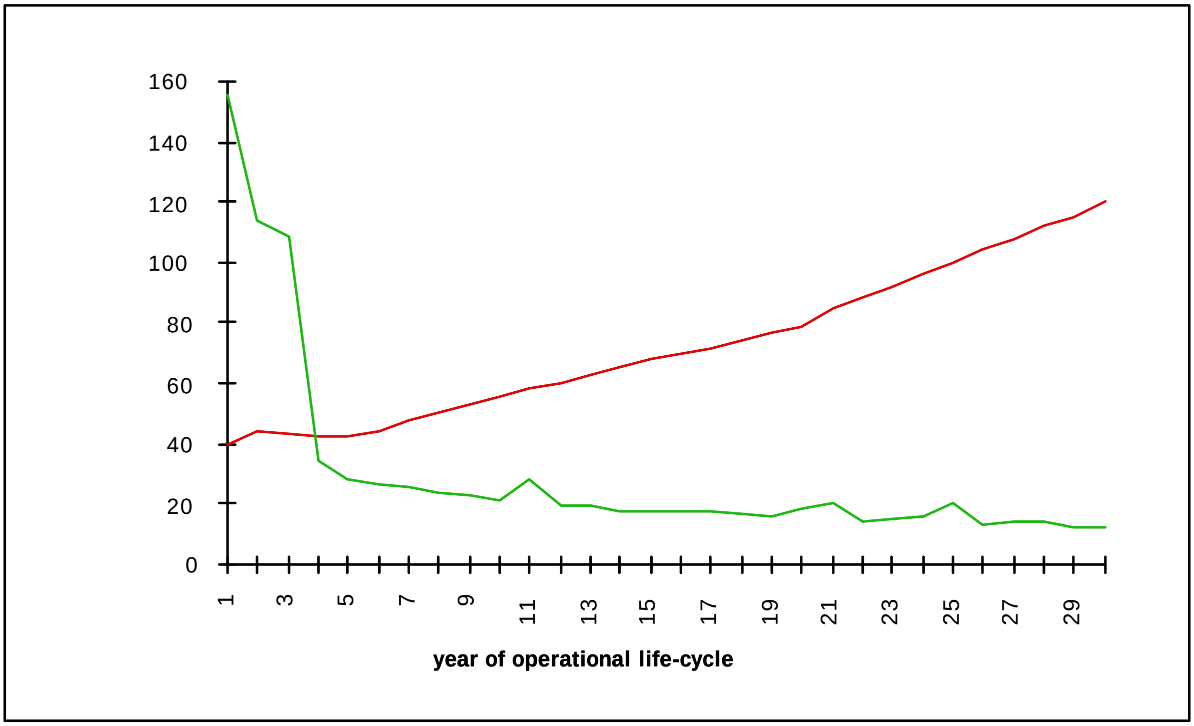


Figure 4-6: Lunar population and specific cost per lunar labour year ($ M 1999)

A programme with huge initial expenditures is unlikely to be approved, and a nearly even distribution of the annual, non-recurrent system costs throughout the programme will be critical.

Table 4-11: Selected Lunar Laboratory development and operating costs
(million $ 1999, 40 year lifespan, 1 direct human labour year= M$ 0.2)

year dev. phase	up-front cost lunar facilities p.a.	up-front cost space transpor-tation p.a.	lunar lab. total annual develop-ment cost	**year of opera-tion**	operation cost lunar facilities p.a.	operation cost LSTS p.a.	lunar lab. total operating cost p.a.

-8	10	125	135	**1**	242	5,974	6,216
-7	290	1,176	1,466	**3**	290	4,369	4,659
-6	675	2,528	3,203	**6**	321	851	1,172
-5	1,060	3,340	4,400	**10**	356	829	1,185
-4	1,300	3,951	5,251	**15**	384	794	1,178
-3	1,900	4,097	5,997	**20**	408	1,027	1,435
-2	2,335	4,649	6,984	**25**	461	1,528	1,989
-1	1,950	5,011	6,961	**30**	512	937	1,449
0	1,680	5,210	6,890	**total**	22,843	70,862	93,705
				ann.av.	571	1,772	2,343

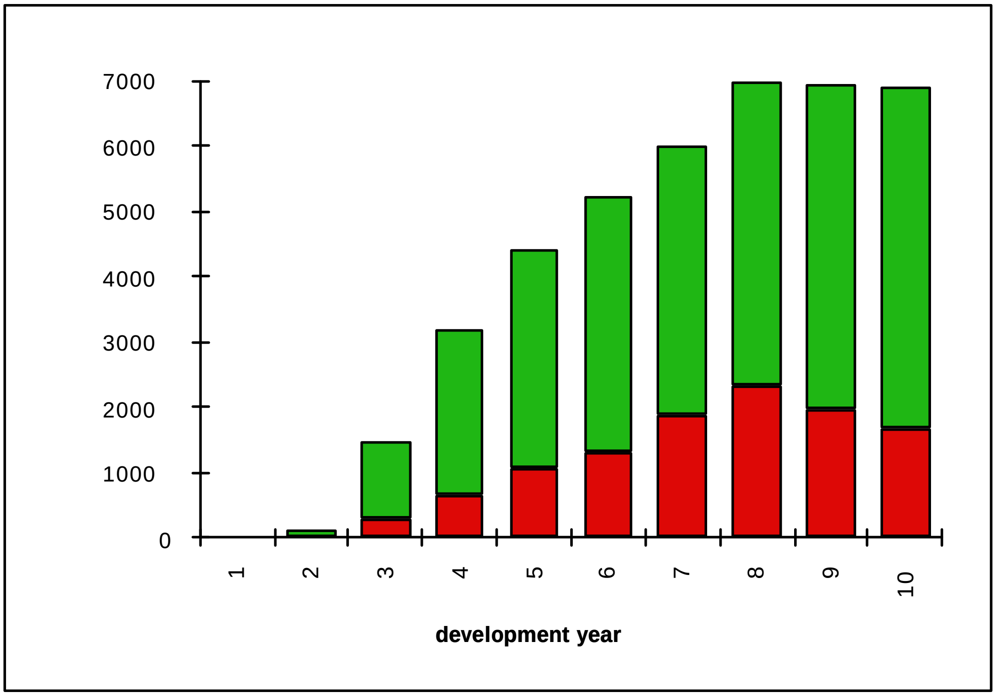


Figure 4-7: Annual distribution of development cost (non-recurrent cost) of the lunar facilities (lower bar) and the logistics system (upper bar)

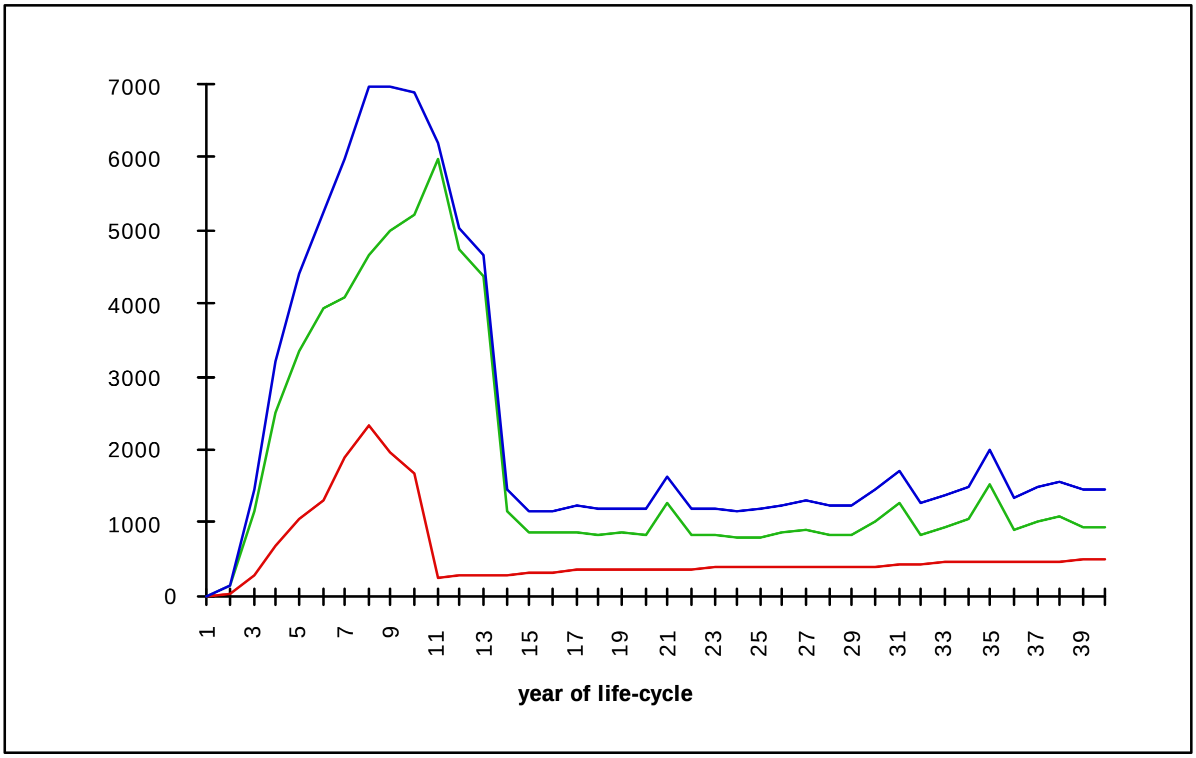


Figure 4-8: Lunar Laboratory Sytem total cost trends (upper curve) with lunar facility costs (lower curve) and space transportation costs (middle curve)

The initial investment levels shown in figure 4-7 imply that a significant programme of lunar development will demand a maximum annual investment of 7 billion dollars in constant 1999 dollars. It should be noted, however, that these funds will be spent on Earth, and will stimulate local economic activity, and moreover the peak funding levels represent only 1 percent of current global military expenditures. Major investments are not required now, and costs will only peak ten years after the beginning of the programme, sometime after the year 2010.

The lifespan costs shown in figure 4-8 provide a forty year overview of the expenditures associated with a lunar laboratory. The annual costs decline sharply once the base is occupied and productive. The burden on the public purse can be reduced by leasing laboratory space on the Moon to commercial corporations, and by selling approximately 100 tonnes of lunar products per annum. If half the laboratory space, as 30 sub-leases, is leased at 250 M$ (1999) p.a. each and half the exported products are sold at 1,000 per kg, then the base will have an annual gross return of: 250 x 30 = 7.5 B $ and in addition 1,230,000 kg x 1,000 $/kg = 1,23 B $.
Hence, this projected lunar base could yield a potential commercial return of between 5 and 10 billion dollar per annum.

Missions to explore interplanetary space or projects to build large orbital installations such as solar power satellites could use elements of the lunar transportation system and may also help defray their fixed costs. In particular the lunar programme's share of the investment needed to develop a mature space transportation system could be reduced by 1/4 to 1/3.
Other economies are possible, for example, by improving the living conditions at the base and so extending the crew's duty cycle.

Today these investments may seem overly ambitious, but they will appear less so during the next century if the world economy continues to grow, aided in part by a growing space sector. In 1996 a group judgement attempted to project existing conditions into the twenty first century and fix the most likely dates when   various lunar related initiatives would be approved. The estimates were grouped into quartiles and the median quartiles then averaged.

Table 4-12: Projected Programme Milestones

1. Some Governments, represented by their Space Agencies, are **entering a formal agreement** to make a multi-year joint planning effort with the objective to prepare feasible options for a return to the Moon to stay:

The earliest possible year			the **most likely year**		
1997	2000	2003	1999	**2005**	2010

2. Assuming that the event listed under 1. above is producing the desired results and the interested governments come to an agreement to proceed with the next phase of lunar development, **the first allocation of sizable funds to** enable the beginning of the development of long lead time items could be available by :

the earliest possible year			the **most likely year**		
1998	2002	2005	2000	**2008**	2010

3. Assuming that the development phase of a new lunar program (including the lunar facilities, equipment and space transportation system) is proceeding without major technical, financial or political hitches, **the first lunar crew could arrive** on the Moon for an extended stay:

the earliest possible year			the **most likely year**		
2005	2009	2012	2009	**2016**	2020

Summary of a representative lunar program alternative :

Several alternative programmes were simulated during an effort to evaluate plans for the next stage of lunar development. The behaviour of a complete lunar base and its infrastructure was modelled, resulting in annual estimates of the most important system parameters.

The creation of a permanently crewed lunar laboratory using a modest extension of current technology was analyzed in detail and the overall costs and benefits estimated. A typical scenario envisaged programme approval in 2005, development proceeding from 2006 to 2015 with an operational life span of thirty years starting in 2016. The base would be designed to support scientific research and technical development and would have an initial complement of 40 people. This would increase to 50 after ten years, 80 after 20 years and 120 after 30 years. The laboratory would conduct trials to extract, beneficiate and process lunar minerals, and could lease laboratory space and services to clients on Earth. At any time the laboratory could be extended or reduced, if results or external conditions warrant.

A modest, properly planned and competently run, lunar base would represent an investment of less than 100 billion (1999) U.S. dollars spread over a 40 year period. The maximum annual, publicly funded, outlay of 7 billion dollars would occur at the beginning of full lunar operations. This is equivalent to one percent of current global military expenditures. The average annual cost over the 40 years would be less than 2.5 billion (1999) dollars, that is one percent of the present U.S. military budget. Consequently, given the political will, a lunar base seems both economically feasible and affordable.

The present study has led to the following conclusions:

1. There is no quick, crude and cheap way to return to the Moon or to conduct a worthwhile programme of lunar exploration as defined by the long range space exploration programme.
2. It is fully possible to plan for a return to the Moon using currently available technology or readily achievable technologies, and to establish semi-permanent or permanent lunar facilities. Such a programme would not be unacceptably risky and would be affordable.
3. Establishing an initial lunar base would need an front end investment of up to 5 billion (1999) dollars per annum during a 10 year period. It is extremely unlikely that the bulk of this funding would come from non-governmental sources, and therefore a lunar base would have to be the outcome of a joint commitment by governments of the spacefaring nations as an investment in the future well being of the global population.
4. Once the initial investments are complete the maintenance cost of the lunar base could decline to less than one billion $ per annum, and such a base would be an attractive venue for research and development.

5. Structure of individual Mars Base Programs

5.1 The Exploration of Mars

5.1.1 Purpose

"Mars is the only planet beyond the Earth-Moon system where permanently settlement seems remotely feasible. One of the primary objectives of early Mars exploration should be to determine how practical human settlement really is. The prospect of the spreading of civilization into the Cosmos offers humanity the opportunity to achieve continuance, expansion, prosperity and knowledge.There are many reasons to explore Mars. One obvious reason is scientific, it is of great importance to explore, document, and analyze the processes that have turned Mars into a barren, inhospitable domain. To give the answers, an international program of automated precursors in parallel with human missions to Mars will best serve humanity. Few scientific questions, such as whether life ever existed on Mars, will be answered by one simple experiment. Only by addressing a range of interrelated geological, atmospheric and biological issues will major questions ultimately be resolved. Some of the principal research areas are the following: Composition and internal structure, geological evolution and ages, external processes, composition and dynamics of the atmosphere, water in Martian history, existence of past or present life on Mars. The resulting knowledge will also help us to protect Earth's natural biosphere." (15)

"It is not possible to foresee in advance exactly what the scientific return from Mars exploration will be. It is clear that robotic missions to Mars must develop greater autonomous capability than we have been able to provide in the early probes. However, it is recognized that the cost of human exploration of Mars raises questions of cost/benefit. Mars offers a rich menu of scientific exploration opportunities, but the potential cost of human Mars exploration demands more than just scientific return. The task is to find a program architecture that does not too strongly compete with Earthly needs for scarce resources." (15)

5.1.2 Precursors

The detailed exploration of Mars began in 1965 when the first pictures were sent back to Earth by the American MARINER 4 spacecraft. The early missions had limited payloads and made severe demands of contemporary space technology, and Table 5-1 lists their results. Many missions failed and some were only partially successful. In all the Soviet Union and Russia have launched a total of 17 probes and achieved the first confirmed soft landing on the Red Planet in 1971. The most successful of the first wave of Martian probes were the American Viking 1 and 2 landers, which, however, did not fulfill their prime mission directive and failed to detect traces of life. Consequently, during the next twenty years, interest in the in-situ exploration of Mars waned, and both of the large Soviet PHOBOS orbiters and the American MARS EXPLORER orbiter all failed during transfer from Earth or in the early stages of their missions. Martian exploration resumed with the success of the modest PATHFINDER and MARS GLOBAL SURVEYOR missions in 1997 and 1998.

Table 5-1: Significant events in the Exploration of Mars:

Name	*launch date from Earth*	*arrival at Mars*	*remarks*
MARINER 4,USA	28.11.1964	14.7.1965	25 min flyby of Mars at 9850 km, 22 pictures
MARINER 6	24.2.1968	1969	flybys at 3500 km
MARINER 7	27.3.1969	1969	20% of surface photographed
MARS 2, USSR	19.5. 1971	27.11.1971	first soft landing, 20 seconds data transmission
MARS 3	28.5.1971	2.12.1971	orbiter and lander

MARINER 9, USA	30.5.1971	13.11.1971	orbiter, 6,786 pictures 11 month, 12 hr orbits
MARS 5	25.7.1973		orbiter, few pictures
VIKING I, USA	20.8.1975	19.6.1976 20.7.1976	orbiter lander, pictures, soil probes
VIKING 2	9.9.1975	8.7.1976 3.9.1976	orbiter ,lander, soil probes, 97% of the surface photographed
PHOBOS 2,USSR	12.7.1988	29.1.1989	enters Mars orbit at 6400 km Phobos pictures 190 km distance, 57 orbits
PATHFINDER	4.12.1996	4.7.97	10 kg rover vehicle
MARS GLOBAL SURVEYOR	7.11.1996	9.9.1997	enters 45 hr orbit 56,000x250 km, reducing altitude by aerobraking to 350x410 km mapping orbit
NOZOMI, Japan	4.7. 1998	June 2003	orbiter, 535 kg spacecraft 150 x 51,000 km orbit planed
Mars Climate orbiter - USA	10.Dec.1998	Sept. 1999	global climate distribution
Mars Polar lander USA	4. Jan. 1999	Dec. 1999	lander south polar region

The results of the most recent missions, together with the possible discovery of signs of ancient life in meteorites that originated on Mars have combined to rekindle interest in the exploration of Mars. Future missions will no doubt be the result of close international co-operation.

Robotic missions prove new technologies while adding to our scientific understanding of Mars, and before human beings set foot on Mars uncrewed proving missions will test the life support and other systems a crewed mission will need. Even after a crew lands on Mars robotic mission will continue to expand our knowledge of the Red Planet.

The Apollo astronauts were like nineteen century mountaineers climbing the Alps. The lunar landing missions were self contained and unsupported. The exploration of Mars will parallel the climbing of the Himalayas. Supplies will have to be delivered by automatic freighters and cached in orbit and at future landing sites on the surface as or before the first crew leaves Earth orbit. Every current and future mission to Mars is a precursor of the human exploration of Mars. These missions will define the most effective way to survey Mars while demonstrating how autonomous and teleoperated systems can assist and enhance the work of the first visitors to Mars.

The International Mars Exploration Working Group (IMEWG) is coordinating all future missions to Mars. The following missions are currently being prepared or planned, but Russian participation is quite uncertain, and the future of some of these missions is doubtful.

Table 5-2: Planned Mars Missions

Name	launch date from Earth	arrival at Mars	remarks
MARS 2001 orbiter USA	Feb. 2001	late 2001	orbiter
MARS 2001 lander USA	March 2001	late 2001	lander, Russian rover
MARS SURVEYOR 2003	March 2003	late 2003	orbiter
MARS EXPRESS-ESA	early 2003	late 2003	INTERMARSNET lander
MARS sample	2005	2006	sample return mission 2007

MARS sample	2007	2008	

5.1.3 Planning for a crewed expedition to Mars

The first serious plans to send men to Mars were published in the early 1950's by W. Von Braun (1). As the APOLLO programme expanded during the early 1960's these plans were enlarged and encouraged within the auspices of the Future Projects Office of NASA/MSFC, and included the participation of representatives of the aerospace industry as together they explored ways to use the SATURN V launch vehicle after the completion of the APOLLO project itself(4,6).

The first opportunity to send a crew to Mars would have occurred during 1984 to 1986. That launch window would have demanded minimal velocity changes and Solar activity and hence interplanetary radiation would be low. The demands of the Vietnam War and the failure of the Soviet lunar programme led to the cancellation of the SATURN V vehicle, and eliminated any immediate possibility of a piloted Mars mission. Only minimally supported studies have been published sporadically since then. (3,5)

In the mid-nineteen eighties the Congress of the United States mandated a National Space Commission that was to propose future national space activities. The result was the SPACE EXPLORATION INITIATIVE that was endorsed by President Bush in 1989. This proposed a permanent return to the Moon, and a possible crewed expedition to Mars (the Stafford Report) (9). This was followed by a series of industrial studies (11,12,13).

Between 1992 and 1994 a team drawn from several NASA centres compiled an initial "NASA Reference Mission" derived from Zubrin's split-mission concept. (7,10,14,21) The reference mission used relatively low cost mission structures that appeared technically feasible and would support a first piloted mission to Mars without incurring unacceptable risks. It was hoped that the split mission concept, with its reduced reliance on a single launch vehicle, would make the mission more attractive to executives and politicians. This reference mission has been the basis of a continuing series of studies.

5.1.4 Mars surface systems and operations

"The role of the Mars surface system is ultimately to provide a complete spectrum of capability for realization of the international exploration community's goals for robotic and human exploration and possible future settlement of Mars. To plan the Mars surface system, it is necessary to examine fundamental top level goals, to derive the next level of requirements, and then to conceptualize a set of relationships, interactions, and phase transitions that best describe a strategic approach which ensures accomplishment of those goals. The implementation schemes will look different, if the goals are limited to Exploration or go a step further to Human Expansion.

There are always several ways to proceed. One way emphasizes global Mars coverage with temporary human presence at any single site. Another way to explore Mars emphasizes growth and evolution outward from a single site with permanent human presence. Within the framework of the Human Expansion goal, it is expected that increasing capability may be provided by utilization of local resources that will enable much longer stays, support other goals, and open the way to long-range surface exploration capabilities. The potential implemen-tation concepts of a Mars exploration program can vary widely depending on the detailed analysis of the requirements and special interests of the international partners involved. The implementation concepts presented in the IAA Mars Cosmic Study report are only to demonstrate that there exists at least one solution to the problem." (15)

5.1.5 Human factors

"An interplanetary space flight or inhabiting a foreign planet for long duration can subject the crew to debilitating, injurious and possibly fatal stresses. Much will be learned in this area by inhabiting and working aboard the MIR laboratory and the International Space Station (ISS) in the next decade. The mission planning should also include consideration of crew selection and performance, habitability of the environments, sociological issues, life support, environmental health, and management of crises and illness. The acceptable level of risk needs to be decided. One serious problem is the radiation environment. The biological effects of the radiation anticipated en route, on Mars surface, and in case of an abort flight, should be precisely determined. For long duration missions, a 1-g environment for the Astronauts would eliminate the potentially mission-defeating effects of hypogravity." (15)

5.2 Mars products and services

5.2.1 Overview

The initial stage of Martian exploration will use both robots and people to survey the Red Planet, and in particular to understand its environment, minerals, and the technology that human beings will need if they are to survive and work there. The Martian polar ice caps contain ice that may exist elsewhere on the planet and it could be used in life support systems or made into propellants. If hydrogen were imported from Earth carbon dioxide in the local atmosphere could be manufactured into oxygen and methane. The latter is an energetic and readily storable propellant.

Table 5-3: The products and possible uses and clients of a Martian Base

products : **buyers:**	**new knowledge**	**services**	**material goods and energy**
Mars enterprises	new information relevant to Mars operations	maintenance and repair, social needs of Mars crew	construction material, feedstock, consumables, propellants, el.& therm.energy
in-space enterprises	research results relevant to space operations	communication, maintenance and repair,	propellants, construction material, energy, consumables,
Earth enterprises	research results relevant to life on Earth	deep space surveillance, entertainment, adventure	soil samples, souvenirs,

5.2.2 Martian Science

{Note: This does not include research into the Martian Moons. They are probably examples of captured main belt asteroids, and are therefore important objects in their own right and should always be included in Martian research }

The resources of Mars will have to be thoroughly surveyed by teams of robots and people working both on the planet and in orbit. The questions they will address can be placed into three categories:

-those which can probably be answered by using robot probes alone

-those for which a human presence would advantageous

-those for which a human presence would be mandatory

The first return from the exploration of Mars would be the scientific knowledge resulting from research conducted there. Martian research will cover a very wide range of studies that should be examined in some detail:

Table 5-4: Science on Mars (14,15)

Questions to be answered:

- Why did Earth and Mars evolve so differently?
- How much can Mars contribute to the understanding of Planetary Evolution and the origin of life in general ?
- Why and when did the Mars climate change?
- Did life ever exist on Mars?
- What is the evidence for the distribution in space and time of water on the surface?
- What is the distribution of subsurface permafrost?
- Are there exploitable resources?
- Is human settlement a practical proposition?

Primary areas of research:

- Composition and internal structure
- Geologic patterns and history
- External processes
- Composition and dynamics of the atmosphere
- Existence of past or present life on Mars
- Distribution of minerals

Primary tasks for robotic missions:

- monitor the atmospheric and climatic processes,
- investigate the intrinsic magnetic field,
- perform global mapping of the Mars surface,
- map crustal thickness and cryolithozones,
- establish the interior structure and activity,
- perform studies to establish the chronology of surface evolution,
- perform in situ studies on Mars rocks and soil,
- provide data for location of landing sites and bases.

Every relevant study has concluded that before the extensive exploration of Mars can begin an economical and reliable system for transporting freight and crews across interplanetary space will have to be developed. Consequently, we have to discuss this problem before we can develop architectures of Martian missions and facilities.

5.3 Launch vehicles and space vehicles

5.3.1 Earth to Orbit launch vehicles

There are many ways by which people and cargo could be transported to Mars. Previous studies have examined missions that needed interplanetary trajectory injection masses from low Earth orbit of between 250 and 1000 metric tonnes. The exploration of Mars can not be considered in isolation, and must related to the then existing governmental and military programmes, and those of the rapidly expanding commercial space sector. All these programmes overlap and any discussion of a Mars programme must assume that some of the development costs will be shared. Unlike a programme of crewed Martian exploration, a lunar transportation system could usefully employ launch vehicles of several sizes, and so the needs of the Martian programme will be crucial. The following considerations will determine the types of vehicle used by an integrated programme of Lunar and Martian exploration:

Arguments in favour of launch vehicles capable of launching large payloads:
- reduced man-power requirements at destination during assembly
- possible use of direct injection from Earth and therefore using the optimum launch window,
- higher growth potential,
- reduced number of launch facilities,
- more efficient landing and launch vehicles.

Arguments in favour of launch vehicles capable of launching smaller payloads:
- better mission flexibility,
- reduced front-end cost,
- reduced noise at launch,
- better use of vehicle design lifetime.
- more commonality with commercial users' demands

A Heavy Lift Launch Vehicle (HLLV) (22,23) emerges as the optimum configuration if all the following competing considerations are taken into account.

1. Nuclear- and solar- electric propulsion systems offer greater performance in space, and have been occasionally tested satisfactorily on the ground, however, they have not been fully tested in space and are not ready to support the first crewed missions to Mars.

2. Nuclear propulsion can not be considered viable for the early missions to Mars. There are no facilities in which to develop nuclear powered rocket engines, and there is little likelihood that funding for their development will be available in the near future. It seems safe to assume that it will be a long time before such engines become available, and that their use would raise a storm of protest by organisations and individuals dedicated to the elimination of nuclear power.

3. The launch vehicle will have to be large enough to place massive elements of a crewed interplanetary vessel bound for Mars into a suitable parking orbit around the Earth, thus reducing the requirement for extravehicular activities.

4. The optimum Earth orbit for departure to Mars changes with each launch window and a permanent construction or propellant storage facility in one orbit would not be an efficient use of scarce resources. Interplanetary dynamics, therefore, do not favour constructing and fuelling a vessel bound for Mars from many small payloads at a major orbital assembly site.

5. Every system of the piloted Mars spacecraft must have been fully proven before construction begins, and existing or modified hardware will be strongly preferred.

6. A expedition to Mars will require surface habitation and equipment, a return vehicle to Martian orbit, and an vehicle to return to Earth. The split mission scenario assumes the interplanetary injection of several space vehicles from Earth orbit during a single launch window. In the light of past experience, and considering the effort needed to launch four necessarily new, and untried, expendable vehicles in a short period of time, a successful mission using non-reusable launchers must be considered highly unlikely.

7. There is no commercial interest in either a very large expendable launch vehicle, or a nuclear injection stage. Only a cost effective, reusable, heavy lift launch vehicle would seem to have a chance of attracting a wide range of users and hence, distributing its development costs satisfactorily. - A chemically powered interplanetary stage would have a large cargo volume and reduce the problems of packaging the payload. After the injection burn the stage could be use with advantage in several ways:

- After any mid course corrections it could act as a counter weight to the payload at the end of tether or truss as the vessel spins to simulate gravity in the crew module.
- The mass of the stage would act as additional meteorite and radiation protection during transfer.
- The propellant and gas residuals would available during transfer.
- The stage could be a heat shield during aerobraking in the Martian atmosphere before the landing stage is released
- The costs of developing a Heavy Lift Vehicle could be shared with lunar and large construction programmes in Earth orbit. A shared production run would mean lower unit costs. The Mars injection stage is practically identical to a lunar ferry or large orbital tug, and its reliability will have been thoroughly proven before the mission to Mars begins.
- After the stage has separated from the lander it could aimed to crash close to the mission's chosen landing site. It could then become a valuable source of material, especially if the crash is softened by air bags or by orientating the stage so that the empty tanks act as shock absorbers.

The conclusion to be drawn from the foregoing arguments is that the primary launch vehicle for a crewed mission to Mars will be for all intents and purposes identical to that needed to support a programme of lunar development.

It must be a fully reusable chemically powered lifter capable of reliably delivering approximately 100 metric tonnes of payload into a direct transfer orbit to Mars or into Lunar orbit. Such a launch vehicle would have a lift off mass of about 6,000 tonnes and would cost about $ B 12 to $ B 15 to develop over a period of six years. Fortunately, such a vehicle has many potential uses and would significantly lower present payload launch costs and hence may attract investment from both government programmes and corporations.

The Reusable Earth Launch Vehicle design presently favoured for for a crewed mission to Mars and therefore an integrated Moon- Mars programme would have the following approximate specifications.

<u>The Launch Vehicle:</u>

Basic performance:

- A three stage, fully, reusable, heavy lift launch vehicle (HLLV) (22,23).
- Launch mass: approximately 6000 tonnes
- Maximum payload into 160 km altitude low Earth orbit: 350 tonnes
- Payload injected into a Mars transfer trajectory: 85 to 120 tonnes (depending on the transfer time and the year of departure according to a 15 year cycle)

The mass breakdown of the third stage of this HLLV, and relationship between the mass of the Mars transfer payloads and the velocity change (delta V) needed to leave low Earth Orbit are presented in the following tables:

Table 5-5: Mass model of the TMI stage (NEPTUNE max payload) (22,23)

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	152.82
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

The conceptual NEPTUNE vehicle would be a three stage fully reusable heavy lifter with a launch mass of 6,000 tonnes capable of launching a maximum gross payload - if fully developed - of up to 416 tonnes into a 160 km altitude low Earth orbit. Assuming a 10% design margin results in a nominal mass for the trans-Mars injection stages of approximately 375 tonnes. Table 5-6 lists the main parameters of the Mars injection stages.

Table 5-6: Trans Mars injection payload capability as function of delta v departing from low Earth orbit (all masses in metric tons)

m-launch	375	375	375	**375**	**375**	375
m-dry	40.3	38.2	36.6	**35.2**	**32.3**	25. 5
m-prop	278	263	252	**242**	**221**	200
m - residuals	5.6	5 .3	5 .1	**4 .9**	**4 .5**	4 .0
m-stage	323.9	306.5	293.7	**282.1**	**257.8**	233.5
prop share	0.858	0.858	0.858	**0.858**	**0.857**	0.856
m- cargo	51.1	68.5	81.3	**92.9**	**117.2**	141.5
m-cutoff	90	112	123	**133**	**154**	175
m -ratio	3.866	3.348	3.049	**2.820**	**2.435**	2.143
ln r	1.352	1.208	1.115	**1.037**	**0.8899**	0.7622
delta v (m / s)	6,220	5,557	5,130	**4,770*)**	**4,094**)**	3,500

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

or presented in a graph illustrating the performance trend of cargo vs delta v

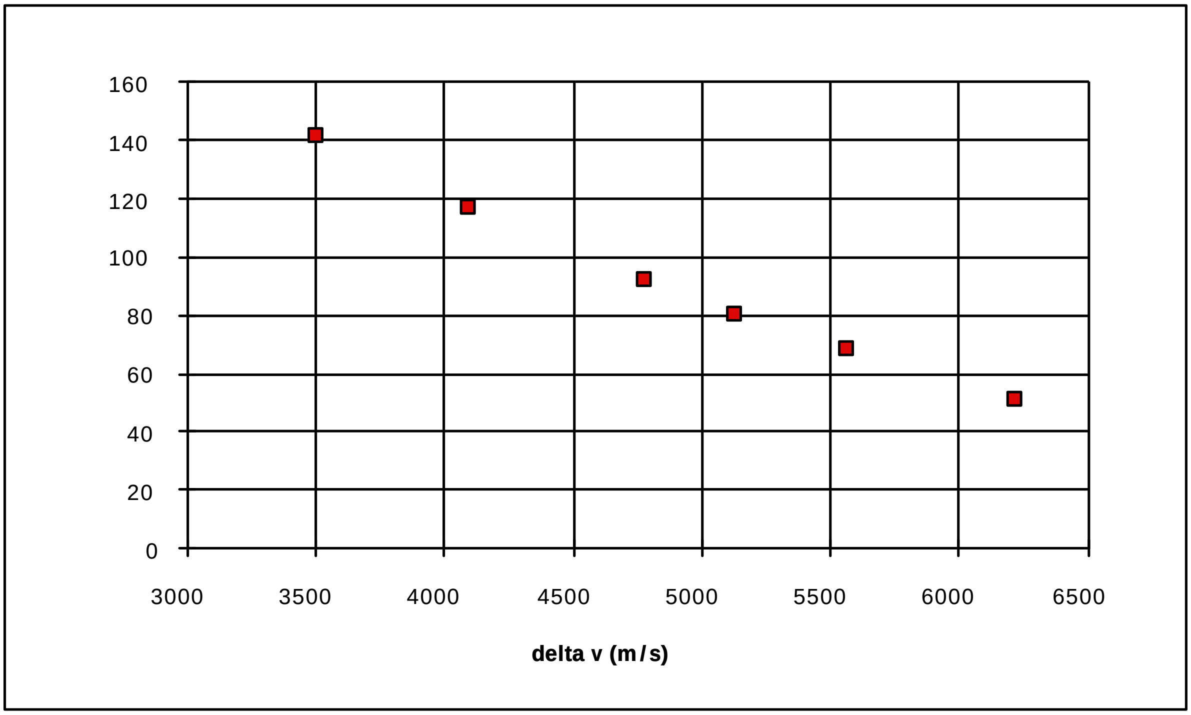


Figure 5-1 : Reusable NEPTUNE cargo capability from low Earth orbit as a function of characteristic velocity

The limited overall payload capacity of the launch vehicle dictates the mass of the Trans Mars Injection (TMI) stage, which in turn limits the design of the vessels that will descend to the Martian surface and return to Earth. They include a Mars landing -, ascent -, Earth return- and Earth landing vehicle.

5.3.2 Mars mission space vehicles

a. EARTH orbit to MARS requirements

A low energy departure trans-Mars-injection(TMI) requires a minimum of 3,700 m/s above Earth orbital velocity. Aerobraking in the Martian atmosphere will reduce the arrival velocity by 1,150 m/s before entry into an orbit around Mars. A propellant reserve equivalent of 200 m/s is available for mid-course and orbital correstions. Descending to Mars will need propellant equivalent to 500 m/s; resulting in a total propellant reserve equivalent to 700 m/s. The exact propellant requirements will have to be calculated for each vehicle design and mission profile.

b. MARS to EARTH requirements

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

c. Mass models and performance

Methane (CH_4) and liquid oxygen is preferred for all flights on the Mars side in an early flight program. In the direct return mission liquid hydrogen and liquid oxygen must be used in case a single stage design is preferred. The engines used in these space vehicles will be clusters of the RL 10 family.

Table 5-7 : Overview of vehicle characteristics required for typical Mars landing and return missions

parameter	Mars cargo lander	Mars crew lander	Mars ascent to LOM	Mars ascent to HEMO	Mars orbit departure	Mars direct to Earth
exhaust vel. c (m / s)	3,700	3,700	3,700	3,700	3,700	4,500
delta v (m / s)	700	700	4,200	5,400	2,917	6,200
mass ratio	1.208	1.208	3.11	4.55	2.20	3.966
init. mass (mt)	120	90	19.6	30.5	110	203
dry stage (mt)	6.5	6.5	3.0	3.2	6.5	13
residuals (mt)	0.5	0.5	0.3	0.5	1.5	3.0
payload (mt)	89	65	3.0	3.0	42	35.0
cut-off mass (mt)	96	72	6.3	6.7	50	51.0
propellants (mt)	22	18	13.3	23.8	60	152
prop. mass fraction	0.77	0.72	0.816	0.865	0.903	0.921

It remains to be determined when and to what degree these propellants required on Mars can be produced by local (ISRU) systems. This is also a matter of the availability of sufficient electric power on the Mars surface, probably requiring a nuclear power plant.

5.4 Individual Mars Programs: Overview

5.4.1 Classifications

The previous IAA study complemented the NASA Mars reference mission design study, and included a survey of the most recent mission concepts that revealed the complex nature of an advanced space mission's systems and structures. These, and similar, studies should be used to compare and analyze the various strategies and concepts currently available to the planners of future space missions(20,21,27,28). The available choices must be clear and address the question:
At any specific time, what mission options are both technically feasible and affordable?

A mission to Mars would be a complex undertaking, and future planners will have consider many system parameters while choosing from a wide range of possible mission profiles. The most promising profiles need to be fully analyzed and modelled.

The various mission profiles can be conveniently classified under five headings:

1. *Single Mission to Mars*
2. *Multiple Mission to Mars*
3. *Martian Outpost*
4. *Martian Laboratory*
5. *Martian Base*

Several iterative group judgements have identified the following programme profiles as worthy of further analysis. They include missions ranging from a single expedition to Mars to a permanent Martian base, and their most important details are listed below.

Table 5-8: Typical Mars Programmmes(27)

program attributes and parameters	**0ption 1.**	**2.**	**3.**	**4.**	**5.**

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

The next table lists the same programmes according their Martian surface structure, the overall mission profile, vehicle design and crew systems. Presenting the database this way confirms the compatibility of the individual programme elements.

Table 5-9: Preferred Martian Programme Architectures: subsystem analysis

op-tion	*Mars surface infrastructure*	*mission profile*	*vehicle design*	*crew system*
1.	habitat solar power plants rover	LEO assembly of entire crew vehicle, LEO departure, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from low Mars orbit, direct Earth entry	Lox / LH2 booster stage, Lox-CH4 Earth propellants for expendable Mars ascent & orbit departure vehicle, no Mars propellants, cargo flights direct,	single 6-person crew vehicle, choice of 6, or 4 people on Mars surface and 2 remaining in orbit, no artificial gravity during transfers
2.	habitat nuclear power plants solar pp. rovers propellant production plants	LEO departure, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from high elliptic Mars orbit, direct Earth entry	Lox / LH2 booster stage, partial Mars propel-lants for ascent vehicle, Lox-CH4 Earth prop.for Mars orbit departure, expendable ascent & return vehicles, cargo flights direct	6-per vehicle, 1 crew vehicle per mission, no artifical gravity during transfer

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

The results of system studies presented below indicate the range of Mars program costs to be expected from single expeditions to permanent Mars installations.

5.4.2 Selected Programme Options

Detailed consideration of the five options listed above, resulted the floowing estiamated cost and mass budgets for their Martian surface facilities and equipment.

Table 5-10: Facilities and equipment mass requirements estimated for options 1 - 5 during their respective life-cycles (metric tonnes)

Equipment inventory:	option 1	option 2	option 3	option 4	option 5
	single expedition	multiple expedition	outpost	laboratory	base
habitats, workshops,-lab modules	81	181	182	365	560
life support system	11	11	22	43	100
production plants	7	12	26	56	160
power plants	63	42	83	215	300
communication system	2	2	3	5	10
surface vehicles	14	16	32	84	200
hand tools, machine tools	10	10	20	50	100
spares	4	12	20	120	200
Mars -Bus hardware	36	48	36	120	120
propellants	0	15	30	150	300

science equipment	3	10	20	50	100
consumables (food, etc.)	10	30	60	300	600
consumables (clothes etc.)	4	12	24	200	400
misc. and reserves	5	61	50	300	600
total	250	462	608	2058	3,750

Table 5-11: Cost of facilities and equipment estimated for options 1 - 5 during their respective life-cycles (million $)

Equipment inventory:	option 1	option 2	option 3	option 4	option 5
habitats, workshops,-lab modules	4,120	5,420	6,130	7,760	9,500
life support system	2,100	1,850	2,200	2,440	3,000
production plants	710	740	1,000	1,000	1,500
power plants	1,140	3,260	4,630	6,750	7,300
communication system	120	70	80	100	200
surface vehicles	460	330	460	620	700
hand tools,machine tools	30	30	40	70	100
spares	100	200	350	650	750
misc. and reserves	50	400	400	400	400
TOTAL	8,830	12,300	15,290	19,790	23,450

Table 5-12: Operational requirements estimated for options 1 - 5 during their respective life-cycles (million $)

operation	option 1	option 2	option 3	option 4	option 5
crew training and salaries	120	130	300	1,770	3,100
science support	600	700	2,000	3,600	5,100
systems engng. & management	1,000	1,200	2,800	5,000	7,000
science equipment	200	300	550	1,150	2,500
propellants	0	15	10	150	250
consumables (food etc.)	20	70	130	160	250
clothes, hygienic materials	30	40	70	210	500
totals	1,970	2,455	5,860	12,040	18,700

Table 5-13: Space transportation system cost estimated for options 1 - 5 during their respective life-cycles (million $)

operation	option 1	option 2	option 3	option 4	option 5
development cost	20,789	25,820	27,540	32,299	28,620
production cost	9,278	14,954	19,989	22,819	32,697
operation cost	1,501	1,151	1,555	4,503	5,227
total space transportation cost	31,570	41,825	49,084	59,621	66,543

What remains to be done is the estimate of the relative benefits of these program options with respect to their likely contribution to the quality-of-life on Earth. A method to do this has been presented in chapter 2 and applied to the defined Lunar program options at the end of chapter 4. The grid used to measure the benefits is a satisfactory beginning. Table 2-10 has presented the frame of reference for this benefit assessment because it has determined the benefit potential of Mars programs in general for the next century. For an initial estimate, the potentials determined for the end of the 21st century have been used(29).

Table 5-14: Preliminary assessment of benefits to be expected per objective by the Mars programs selected

	OPTION	**single exp.**	**mult. exp.**	**Mars outpost**	**Mars laboratory**	**Mars base**
A	**HUMANISTIC OBJECTIVES**	**1**	**71**	**94**	**130**	**145**
a.1	enhance the evolution of the human culture beyond Earth	-43	-18	-5	9	13
a.2	establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system and learn to live in isolated, extreme environments	25	46	45	46	49
a.3	enhance the educational system and motivation to learn	12	12	12	15	15
a.4	provide a survival shelter for artifacts, documents and some elements of the human race in case of a global catastrophe	-23	1	11	23	27
a.5	assist in reducing tensions +conflicts, thus contributing to peace on Earth	10	10	11	12	14
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	20	20	20	25	27
B	**POLITICAL OBJECTIVES**	**80**	**110**	**118**	**123**	**141**
b.1	demonstrate the potential growth existing beyond the limits on Earth	5	21	26	27	33
b.2	provide more opportunities for international cooperation	33	33	32	31	32
b.3	extend the infrastructure and experience for global enterprises	14	13	12	12	12
b.4	provide a peaceful outlet for national, competitive high technology urges and a useful employment of existing industrial-military capabilities	23	22	22	23	25
b.5	enhance the national pride and prestige of participating nations	5	21	26	30	39
C	**SCIENTIFIC OBJECTIVES**	**177**	**263**	**241**	**237**	**267**
c.1	improve the understanding and control of our own planet	0	0	2	10	20
c.2	improve our knowledge of the Moon and its resources	17	30	37	48	56
c.3	improve our understanding of the solar system beyond the Earth-Moon double planet	49	91	79	67	72
c.4	improve our understanding of the universe beyond our own Solar System	37	59	49	42	42
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	74	83	74	70	77
D	**UTILITARIAN OBJECTIVES**	**-163**	**-54**	**0**	**72**	**105**
d.1	provide rewarding job opportunities and thus stimulate the economy on Earth in general	9	9	8	9	10
d.2	stimulate the development of the educational system and advanced technology on Earth	15	17	15	17	20

d.3	produce marketable products for extraterrestrial and for terrestrial use	0	0	0	1	2
d.4	contribute to the supply of space based energy to the the Earth	1	1	1	1	1
d.5	provide an isolated extraterrestrial depository to store high level wastes	0	0	0	1	1
d.6	enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources	-192	-98	-47	11	28
d.7	provide thrust and focus for continued development of space technology other than in the area of space transportation systems	4	17	23	32	43
	total benefits expected	**95**	**390**	**453**	**562**	**658**
	percent of maximum defined	**7**	**28**	**33**	**40**	**47**

With these preliminary values, it is now possible to compare the primary characteristics of all five MARS options analysed, including their expected benefits and cost. They are summarized in the following table and diagram.

Table 5-15: Overview of Mars Program Options(27)

Option	**1**	**2**	**3**	**4**	**5**
Mars facility:	**single expedtion**	**multiple expedition**	**Mars outpost**	**Mars laboratory**	**Mars base**
program duration (years)	11/14	15	22	37	35
operational period(years)	4/7	8	15	30	25
total labor years on Mars	**7(14)**	**20(30)**	**124**	**423**	**1,008**
total mass imported (mt)	250	462	733	2,058	3,750
tot.production on Mars (mt)	0	120	600	2,500	5,000
max.no. of crew members	6	6	12	48	100
no. of passenger roundtrips	6	18	36	120/78	192/88
av.space duty cycle of crews	3 years	3 years	5 years	5 years	10 years
reserve transp. capacity (%)	50	33	10	5	15
cost of Mars GSE & supplies	10.800	14.755	21.930	31.830	43.100
cost of space transportation	33.922	41.825	47.131	59.621	66.543
total program cost (B$)	**44.722**	**57.080**	**69.161**	**91.451**	**109.643**
cost per Mars labor-year (M$)	**6 390**	**2 854**	**558**	**216**	**109**
average annual program cost /calender year over life-cycle	**3.195**	**3.805**	**3.144**	**2.472**	**3.133**
total benefits expected	95	390	453	562	658
benefit/ average annual cost	30	103	144	228	210

The trend of systems effectiveness comes out more clearly in the following graph:

Figure 5-2: Trend of specific cost per 365 day labor-year on Mars as a function of life-cycle labor years

One of these options has been selected as a typical model for a more detailed presentation. This is option 3, because it is a middle of the road program and appears technically feasible and financially affordable(27,28).

5.5 A representative Mars Program: Mars Outpost (Option 3)

This option envisions a crew of 6 to 12 people on Mars, using 7 launch windows during 15 operational (Earth) years, in a similar operational mode as option 2, but with overlapping duty cycles. This requires an average mission time for the crews of 5 years instead of 3 years. In contrast to option 2, this mission mode allows permanent use of the infrastructure on the Mars surface, omitting the need of mothballing the facilities and equipment for several months. This concept will increase the number of Mars labor-years from 20 (option 2) to 124.

Table 5-16 : Definition of subsystems required for program option 3

Mars surface infrastructure:	**mission profile:**	**vehicle design:**	**crew system:**
habitat nuclear and solar power plants rovers propellant production plants	no Earth orbit assembly, direct LEO departure, crew fast,cargo slow trajectories, aero-capture to elliptic Mars orbit and slow descent, ascent, depart from low Mars orbit, direct entry into Earth atmosphere	Lox/LH2 booster stage, Mars propellants for ascent vehicle , Lox-CH_4 Earth propellants for Mars orbit departure, expendable ascent & return vehicles,	6-per vehicle, 2 crew vehicles per mission ,partial gravity on E-M transfer after mid-course maneuver, on Mars surface 6 - 12,

Table 5-17: Summary of program attributes and parameters of program option 3

program attributes and parameters
1. No assembly of space vehicles in Earth departure orbit

2. Earth departure orbit from LEO , crew on fast-, cargo on slow trajectories
3. E-M-E passenger ferry vehicle :expendable
4. Number of vehicles during a specific launch window : 3
5. Crew size per vehicle during transfer :
   2 x 6 one first crew flight, than 6 per launch window
6. Propellant type for Earth departure stage : LH2/LOX
7. Propellant source for TMI stage: Earth only
8. Propellant source for Mars ascent vehicle: CH_4-LOX Earth- & Mars produced
9. Type of Mars ascent vehicle for crew : expendable
10. Propellant of Mars orbit departure vehicle (CH_4-LOX Earth)
11. Earth capture by direct entry
12. Gravity during transfer : E-M after midcourse maneuver 0.3 g, none on return
13. Mars power plant type: solar & nuclear
14. Maximum crew size on Mars surface during life-cycle : 12
15. Duration of life-cycle (years): 7 + 15 = 22

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

Table 5-18 : Estimates of logistic requirements for Mars infrastructure for option 3

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

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

Table 5-19: Estimates of operational requirements for option 3

Equipment inventory and operational requirements:	ref mass (mt)	ref. vol (m^3)	dev. cost (M$)	unit prod cost (M$)	no. units	total mass (mt)	tot. oper. cost (M$)
crew training and salaries	0	0	10	15	20yr	0	310
science support	0	0	100	100	20yr	0	2,100
systems engng. & management	0	0	0	120	22yr	0	2,640
consumables (food etc.)	10	20	10	20	6	120	130
clothes, hygenic materials	4	10	10	10	6	48	70
spares	4	20	50	50	6	24	350
hydrogen feedstock	5	30	0	5	6	30	30
Mars ascent vehicle partly fueled	12	300	0	0	6	72	0
totals	45	380	480	-	-	**294**	**5,630**

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

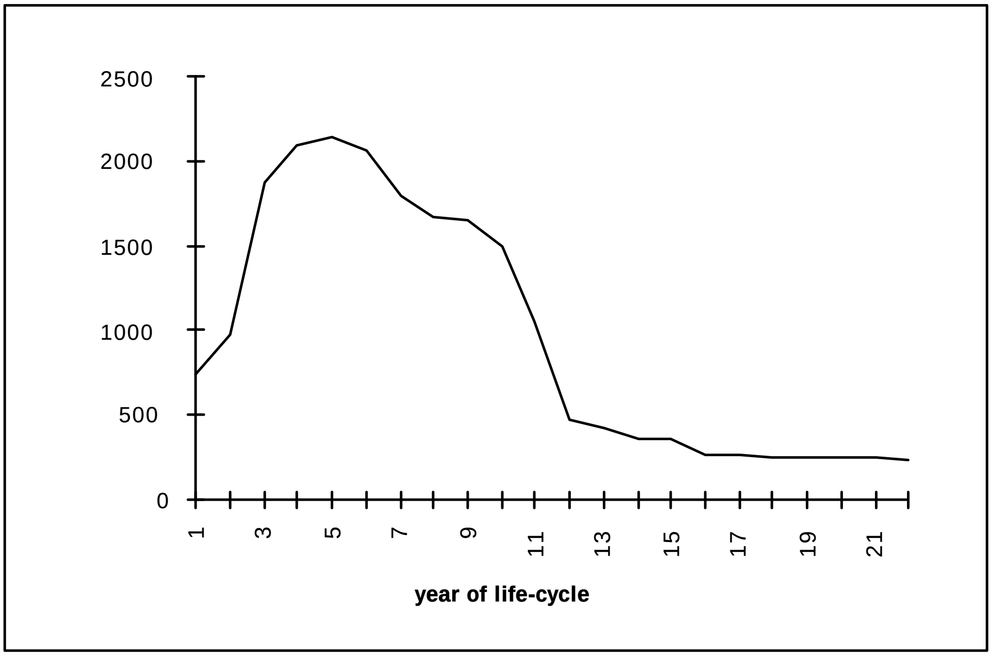


Figure 5-3: Estimated distribution of budget requirements for the Mars infrastructure of option 3

The following space vehicles comprise the space transportation system supporting this program option logistically(14,15)

Table 5-20: Mass model and cost estimates for the space transportation system

	ELV+ TMI §	ERV	MLV	MAV #	CM *)	total
LC no.scheduled launches	15	6	15	6	6+6	-
back-up launches	3	1	3	1	1+1	-
launch mass (mt)	6,000	120	110	30.5	36 + 6	-

dry mass (mt)	752	6.5	6.5	6.2	30 + 6	-
propellant mass(mt)	5,174	63	22	24	0	-
payload mass(mt)	110	30+6	89	3.0	0	-
development cost(M$)	**16,430**	**1,302**	**1,895**	**2,222**	**5,285**	**27,134**
1st unit production (M$)	2,872	163	131	250	696	-
total production cost(M$)	**9,155**	**1,036**	**2,140**	**1,692**	**3,708**	**17,831**
operating cost (M$)	**1,999**	**91**	**261**	**85**	0	**2,166**
total cost logistics(M$)	**27,585**	**2,430**	**4,296**	**3,999**	**8,993**	**47,131**
total cost per flight (M$)	1,839	405	286	667	1,499	-
direct cost for reuses (M$)	281	179	139	219	720	-

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

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

Total programme manifest:

Payload capacity of 18 scheduled launch vehicles planned:

6 crew vehicles x 65 mt		390	
1 back-up to Mars orbit for return vehicle		(110)	
6 Earth return vehicles to Mars orbit		(660)	
5 cargo vehicles x 89 mt (max)	445		
total Mars surface (mt)			835

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

Cost Summary of program option :

Space transportation system	47,131 M $
Mars infrastructure acquisition and operation	21,930 M $
Total program cost	**69,161 M $**

Average annual cost during 22 year life-cycle	**3,144 M $**
Program effectiveness @ 124 person-years (M$/person-year)	**558 M $**

The total annual budget requirements are presented in the next graph. It reflects the mission departure years which happen every two years during the respective launch window. The peaks showing up in this plot are also due to the assumption that the cost of a newly purchased vehicle is paid fully in the year of delivery. This is a simplified assumption because in reality these cost are spread over three years. Thus it is possible to smooth this curve considerably.

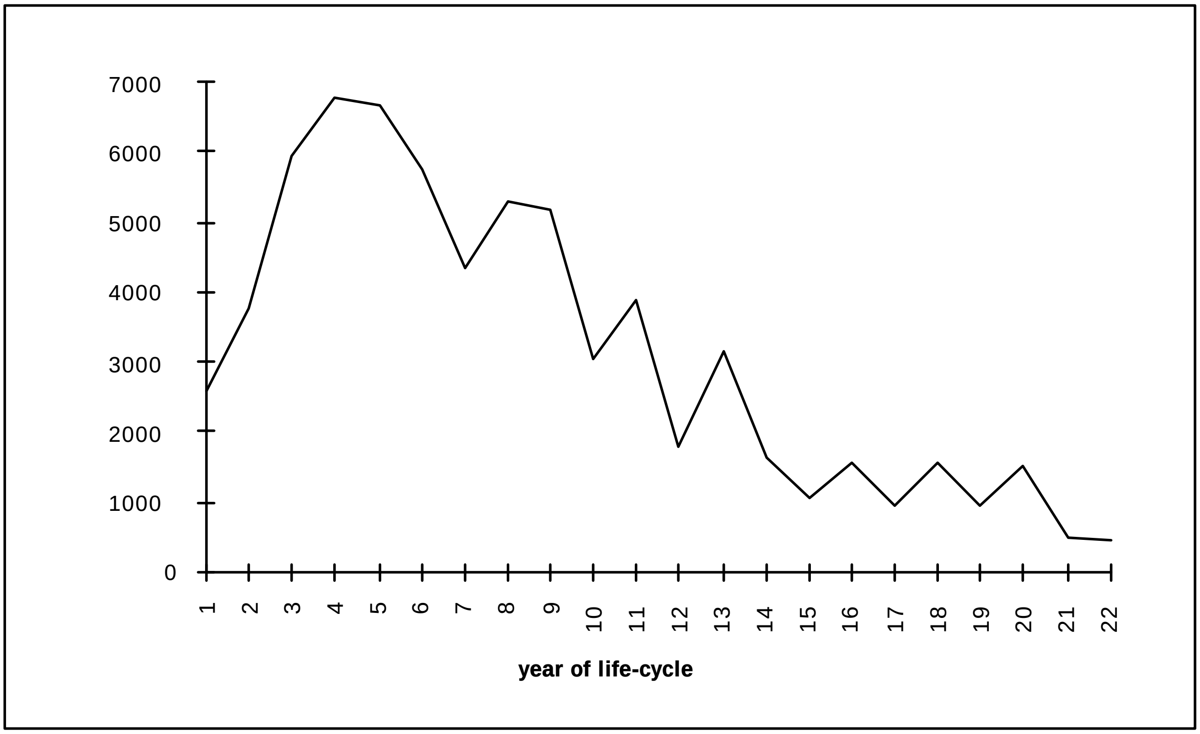


Figure 5 - 4: Estimated annual total cost of option 3 versus program life-cycle

Additional refinements of the proposed concepts and improved tools for program analysis are essential before final conclusions can be drawn. The aspect of when such a program is to be launched and executed is very influential. As far as the timing of a human Mars program is concerned, this is presently a wide open question. The key is funding and the level of risk considered to be acceptable. But there is an estimate on possible and likely milestones available, obtained by a group judgment of 18 people made in December 1997.

Table 5-21: Estimated range of milestones on future Mars exploration

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

the earliest possible year	the **most likely** year
2001 2005 2010	2006 **2010** 2020

2. Assuming that the event listed under 4. above is producing the desired results and the interested governments come to an agreement to proceed with crewed Mars exploration **the first allocation of funds to** enable the beginning of the development of long lead time items could be available by :

the earliest possible year	the **most likely** year
2004 2006 2012	2010 **2012** 2022

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

the earliest possible year	the **most likely** year
2013 2017 2025	2018 **2025** 2032

The Exploration of MARS: Summary

Detailed models have simulated five exclusive programmes of Martian exploration. The resulting analysis led to a year by year evaluation of the most important programme parameters and a demonstration of the system behaviour as a whole(27,28).

Possible missions were entered into five classes, and a representative mission, the Martian Outpost was selected for the purpose of illustrating trends to be expected. This example of a Mars mission architecture was then analyzed in greater detail to yield estimates of the associated costs and returns. Typically the programme would be approved in 2010, with a representative six year development stage from 2011 to 2017, and the first mission to Mars scheduled for 2018. During the following 25 years the outpost would be supplied by flights during all 12 available launch windows. The first crew of a Martian scientific outpost would have 12 members, of whom 6 would be the permanent.

Properly planned and managed the establishment and operation of this modest Martian outpost would cost about 70 billion $ (1999) U.S. spread over 32 years. The maximum annual cost of about 7 billion $ would occur just before the first mission to Mars. This is equivalent to one percent of current global military spending. The average annual cost over a programme life of 40 years would be less than 3 billion dollars, or about one percent of the present United States military budget. Clearly, given the political will a crewed programme to explore Mars is both affordable and technically feasible.

The present study has led to the following conclusions:

1. There in no quick, crude and cheap way to conduct a worthwhile exploration of the planet Mars without unacceptable risks or violating the objectives of the long range space exploration programme.

2. It is possible to plan for a mission using current and readily developed technology that would send a small crew to Mars and establish a semi permanent outpost. Such a mission, however, would have very limited scientific returns.

3. A programme to explore Mars would have to justify a front end investment of up to 7 billion (1999) dollars per annum over a 10 year period. This would have to be the result of a joint commitment by the governments of several space faring nations to invest in the exploration and development of extraterrestrial resources for present and future well being of the global population.

4. If the non-recurrent costs could be shared with other large space enterprises, such as a lunar base or the installation of solar power satellites, the burden on the Mars programme could be substantially reduced. Pooling experience between programmes would reduce the risks for all.

6. Integrated Programmes of Moon-Mars Exploration and Development

6.1. Commonalities of Moon and Mars installations

6.1.1 Functions

A serious effort to integrate the development and operation of installations on two extraterrestrial bodies must first identify the needs and purposes of those installations. Their two separate manifests must include demands for human labour, equipment, power and consumables and miscellaneous facilities. Each installation will be designed for a specific purpose that will, in turn, determine the overall programme profile. The progress of a joint effort will be controlled by a wide range of influences. The most significant influences have been identified and their relative importance is listed in the overview tables. Despite their strong similarities there will always be significant differences between a Lunar base and Martian exploration, in particular, there will be early opportunities for commercial development on the Moon, but not Mars.

Table 6-1 : Extraterrestrial bases: General functions
(* unlikely to apply to Martian installations)

A. Science and technology:

S01: Operation of research laboratories and observatories
S02: Operation of mobile research equipment
S03: Operation of component, subsystem and system test facilities

B. Production of raw materials:

P01: Mining of minerals
P02: Beneficiation of soil and minerals
P03: Production of gases, raw materials and feedstock
P04: Production of metallic raw-products
P05: Production of non-metallic raw-products

C. Manufacturing of end-products and services:

M01: Manufacturing of structural components for local use
M02: Production of foodstuff for local use
M03: Manufacturing of other products for local use
M04: Production of propellants
M05: Assembly of parts and subsystems for local use
M06: Manufacturing products for export (*)
M07: Assembly of products for export (*)
M08: Services produced for external customers (*)
M09: Energy for export (*)
M10: Operating facilities for tourism (*)

D. Direct support operations:

DS01: Supervision and control of equipment and processes,
DS02: Internal and external communication services, data management
DS03: Electric and thermal power supply for internal users
DS04: Housing of local personnel

DS05: Life support for local personnel
DS06: Health and recreation services for local personnel
DS07: Services for the space transportation system at the local spaceport
DS08: Personnel transportation on surface
DS09: Material transportation on surface
DS10: Construction and extension of facilities
DS11: Maintenance and repair of facilities and equipment
DS12: Collecting and recycling of waste and scrap
DS13: Storage
DS14: In-situ training and specific education (*)

6.1.2 Facilities and equipment

It seems unlikely that all these activities could be fulfilled in an alien environment by an initial crew of only 6 or 8. Many planned Lunar or Martian missions assume that a small crew size will minimise costs. This would be true, but the corresponding returns would be small. The labour of the on-site crew could be supplemented on the Moon by teleoperated robot drones controlled from the Earth. The communication delays would prevent this from happening on Mars, however by the time a crewed mission arrives on Mars pseudo intelligent semi-autonomous robots may be available to assist the explorers. In practice an extraterrestrial base with a life span of years or decades would probably need a multidisciplinary crew of about fifty that would be replaced every few months (Moon) or years (Mars).

Table 6-2 : Infrastructure facilities and equipment with particular consideration of their relevance for lunar and Mars bases (xxx= high relevance, ... x = modest relevance)

System Element	Relevance for Lunar Base	Relevance for Mars Base
Research laboratories, observatories and related equipment	XXX	XX
Habitats (living quarters, sleeping areas, food preparation, eating areas, laundry facilities, recreation facilities, hospital, space suits)	XXX	XXX
Control Center (communication, data storage & processing, software)	XXX	XXX
Maintenance and repair facilities (workshops, tools, equipment)	XXX	XXX
Storage facilities (spares, waste, import products, export products)	XXX	XXX
Power plants (power conversion,- storage & distribution equip.)	XXX	XXX
Carpool (garage, surface vehicles, loaders, haulers, roads etc.)	XXX	XX
Spaceport (launch and landing facilities, propellant storage, servicing equipment, lifting devices for unloading , etc.)	XXX	XX

Table 6-3: Production facilities & equipment with particular consideration of their relevance for lunar and Mars bases -(xxx= high relevance, ... x = modest relevance)

System Element	Relevance for Lunar Base	Relevance for Mars Base
Mining facilities & equipment(movers, drills, beneficiation equip.)	XXX	X
Chemical processing facilities (for gases, liquids, prop. and solids)	XXX	XX
Mechanical processing facilities(furnaces, mills, machine tools)	XXX	X
Fabrication facilities (for solar cells, cable trees, radiators etc.)	XXX	X
Biological production facilities (for vegetables, meat, water, air)	XX	XXX
Assembly facilities and equipment (tools, jigs, shops).	XXX	X

6.1.3 The Scientific Objectives of an Integrated Programme

A similar range of science related activities will dominate the early exploration of both the Moon and Mars, and many interesting research fields are involved, however, they will not all be afforded a high priority, either by the research community, or the public at large. Clearly the number of projects and the intensity of the research effort will vary to suit the available research facilities. A successful programme of lunar or Martian research will have to be carefully planned if it is to use those facilities effectively and economically, and yet be able to respond to the unexpected.

The demand for research time on an extraterrestrial base will be very high, and the competition for access fierce. If an experiment is to be participate it will have to be justified in detail. The results of the work carried out during the past few decades will act as the foundation of the studies performed at an extraterrestrial base. Mission planners will have continuously to review the latest results when allocating scarce resources to the most promising areas of research. The next table presents the results of an expert group judgement that listed the current relative importance of various field of research.

Table 6-4: Comparison of scientific activities on Moon and Mars
Scale used: very important = 3 ; important = 2, desirable = 1

RESEARCH FLIELDS OF LUNAR AND PLANETARY SCIENCE:	**of, from and on the Moon**	**of, from and on Mars**
1. Global mapping from orbit	**2.64**	**2.64**
2. Geological transverses	1.92	**2.38**
3. Search for mineral occurrences	**2.86**	**2.14**
4. Passive data collection, search for geologic activities	1.31	**2.15**
5. Astronomical interferometry	**2.25**	0.91
6. Radio Astronomy	**2.36**	0.91
7. Neutrino Astronomy	**2.00**	1.00
8. Plasma and field observatory	1.77	1.18
9. Optical Astronomy	**2.36**	1.00
10.High-energy astrophysical observations	**2.67**	0.91
11.Particle Physics	**2.00**	0.89
12.Sociology & psychology experiments and studies	**2.00**	**2.00**
13.Health & medicine, human functions and performance	**2.54**	**2.08**
14.Exobiology experiments	1.67	**2.38**
15.Biological experiments	**2.00**	**2.14**
16.Material science	**2.31**	1.27
17.Applied technology	**2.50**	**2.00**
18.Pilot production facilities and processes	**2.93**	**2.50**

6.1.4 System Performance

The parameters and state variables listed below were weighted according to their influence on overall system costs, and then used to measure and compare the performance of the various facilities and installations.

Table 6-5 : Performance characteristics of typical extraterrestrial installations
(e.g. specific cost of labor, specific cost of products)
Legend: very great importance = xxx; great importance =xx; modest importance =x

system parameters:	Moon	Mars
1. number of people required locally for R & D and external services	xxx	xx
2. number of people required for production	xxx	x
3. number of people required for housekeeping, maintenence and repair of existing facilities	xxx	xx
4. number of people required for facility extensions	xxx	x
5. average duty cycle of crew members (months)	xx	xxx
6. mass of locally produced propellants (t/p.a.)	xxx	x
7. mass of other products p.a. for local use (t/p.a.)	xx	x
8. mass of other products for export (t/p.a.)	xxx	-
9. mass of local facilities and equipment (t)	xxx	xx
10. mass of imports required (t/p.a.)	xxx	xxx
11. duration of acquisition period (years)	xx	xxx
12. duration of operational period (years)	xx	xxx
13. specific development cost of local facilities and equipment	xx	xx
14. specific production cost of local facilities and equipment	xx	xx
15. specific assembly cost of lunar facilities and equipment	xx	xxx
16. financing cost -if any	xxx	xxx
17. insurance cost - if any	xx	xxx

6.1.5 Technology

An extraterrestrial base will need facilities, equipment and vehicles. Before a programme to establish such a base begins, mission planners will have to review current space technology and identify those areas which will need further development. The first attempt to assess contemporary space technology in this way was a group judgement conducted in March 1998. The judges ranked the relevant technologies on a scale of 1 to 4 (most development needed). They then estimated to a rough order of magnitude (ROM) the number of person-years needed to develop a space qualified product.

Table 6-6: Assessment of technologies required

1 = slight advances
2 = considerable advances
3 = major advances
4 = entirely new development
MY = labor-years required, rough order of magnitude (ROM)

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 for transfer and propulsion	3.20	3.40	450
vehicle and 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
remote exploration from secure positions	1.40	2.20	400
ruggedness of reusable space subsystems	2.25	2.50	200
solar heated propulsion systems	2.00	2.38	290
space assembly procedures and equipment	1.78	2.44	250
highly autonomous space systems	1.90	2.60	500
crew health support equipment	1.50	2.38	20
high data rate communication systems	1.30	1.90	200
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
high energy storage devices	2.44	2.44	225
high temperature materials	1.50	1.78	180
system control & management	1.25	1.50	150
data processing and valuation	1.30	1.60	150
mineral analysis	1.10	1.44	20
beneficiation equipment	2.13	2.25	50
low maintenance systems	2.00	2.50	220
portable life support systems	2.00	2.40	180
robotic construction equipment	2.45	2.73	320
superinsulation	1.57	1.71	40

6.2 Logistic Overlap

6.2.1 Selecting a transportation system

An extraterrestrial base will depend on a reliable, economical space transporta-tion system (STS). This will have to be carefully chosen from several competing concepts. The selection criteria must not be too restrictive in case they exclude an unconventional, but promising design. The following list was developed by the IAA Lunar Development Subcommittee in 1993, and should be used to compare possible lunar transportation systems. (16,22)

Table 6-7: Space Transportation Systems: Performance

01. Probability of mission success.
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 lifespan.
03. Scheduling confidence.
The confidence of the investors, developers and the potential customers that the target dates for the initial operational readiness and planned annual flight rates will be achieved.
04. Single flight payload capability.
Size (mass, volume and dimensions) of the payloads a single flight of the lunar space transportation system can load, ship and unload under optimum conditions to various destinations when carrying cargo or passengers.
05. Annual payload capacity.

The cumulative payload capability per year ("transportation volume") of the individual space transportation system allowing for growth from the initial annual capability during the entire lifespan, as an indicator for "overall systems performance".

06. Operational flexibility (resiliency).

The space transportation system's capacity to respond rapidly to unexpected mission, payload and organizational changes, technical and funding problems or serious accidents.

07. System compatibility.

The compatibility of the elements of the lunar passenger and cargo transportation systems with other existing or planned near Earth or interplanetary transporta-tion systems.

08. Development risk.

The relative maturity of the technologies employed in the selected elements of the lunar transportation system, reflected as confidence in the 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 operational 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 transporta-tion system, the peak of the annual funding requirements, and the lifespan, average, annual funding requirements, determine the relative acceptance by investors.

11. System life expectancy.

Includes the length of the acquisition cycle, and emphasizes the expected availability and utility of the space transportation system, over the operational life time, yielding the expected "return-on-the-investment" .

12. Environmental and social acceptability.

This criteria covers all other factors affecting the operation of the individual space transportation systems. Environmental considerations are particularly important but includes other social considerations of interest to the relevant groups within the national and international bodies participating in this selection process.

The selection criteria governing the choice of future space transportation systems were examined twice during 1993. The final ranked list placed them in the following descending order of importance,(16,22) and may be used to select the best suited to support an integrated programme of Lunar and Martian Exploration.

Table 6-8 : 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. System compatibility	4.1
Total	100.0%

6.2.2 State-of-the-art of space transportation systems

A space transportation system for missions to the Moon and Mars will be assembled from the best available or projected technologies. The following guidelines may govern the choice of technologies, which are based on current experience and on projections into the first half of the 21st century.

01. People and cargo were reliably and safely transported by rocket to the Moon between 1968 and 1972 during the APOLLO programme. (However, one should not overlook the fact that each APOLLO mission was scrupulously prepared and strenuously checked, and hence costs were so high that routine flights would have been rendered impracticable).

02. The present U.S. space shuttle was not designed for and is not suitable to support missions to the Moon or Mars, and will probably have been phased out of service before the next wave of human space exploration begins. Consequently, although some of its subsystems may incorporated in a future space transportation system, the space shuttle as a whole is unlikely form a part of that system.

03. The International Space Station (ISS) is currently under construction and will become operational in low Earth Orbit early in the 21st century. It will be a research station and could not act as a transportation node for the lunar and planetary STS. It could, however, provide facilities for crew training and space- rating components.

04. One or more Space Operations Centres(SOC's) will be probably required in low Earth orbit (LEO) and/or lunar orbit (LUO). They will act as the transportation nodes of the lunar STS where lunar ferries can be loaded, refuelled, and maintained.

05. PROGRESS automatic supply vessels have regularly docked with the MIR space station in low Earth Orbit, and space operations centres could also be replenished by robotic freighters.

06. Chemically fuelled rockets are a proven and practical means of space propulsion, and will certainly continue to be used during the first half of the 21st century, perhaps using liquid oxygen manufactured on the Moon. High efficiency, low thrust engines such as ion or solar thermal thrusters may be used to propel automatic interplanetary probes or cargo vessels, and deep space probes may eventually unfurl solar sails to harness the pressure of light from the Sun.

07. Liquid oxygen/liquid hydrogen engines, that are, when possible, derived from existing propulsion systems are to be preferred for transporting crews.

08. The overall efficiency of the transportation system would be greatly improved if liquid rocket propellant could be manufactured on the Moon or Mars, and thus production should begin as soon as it is economically justified.

09. Automatic probes have landed softly and at precise locations on the Moon and Mars on many occasions. The technology required is well tested and readily available. If a crewed vessel experienced difficulties during decent to the Moon or Mars, the captain could override the automatic pilot.

10. Advanced tele-manipulators will be fitted with space based, very high capacity data communications systems and deployed as Tele-explorers and Tele-operators on the Moon and in space.

Despite being designed to support differing missions, at different times and locations, the lunar, Martian and deep space transportation systems will have many inherent similarities. The importance attached to a particular aspect of performance will vary, and the following table lists the major parameters affecting the cost of transporting passengers and cargo to the Moon and Mars.

Table 6-9: Lunar and Interplanetary transportation systems: Performance parameters

LEGEND: The relative importance of the parameters listed is indicated by:

very great importance = xxx; great importance = xx; modest importance = x

system parameters:	Moon	Mars
number of different space transportation systems employed in support of the extraterrestrial base during its total life-cycle	XX	XX
single flight payload capability -cargo and / or passengers	XX	XXX
annual launch rate of transportation system and mission share	XXX	XX
acquisition cost of space transportation systems employed	XX	XXX
share of the amortization burden of the mission specific logistic system	X	XX
annual production cost of vehicle subsystems	XXX	XX
annual operation cost of space transportation system	XXX	XXX

In most cases the differences are not large, but they will have to be considered when designing a common or modular transportation system, and some design compromises are inevitable.

6.2.3 Candidate space transportation systems

Current launchers could not support the human exploration of the Moon or Mars. The following launchers could be built using existing technology:

1. Expendable launch vehicles, for example a modernised SATURN V or ENERGIA with an Earth to Orbit (ETO) payload of 100 metric tonnes.
2. Expendable heavy lift launch vehicles derived from the SATURN V or Shuttle systems with an ETO payload of 200 metric tonnes.
3. A reusable single stage ballistic vehicle with ETO payloads of up to 20 metric tonnes.
4. Reusable Shuttle derived medium launch vehicle with an ETO payload of about 100 metric tonnes.
5. Reusable heavy lift launch vehicle of the Post-SATURN class with an ETO payload of 300 to 350 metric tonnes.

Table 6-10 presents the major characteristics of these vehicles.
Legend: Groeth ratio = Launch mass / payload mass

vehicle type	1.	2.	3.	4.	5.
Number of stages to LEO	2	2	1	2	2
Launch mass (mt)	2,837	4,000	800	1,940	6,000
Payload mass to LEO (mt)	137	200	20	112	350
Growth ratio	20.7	20.0	40	17.3	17.1
Development cost (B $)	8.260	10.500	9.538	11.059	19.635
First unit cost (B $)	1.859	2.500	576	1.302	3.445
Reference	(23)		(23)	(22)	(22)

The first two types of vehicle will result in roughly the same overall costs, since the advantages of scale are balanced by lower production numbers and hence higher unit fixed costs. Thus, the larger expendable vehicle(2.) will not be considered further.

The following data represent the total lifespan cumulative payload volume per 1000 metric tonnes and the equivalent cost per flight in million $ per flight or specific cost in $/kg.

Table 6-11: Total cost per flight versus life-cycle cumulative cargo
cumulative payload in terms of 1,000 mt = M $/flight

vehicle 1.	3.	4.	5.
17,100 mt = 1,042 M $ per flight	6 = 68	56= 87	33=380
34.2 = 905	18 = 29	168= 49	66=214
68.5 = 819	60 = 14	338= 39	132=139
137 = 773	180 = 8.6	672= 33	264=117

Table 6-12: Total specific transport cost (i.e. arrival cost) to a 400 km Earth orbit as a function of lifespan cargo delivered.
cumulative payload in terms of 1,000 mt = ($/kg)

1./2.	3.	4.	5.
@ 17,100 mt= 7,610 $/kg	6 = 3,420	56 = 776	33 =1,150
34.2 =6,610	18 = 1,440	168 = 435	66 = 650
68.5 =5,980	60 = 680	336 = 351	132 = 420
137 =5,640	180 = 430	672 = 296	264 = 340

A double logarithmic graph shows the variation in specific delivery costs to low Earth orbit for the expendable and reusable launch vehicles. This clearly shows that expendable vehicles are not economically viable when called upon to supply cumulative transport loads of more than 4,000 metric tonnes. Launch site assembly and fuelling will further add to their cost.

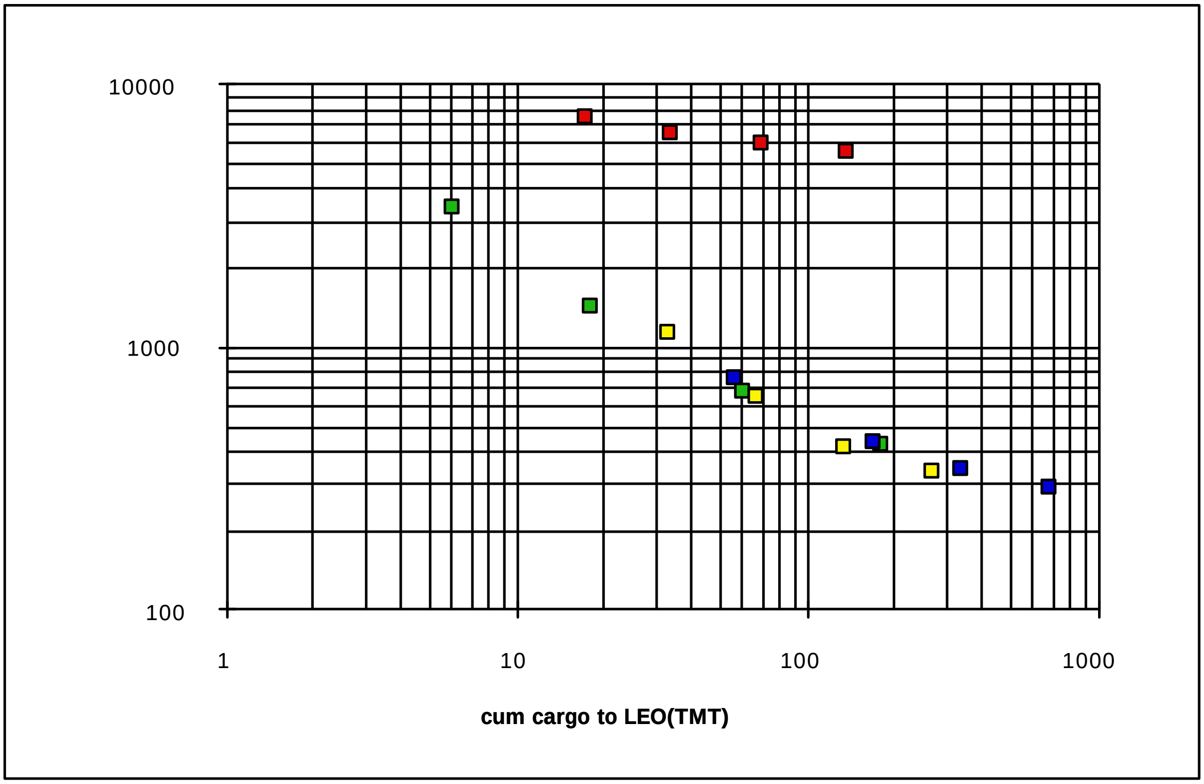


Figure 6-1: Specific delivery cost to Low Earth Orbit as a function of transported load for Expendable and reusable vehicles. (upper curve = Expendable vehicles) (TMT = thousand metric tonnes)

Note: This shows delivery costs to low Earth orbit, NOT departure costs. Vessels using non-direct trajectories will have to be assembled, fuelled and checked out in LEO before proceeding to the Moon or Mars. Some of the cryogenic fuels evaporate while the vessel remains in the parking orbit, and the crew will have to be supplied and housed. Missions supported by launch vehicles with small payloads, for example the 20 metric tonne payload of an SSTO vehicle, will have extended orbital stays, and a prolonged stay in low Earth orbit will add considerably to the overall cost of the mission. Alternatively, there would be virtually no additional costs if the entire interplanetary vessel can be carried into orbit by a single launch vehicle, such as a heavy lift launch vehicle with a 350 metric tonne payload.

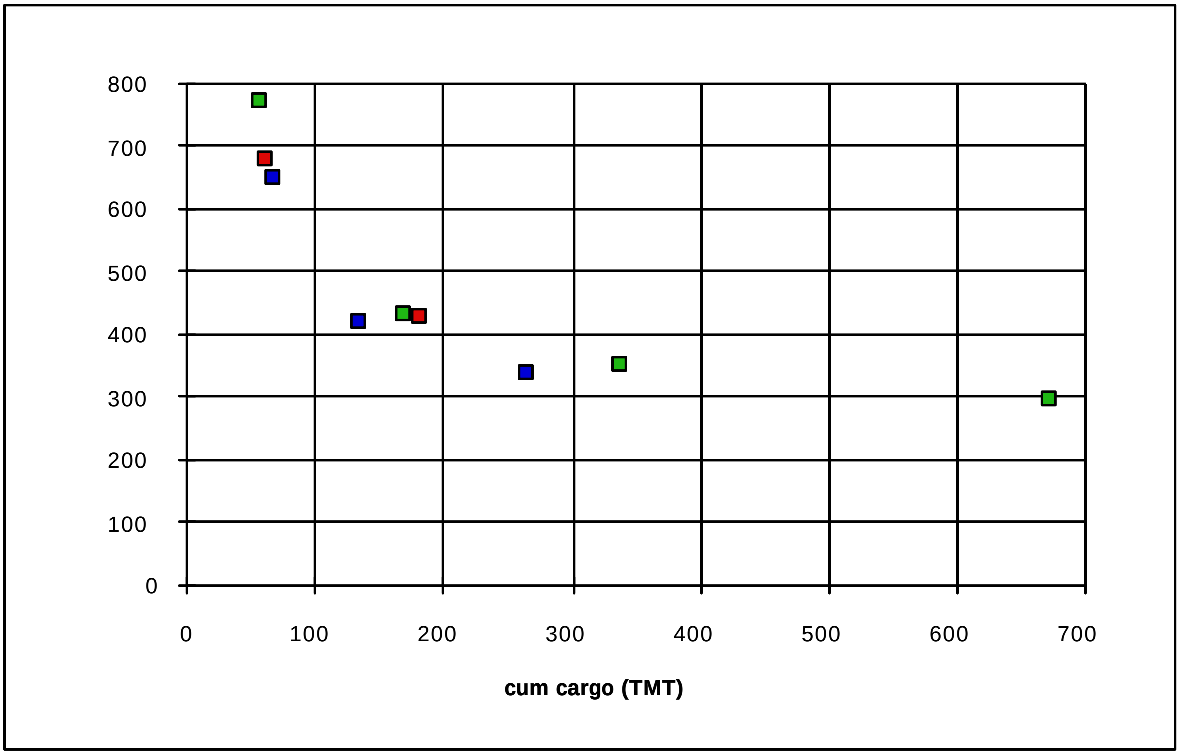


Figure 6-2: Specific deliver cost to low Earth orbit of expendable and reusable launch vehicles as a function of the lifespan cumulative transportation volume (higher end, linear scale)

Overall mission costs are often erroneously based on the delivery cost into low Earth orbit. The cost of an interplanetary mission must be estimated from the total cost of delivering cargo to the destination. The most powerful influence controlling the cost of a crewed mission is the total round trip cost, and the space transportation system must designed to reduce that cost, for passenger transportation dominates the overall mission cost. For each reference mission the specific transportation costs for crew and cargo must be estimated on a case by case basis. To go from low Earth orbit to lunar orbit, or from low Earth orbit into a Martian transfer trajectory requires approximately the same change in velocity, about 4,100 m/s. This requirement can be used to compare the performance of the launch vehicles needed for an integrated Moon-Mars programme. (23)

The demand for space based products and services is dependent on the specific space transportation cost (23). - A larger market will result in a more cost-effective transportation system. However, the specific transportation cost is also related to the vehicle size, and hence vehicle size and market size are interrelated. A limited demand for small payloads and short lifespans tends to favour small expendable launch vehicles. A large market for massive payloads with long lifetimes will need heavy lift launch vehicles with high launch rates.

Declining specific launch costs during the 21st century will eventually lead to a rapidly expanding demand for space based products and services. This market may sustain a fleet of heavy lift launch vehicles that could service high energy missions to geostationary orbit, lunar orbit and even interplanetary voyages.

Consequently the designs of two possible, reusable heavy lift launch vehicles were examined in detail in an attempt to determine the optimum vehicle for a particular market size. One launcher was derived from the Shuttle with a launch mass of about 2,000 metric tonnes, and the other was a sectionalized, modular HLLV based on the NEPTUNE concept, with a launch mass ranging between 3,000 and 6,000 metric tonnes. A joint programme of lunar and Martian exploration would need the equivalent of between 20,000 and 40,000 metric tonnes of cargo on the Moon and Mars, which is about half the total cargo mass that must be delivered to lunar orbit or into Mars transfer trajectory.

Heavy Lift Vehicles will be developed to serve a rapidly expanding market for space based products and services during the first half of the next century, and it is possible to estimate the vehicle mass and type best suited to serve a given size of market. The next table ties the economic performance of a given size of launcher to possible market demand. The two most promising vehicles were selected and their performance plotted as figure 6-3, which shows the economic cross over as vehicle size increases. The change that follows from increasing the cargo mass in lunar orbit from 45,000 to 90,000 metric tonnes is too small to be significant.

This analysis is based on current assumptions and projections about future market trends and improvements in space technology, and hence should be considered as a starting point for further work. The present results are preliminary data. A detailed programme analysis would have to consider the effects of every significant parameter, and in particular, the effort expended during orbital operations, which in turn is dependent on the size and volume of each payload.

Table 6-13: Lunar orbital and Martian transfer cargo delivery: Economic performance

launch mass: LC cumulative cargo:	6,000 mt	4,500 mt	1,940mt
15,000 mt	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

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!

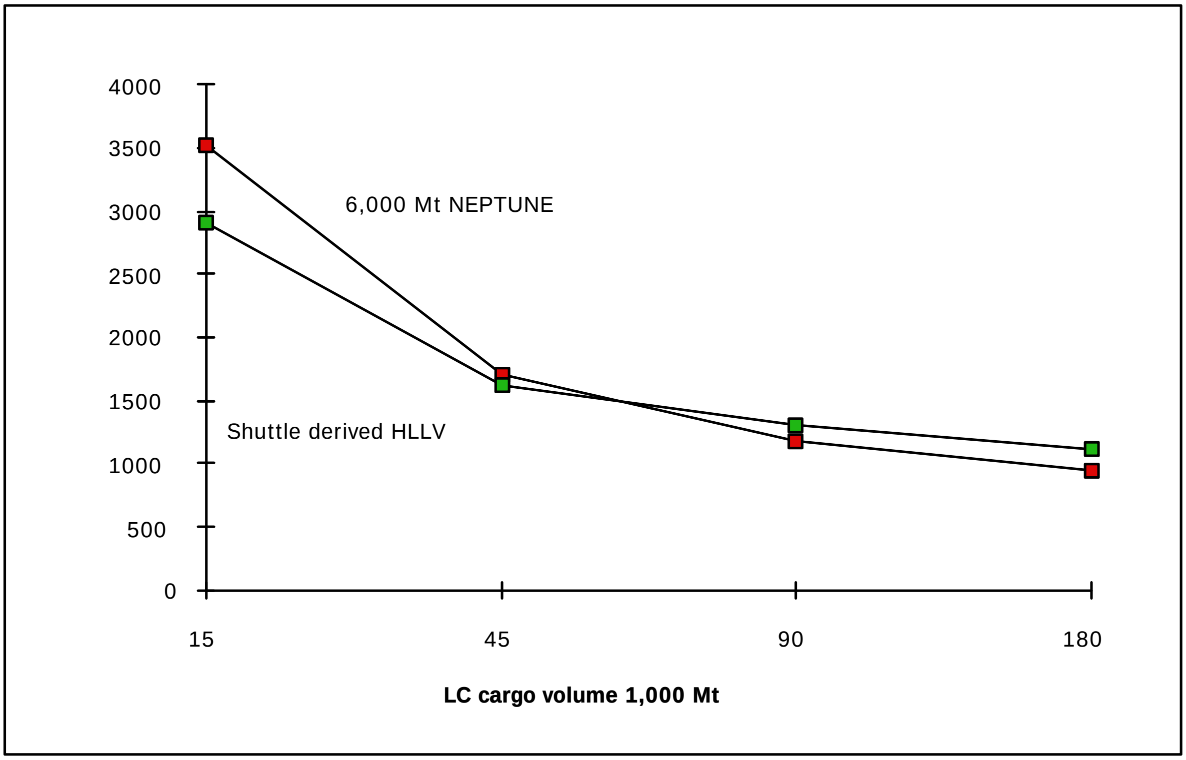


Figure 6-3: Specific Cost comparison for cargo to lunar orbit: Shuttle derived HLLV and modular NEPTUNE HLLV

Note: These costs are 3.5 times the costs of shipping cargo into Low Earth Orbit, and half the cost to ship to the lunar surface.

6.3 Possible integrated Moon-Mars programme options

The immediate problem confronting an international planning effort will be to combine the various, crewed, lunar and Martian programme options to take full advantage of the human presence while striking an optimum balance between cost, benefits and risk. It would, in theory, be possible to select each of these options in isolation, however, advantageous synergies may be possible between the lunar and Martian efforts, even though several of the possible 25 combined programmes are poorly balanced and should be quickly rejected.

An integrated Moon-Mars programme will generate many secondary benefits long before the primary goals of a lunar settlement and a Martian base could be achieved during the second half of the 21st century. But, if these very important secondary benefits are to be forthcoming, any selection process must be preceded by a detailed scrutiny of each lunar or Martian programme option that identifies when and how these benefits may be won. The following two tables list the various options, and some current estimates of possible returns.

Table 6-14: Benefit/cost ratios of the possible combinations of lunar and Mars program alternatives

a. Preliminary estimates using global benefit judgments and total systems cost(26)

benefits per Billion $	temporary lunar outpost	permanent lunar outpost	lunar laboratory	lunar factory	lunar settlement
single Mars expedition	7.3	6.5	**12.3**	7.6	6.9
multiple Mars expeditions	7.8	6.9	**12.2**	9.0	7.1
Mars outpost	10.4	8.7	**13.9**	9.9	7.8
Mars laboratory	10.3	8.8	**13.3**	9.9	7.9
Mars base	11.7	10.0	**14.2**	10.5	8.4

b. Refined analysis using benefit estimating relationships and average annual system cost (28)

benefits per B $	temporary lunar outpost	permanent lunar outpost	lunar laboratory	lunar factory	lunar settlement
single Mars expedition	146	197	202	245	287
multiple Mars expeditions	214	227	230	260	**303**
Mars outpost	212	269	269	287	**339**
Mars laboratory	266	**334**	**329**	**323**	**390**
Mars base	251	**310**	**307**	**310**	**368**

These tables do not, however, as yet, include savings gained by combining the lunar and Martian programmes. At this stage it seems savings of up to 20% could be gained by combining separate programmes of Lunar and Martian exploration in a single integrated programme. It should also be noted that in calculating the values of the last tables, possible commercial sales have not yet been taken into consideration. This would lead to much more favourable benefit/cost ratios of combinations including larger facilities!

The joint planning work is at an early stage and it should be emphasized that the following are only preliminary estimates, and considerable work will be needed before valid conclusions can be drawn.

The combinations that result in the best benefit/cost ratio, (such as a Lunar Base with a Martian Base) can not be recommended as they are the most ambitious options and consequently the most costly, and therefore are unlikely to proceed. Consequently at this, admittedly preliminary, planning stage three combined programmes clearly warrant special consideration and detailed examination for possible synergies.

(1) A lunar laboratory combined with multiple missions to Mars. Compared to combinations that involve a single expedition to Mars, this pairing results in a favourable benefit-cost ratio, along with lower overall costs and risks.

(2) A lunar laboratory combined with a Martian outpost. Of all combinations that result in high benefit/cost ratios this pairing has the lowest absolute cost.

(3) A Lunar base combined with a Martian laboratory. This combination may not be affordable, but would have the highest number of common systems.

Any major programme decision must be justified by the relevant programme performance indicators. These indicators, in turn, can only be derived after the reduction of a considerable volume of detailed data, and what follows is an early attempt to define the essential information that will be needed to support the approval of a joint programme of Lunar and Martian exploration.

6.4 Relevant Information

During the 1920's and 30's the U.S. Corps of Engineers developed the cost/benefit analysis while seeking Congressional funding for their large civil engineering projects. An accurate estimate of programme costs and benefits has to be based on a detailed understanding of a proposed programme's goals and objectives. In other words, any large scale technical programme has to be thoroughly simulated before construction begins. A recent group judgement identified the following as defining overall programme performance:

In descending order of importance:

1. Average annual cost.
2. Base facilities development and production cost.
3. Space transportation system development cost.
4. Total lifespan base facilities operational cost.
5. Total logistic cost during operational lifespan.
6. Total program lifespan cost (sum of 2.+3.+4.+5.).
7. Cost share of locally produced extraterrestrial products for commercial users.
8. Duration of anticipated base lifespan (years).
9. Lifespan base cost excluding logistics (= 2. acquisition + 4. operation) .
10. Total lifespan logistics cost (= 3. +5.).
11. Maximum number of base inhabitants during the lifespan.
12. Total lifespan mass of extraterrestrial products (metric tons).

Only a thorough analysis of these programme parameters would yield the minimum information needed to justify an investment of the size, duration and importance required to sustain a possible joint programme of Lunar and Martian exploration.

6.5 General Selection Criteria

Once the potential investors are satisfied with the compiled information, a programme profile will be selected according to carefully chosen criteria. For example:

a. Relative risks of the undertaking. These will have to be stated explicitly in order to define the probability of the success of the mission.

b. Minimum cost for comparable benefits. For this purpose the programme benefit is tentatively defined as the aggregate of the returned benefits of each sub-programme.

c. Financial regularity.

The programme must have a smooth financial requirement. Changes in programme funding must be gradual and as far as possible reflect a constant share of the participating nations' gross national products.

d. Sunset clauses. All participants must be assured that each programme phase must be completed with expected results within one or two decades, and within a predetermined budget. Each component activity, and the programme as a whole, should be reviewed periodically (e.g. every five years) and resources reallocated according to needs, past performance and the dictates of current political and economic circumstances.

e. Growth Potential.
When circumstances warrant all parts of the programme should be capable of expanding rapidly, but without excessive waste and
duplication.

7. Representative Options of Integrated Moon-Mars Programmes

7.1 Examples of integrated Moon-Mars programmes

A joint programme of crewed Lunar and Martian exploration will present planners with the immediate task of identifying the optimum programme synergies without sacrificing the benefits or increasing the risks. At first sight the two interplanetary programmes appear to overlap beneficially in several areas, namely:

- sharing non-recurrent cost of space transportation system elements,
- sharing non-recurrent cost of base infrastructure subsystems,
- reduction of production cost due to higher production numbers,
- reduction of operating cost due to joint use of ground crew and facilities,
- higher probability of mission success increases mission benefits,
- faster acquisition of new knowledge and cross fertilization of partial programs,
- increasing the stability of both programs,
- greater flexibility in case of unexpected events,
- potential use of lunar propellants for interplanetary ferry vehicles.

It was already pointed out that with five program options each for Lunar Base Programs and Mars Exploration Programs, there are 5 x 5 = 25 combinations possible. A preliminary assessment led to those combinations which are near term candidates and may be analysed with priority. This was discussed already in chapter 6 and a table was presented with the benefit/cost ratios (Table 6-14).

The evaluation of the available data on system performance led to the recommendation to study some examples which illustrate the type of a detailed international analysis to be made such as :

A. the combination of **Lunar Laboratory and Multiple Mars Expeditions,**

B. the combination of the **Lunar Laboratory and the Mars Outpost**,

C. the combination of a **Lunar Laboratory/Base and a Mars Laboratory**.

7.2 Developing a joint infrastructure

The first step in planning a successful programme of Lunar and Martian exploration is to prepare a model of the infrastructure needed to support a lunar laboratory or a Martian outpost. The infrastructure needed to support a Martian outpost will cost about the same as that needed by a series of expeditions to Mars, and so those programmes will considered together. These preliminary estimates are the result of projecting models of current and past experience into the next century, and could be readily improved by further studies.

Table 7-1: Lunar Laboratory - Martian Outpost: Infrastructure

Equipment requirements:	general development 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	500	50	50	600	50
160 kW nuclear power plant	2000	100	300	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, hygienic materials	50	20	20	90	10
spares	10	10	10	30	50
engineering support , upgrading & misc.	1000	250	250	1500	0
TOTAL	8240	2815	1825	**12880**	1670
Lunar share (50%)	4120	2815	0	6935	
Mars share (50%)	4120	0	1825	5945	

Development cost for separate Lunar Laboratory infrastructure 8,400 M$

Development cost for separate Mars Outpost infrastructure 7,140 M$

total 15,540 M$

Development cost of combined Lunar Laboratory and Mars Outpost 12,880 M$

Estimated development cost savings of combined program 2,660 M$

The following table contains a summary of the total expenditures incurred during the complete lifespan of the lunar laboratory and the Martian installations. Savings accruing from integrating the management and administrative services and the joint use of ground facilities, or the engineering and science support teams and their equipment have not been included. Many other savings resulting from a combined programme have certainly not yet been identified.

Table 7-2: Overview of expenditures for the Moon and Mars infrastructure development, production and operation

Lunar and Mars installations cost centers	**A. lunar lab. + multiple Mars expeditions**	**B. lunar laboratory+ Mars outpost**
1. Duration of anticipated base life-cycle (years).	10 + 30/10	10 + 30/15
2. Maximum number of base inhabitants during the life-cycle.	120 + 6	120 + 12
3. Lunar share of base facility & equipment development cost (B $)	6.9	6.9

3.a Mars share of base facility & equipment development cost(B $)	6.0	6.0
4. Lunar Base facilitiy production cost (B $)	2.8	2.8
4a Mars infrastructure production cost (B $)	5.2	8.8
5. Lunar base operation cost (B $)	14.5	14.5
5a. Mars facility life-cycle operation cost (B $)	2.7	6.1
6. Total development cost of Moon & Mars facility & equip. (B $)	12.9	12.9
7. Total production cost of Moon & Mars facility &. equip. (B $)	8.0	11.6
8. Total operating cost of Moon & Mars installations (B $)	17.2	20.6
9. Total cost of base infrastructures acquisition & operation (B $)	**38.1**	**44.9**
10. average annual cost of base infrastructure (B $)	2.94	3.27
11. total number of labor years available on Moon & Mars	2170+20	2170+124
12.Total life-cycle mass of extraterrestrial products for export(mt)	2460+ 2	2460+3

7.3 The integrated space transportation system:

The same launch vehicle will service both the lunar laboratory and the Martian outpost, and the other space vehicles will use closely related propulsion, electrical and propellant handling subsystems. The launch vehicle is the previously described, reusable Heavy Lift Launch Vehicle (HLLV) with a nominal payload delivered into low Earth orbit of 375 metric tonnes. The lunar transportation system includes a space operations centre in lunar orbit and uses liquid oxygen manufactured on the Moon. When the Martian manufacture of propellants, wholly or in part from local resources, becomes feasible, they will be used by the Martian transportation system.

A detailed comparison of the space vehicles that will support options 2 and 3 used a common mass model to identify additional savings. Savings accruing from higher subsystem production rates and hence lower unit prices, common ground support teams and a common base of experience leading to increased mission reliability have not yet been included.

Table 7-3 : Mass models of space vehicles used in an integrated Moon-Mars program

vehicle type: vehicle parameter:	Lunar Bus - down	Lunar Bus - up	Mars cargo lander	Mars crew lander	Mars ascent to HEMO	Mars HEMO departure
exhaust velocity (m/s)	4,500	4,500	3,700	3,700	3,700	3,700
delta v (m/s)	2,000	2,000	700	700	5,400	3,428
mass ratio (-)	1.56	1.56	1.208	1.208	4.55	2.526
initial mass(mt)	170	136	120	90	30.5	120
dry stage(mt)	19	19	6.5	6.5	3.2	5.5
residuals(mt)	1	1	0.5	0.5	0.5	1.5
propellants(mt)	61	49	22	18	23.8	72.5
cut-off mass(mt)	109	87	96	72	6.7	47.5
payload(mt)	82	63	89	65	3	40.5
propellant mass fraction(-)	0.92	0.92	0.77	0.72	0.865	0.930

Table 7-4: Overview of the space transportation system cost

Performance and cost centers	**A. lunar base + multiple Mars expeditions**	**B. lunar laboratory+ Mars outpost**
1. Duration of anticipated base life-cycle (years).	10 + 30 / 10	10 + 30 / 15
2. Development cost of 3 stage Launch vehicle for Lunar orbit or Mars transfer injection (B $)	19.214	19.214
3. Development cost of Lunar bus for Lunar orbit to surface roundtrips using lulox(B $)	1.399	1.399
4. Development cost of HLLV + Lubus crew modules and space operation center in lunar orbit(B $)	7.783	7.783
5. Development cost of space vehicles for Mars mission (B $)	5.385	5.945
6. development cost for crew moduls of Earth return vehicle and reentry capsule(B $)	4838	4838
7. Total space transportation system development cost including product improvement during life-cycle(B $)	**38.6**	**38.9**
8. Production of HLLV incl. exp.third stages for Mars transfer(B $)	17.430	18.980
9. Production of lunar bus(B $)	0.836	0.836
10. Production of crew modules HLLV and Lubus(B $)	2.987	2.987
11. Production of Mars space vehicles(B $)	3.224	4.836
12. Production of Mars crew modules(B $)	2.784	4.176
13. Total production cost of Moon-Mars vehicles(B $)	**27.3**	**31.8**
14. Operation of Earth- lunar transportation system(B $)	11.865	12.160
15. Operation of Earth - Mars transportation system(B $)	0.132	0.217
16. Total operating cost(B $)	**12.0**	**12.3**
17. Total logistic cost during operational life-cycle(B $) (development, production and operation)	**75.9**	**83.0**
18. average annual cost of space transportation system (B $)	1.90	2.08

7.4 Summary and Conclusion

The information required to justify the approval of an integrated programme of lunar and Martian exploration will only become available after a thorough analysis of every aspect of each alternative programme. Examples of the selection criteria that would govern the possible choice of two near term joint programmes are shown below. They constitute a the smallest acceptable foundation for a programme of the size, cost and importance being considered.

Table 7-5: Summary Data of selected integrated Moon-Mars Programs

Initial program options	**A. lunar lab. + multiple Mars expeditions**	**B. lunar laboratory .+ Mars outpost**
1. Duration of anticipated base life-cycle (years).	10 + 30	10 + 30
2. Max. no. of base inhabitants during the lifespan	120 + 6	120 + 12
3. Total cost base infrastructures acquisition & operation (B $)	**38.1**	**44.9**

4. Total logistic cost during operational life-cycle(B $) (development, production and operation)	**75.9**	**83.0**
5. Total Program cumulative cost (B $)	**114**	**128**
6. Average annual cost during 40 year life cycle (B $)	**2.85**	**3.20**
7. total no. of labor years available on Moon & Mars	2,170+20	2,170+124
8. Specific cost per extraterr. labor-year (M $/lab.year)	52	56
9.Total life-cycle mass of extraterrestrial products (mt)	2,460+ 2	2,460+3
10. Total benefits with respect to *Quality of Life*	2,380	2,820
11. Benefit to cost ratio	20.9	22.0

If we put all the available information together including a recently analysed more ambitious program (29) the following trend emerges:

Table 7-6: Comparison of programs analysed

Pro-gram	extraterrestrial facilities	labor-years on Moon	labor-years on Mars	total extra-terrestrial labor years	total cost	cost p.a.	cost p.lab-year
A	lunar laboratory + mult. Mars exped.	2170	20	2190	114	2.85	52
B	lunar laboratory + Mars outpost	2170	124	2294	128	3.20	56
C	lunar base + Mars laboratory	4585	1183	5768	190	3.81	33

CONCLUSION:

The first two more modest examples (A & B) demonstrate how even simple and unoptimized examples illustrate the cost reduction of an integrated Moon-Mars programme. The overall programme cost is considerably lower than the total cost of separate programmes to go to the Moon and Mars. The integrated programmes result in total costs of 114 B$ and 128 B$ (1999), while adding the costs of similar, but separate, programmes yields 150 and 164 B$. The integrated programmes represent savings of 24% and 22% respectively. An integrated programme of Lunar and Martian exploration and development can be expected to yield even greater savings if all possible synergies are implemented.

The more ambitious programme (C) would be considerably more cost effective than either of the previous two examples, but would cost 192 B$ over five decades. A 60 percent rise in cost would raise the overall programme performance by 160 percent.

All of these illustrative examples and others to be of interest have to be analysed in more depth to obtain the required and still missing information such as the *risks involved to arrive at final conclusions : whether or not a combined Moon-Mars program should be undertaken, when to begin and for how long, and last not least ,what type of a program should be initiated. This requires a multi-national coordinated study approach lasting probably two to three years.*

8. Stages in Development

As presently envisioned an integrated programme of Moon-Mars exploration and development would entail the following stages, which reflect the size and structure of the programme under consideration.

1. Preparatory Stage (less than $100 million)
2. Enabling Stage (approximately $1 billion per annum)
   2.1 Extraterrestrial facilities and equipment
   2.2 Logistic infrastructure
3. Systems Development Stage (approximately $5 billion per annum)
4. Primary Systems Acquisition Stage (TBD)
5. Initial Operations Stage (TBD)
6. Extended Operations Stage (delayed TBD)

The following stages are envisioned:

8.1 Preparatory Stage (PS) (Two Years)

The two year preparatory stage should encompass three activities that will prepare a comprehensive set of plans, models and data that will support the subsequent decisions of the programme executive.

a. The establishment of an International MM Planning Office to prepare the 21st century MM programme scenarios. These will present a wide range of planning options to form the foundation for later executive actions. The collective history of past missions to the Moon and Mars will be the point of departure for studies that will review and verify the objectives of the joint programme. Some studies will concentrate on lunar activities, others on the exploration of Mars, but all be developed with a view to defining the most advantageous outcome of all the MM programme's activities acting in concert. The MM planning office will select the most promising scenarios and compile realistic schedules, cost and benefit estimates and risk assessments for each. The results will, in turn, be used to create organisational models of each programme stage. Two international technical planning teams will support the work of the planning office:

b. The International Space Systems Technical Planning Team will assess state-of-the-art space technology and space qualified systems. This team will define the extraterrestrial facilities needed by each programme scenario in detail, including identifying and fully specifying any long lead time elements, so that a subsequent programme of development can be priced and scheduled with a high degree of confidence.

c. The International Launch Systems Technical Planning Team will assess current space transportation systems. This team will identify and fully specify the long lead time elements of all launch vehicles, components of the logistic infrastructure, space vehicles and the essential in-space service facilities needed during every scenario. The overall planning team will use these specifications to draw up tentative schedules and funding requirements.

Within 18 months of the start of the planning process, the planning teams will submit a draft of the proposed integrated programme to representatives of the participating governments and associated non-governmental sponsors. A final report will be completed within two years.

8.2 Enabling Stage - Four Years

If the report of the planning team justifies continuing the MM- programme, and following approval of the necessary funding, work will begin on developing the relevant technologies within the framework set down by the planning team. An International MM- Mission Office will be established which will have the responsibility of coordinating and supervising these efforts. This office will also prepare for the establishment of an International Agency that will take responsibility for the subsequent stages of the MM programme.

8.2.1 Extraterrestrial facilities and equipment

Those elements and key technologies of the extraterrestrial infrastructure that can not be transferred from existing or projected national programmes, must be developed during the next four year period. A planning team will construct and test detailed models of the logistics of a lunar base and the needs of the crewed exploration of Mars, and in particular they will simulate the establishment and initial operation of a lunar base and the first expeditions to Mars. This work will not imply a firm commitment to proceed with the acquisition of a lunar base or begin crewed flights to Mars, for after four years the work of the Mission Office will be the basis of a complete review of the technical and financial feasibility of the subsequent stages of the MM programme.

8.2.2 Space Transportation and Logistic Infrastructure

Those elements and key technologies of the space infrastructure that can not be transferred from existing or projected national programmes, must be developed during this four year period. A series of projects will demonstrate the technical and financial feasibility of the necessary space transportation systems. Again this work will not imply a firm commitment to proceed with the deployment of a logistics structure to support a lunar base or crewed flights to Mars.

8.3 Systems Development Stage

Following two years of planning and four years of development, and provided the interim results predict that the subsequent programme can be both technically feasible and financially viable, an international agency will be established that will co-ordinate the subsequent stages of the programme. The schedule drawn up during the planning stage will guide the development of the programme's main elements. The eventual budgetary and technical constraints will define the scope of the programme, but a policy of, 'rapid prototyping' should ensure that, given adequate means, the initial lunar outpost will be acquired by the time of the first of the regular five year performance reviews.

The following is included to illustrate the structure of a typical development programme.

Table 8-1: The major subsystems that should be developed
during the first decade of an integrated Moon-Mars programme:

1. A fully reusable heavy lift launch vehicle (HLLV) to transport passengers and cargo between the Earth and Low Earth Orbit and possibly beyond.
2. A fully reusable lunar launch vehicle to transport passengers and cargo between the lunar surface and lunar orbit or Mars respectively.
3. A space transportation node in lunar orbit and / or in planetary departure orbit.
4. A habitat module complete with all life support systems.
5. Power plant modules to generate electrical energy and direct thermal flows.
6. A production module capable of manufacturing LOX & construction materials.
7. A workshop module for system maintenance, repair and improvement.
8. A laboratory module for research and development.
9. Surface support equipment, transportation and launch services.
10. A command and control centre including communications and systems control facilities.

The programme will specify that all the above must be rated for use on the Moon or the Martian surface. The programme must not generate an excessive demand for funds at any time, and in particular during the period preceding the first review. All changes in the budget must be gradual and predictable, and growth rates must remain manageable.

Table 8-2: Development period and intensity of development effort required for the individual major system elements during the first decade of a balanced program, beginning about 2005. (x = low-,-- xxxx= very high level of effort)

subsys.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1.year	x			x						x
2	x			x	x					xx
3	xx	x		x	x					xx
4	xxx	xx	x	xx	x				x	xx
5	xxxx	xx	x	xxx	xx	x		x	x	xx
6	xxxx	xxx	xx	xxx	xxx	x	x	xx	x	xx
7	xxxx	xxxx	xx	xxx	xxx	xx	x	xx	x	xxx
8	xxx	xxx	xx	xxx	xxxx	xxx	xx	xx	xx	xxx
9	xx	xx	xxx	xxxx	xxxx	xxxx	xxx	xxx	xxx	xxxx
10	xx	xx	xxx	xxxx	xxxx	xxxx	xxxx	xxx	xxx	xxxx

Preliminary estimates predict an average annual budget of approximately 7 billion dollars U.S. (1999) during the first ten years of the programme, possibly starting in 2005.
The total for this period is approximately the same as the estimated overall cost of the International Space Station. To put this sum into context, it is less than 1 percent of the current military expenditures of the space-faring nations, or approximately 12 percent of the 1995 global expenditure on all space activities. The maximum demand for funding approaches 10 billion dollars U.S. (1999) during the 7th or 8th year of the development period.

As the programme continues its focus would move beyond the Earth to the Moon and Mars, and the following illustrate the activities involved.

8.4 Establishment and Occupancy of the First Outpost

The first outpost on the Moon would be designed to house a small crew in safety and reasonable comfort for not less than six months. All the essential functions of the outpost would be tested for a year before the arrival of the first working crew. This outpost would constitute the smallest segment of the base acquisition stage and would become the core of a growing lunar base. Once established the outpost would pave the way for:

8.5 Lunar Laboratories

Drawing on the experience of the MIR and ISS space stations, once the core of the lunar base is crewed and operating, its crew would gradually extend the base facilities. The establishment of a lunar laboratory would be assigned a high priority. This laboratory would not only be used by the programme participants, but its space could be made available to other interested parties at affordable rates, thereby defraying the cost of running the base.

This stage in the programme should last for up to a decade, and could be terminated if the real costs severely exceed the original projections, or if the political, scientific and financial returns are not up to expectations.

8.6 Lunar Production Facilities

Over 40% of the mass of lunar regolith (soil) is chemically bound oxygen, much of which could be extracted in a solar retort. The demand for oxygen will be high, for it will be consumed by any life support system, and four fifths of chemical rocket propellant is oxygen. The Lunar Prospector probe has recently revealed that, perhaps, several billion tonnes of ice lie in permanently shadowed regions near the lunar poles. That ice could be the basis of a future lunar manufacturing complex supplying hydrogen and oxygen to processing plants and space transportation systems. Clearly a lunar plant to extract oxygen from local materials must established at the earliest possible date. By adding an element of self sufficiency it would improve crew safety and potentially reduce the cost of the base's logistical support. Eventually such a plant could expand to manufacture building materials, glasses and metals for use by the base. Like other base modules, these manufacturing facilities should be assembled and fully tested on Earth before being shipped to the Moon as prefabricated units.

The immediate goal will be to give the lunar base as high a level of self sufficiency as quickly as possible and consequently reduce the shipment of bulk materials from the Earth. It will, however, be one or two decades before a substantial range of manufactured products can be produced on the Moon from local feedstock.

8.7 First Crewed Martian Landing

The decision to approve an expedition to land human beings on the planet Mars could be made at any time during the acquisition and operational stages on the integrated programme. Although this expedition will surely rivet the world's attention it will not reflect the philosophy behind the Apollo lunar landings, and be a self justifying technological spectacular. Rather it should open the way for the continuing human exploration of a new planet. Such an expedition will only be approved after a dense series of pathfinder robot missions have proved that the risks and costs are acceptable and that there is a major advantage in having human beings on the planet.

Contemporary lunar activities will have a considerable bearing on the timing and nature of the decision to 'go for Mars'. When that decision is made the resources, systems and, most importantly, the experience gained from working on the Moon will be available to participants in the Martian programme.

Hopefully, we have now arrived at the end of the third decade of the 21st century, and looking further along the highway that leads to the Moon, Mars, and beyond to the farthest reaches of Solar System, would be both presumptuous and premature.

9. First Organizational Step

9.1 General considerations

The Lunar survey and development of the Moon, and the exploration of Mars must reflect the highest aspirations of our civilization. These endeavours may start as adventures that will challenge the world's boldest spirits and task its finest talents, but they will continue only if they enrich the global human condition. All nations and cultures will be welcome to participate. The operations of the joint programme must conform to the highest possible standards, while illustrating its global nature in its overall organization and executive bodies. Its funding mechanisms, the location of its headquarters and operational venues, its working language and protocols, and the members ofits task forces, committees, and staff, will reflect the contributions of the participants.

9.2 The preliminary planning stage:

The next stage in lunar development would follow the signing of a *Memorandum of Understanding* to establish an officially recognised effort that would prepare detailed plans for a permanent return to the Moon. This would involve five hundred person-years of work extending over two years and at a total cost of not more than $100 million.

A legal regime that would recognize the development of the Moon already exists under the provisions of previously signed space treaties. The IAA Subcommittee on Lunar Development has prepared the following draft memorandum of understanding to act as the first formal step towards an international effort to establish a lunar base.

Memorandum of Understanding on the Establishment of an International Moon-Mars Planning Office (IMMPO)

Preamble

In recognition of exceptional faculties, status and special needs of humankind in the solar system and perhaps in the Universe as a whole and with awareness of the responsibilities this implies, in order to preserve life, and improve its quality on its home planet, humankind is destined to explore the frontiers of this solar system as specified already in the Outer Space Treaty of 1967 opening the neighbouring celestial bodies for their exploration, development, use and settlement,
it is resolved to start the development of lunar resources in the spirit of the Moon Treaty of 1979 by agreeing to establish an "International Moon-Mars Planning Office (IMMPO)".

Article 1 : Objectives

An International Moon-Mars Planning Office shall be established to compile essential planning information concerning the ways and means to explore and utilize the resources of the Moon and Mars for the benefit of humankind. This office shall provide within a period of no more than 24 months:

- a draft of the preliminary lunar development plan in sufficient detail to
  (1) enable a decision on the predevelopment activities and the eventual establishment of an "International Moon-Mars Development Agency (IMMDA) at a later time, and
  (2) prepare a detailed initial program which may be adopted by the interested governments;

- a draft of a charter for the "International Moon-Mars Development Agency (IMMDA)" which may be assigned the responsibility for the preparation and execution of plans for the development of lunar resources; and
- a draft of a tentative schedule and procedures to put the IMMDA in operation, if such an organization is agreed upon.

Article 2 : Parties

Parties of this Memorandum of Understanding shall be the National and Regional Space Organisations ....

authorized by their respective Governments and/or International Institutions willing and capabale to initiate steps towards a human tended International Moon-Mars exploration and development.

Article 3 : Organisation

1. The IMM-Planning Office(IMMPO) shall be comprised of the national and regional "Task Teams", which shall remain attached to their parent institutions.
2. The heads of those national or regional task teams which provide ten percent or more to the overall effort shall constitute the" Board of Directors".
3. A host country shall provide offices and administrative support for the Executive Office of the IMMPO.
4. The head of the national or regional task team of that country hosting the executive office shall also act as the Executive Director of the IMMPO unless the Board decides otherwise with a 3/4 majority.
5. In case several countries make an offer to host the Executive Office, this office shall rotate between them in alphabetical order with the provison that the period of rotation shall not be less than one year if concurred in by the majority of the Board of Directors.
6. The hosting meetings shall rotate among the participating countries.
7. The Chairman of the UN Committee on Outer Space, if so mandated by the UN, shall be an ex - officio member of the Board of Directors.
8. International organisations involved in space matters shall be entitled to nominate liaison officers in an observer status at the Executive Office of the MMPO or at any regional task team office of their choice at their own cost, subject to approval by the Board of Directors.

Article 4 : Funding

1. International transfer of funds during this two year planning effort is not anticipated.
2. All personnel assigned to the task teams or delegated to the Executive Office shall be paid by the respective participating country.
3. The administrative support of the Executive Office shall be paid for by the hosting country.
4. Studies contracted to third parties may be paid by sponsors outside the IMMPO, subject to approval by the Board of Directors, preventing interference and/or possible profiting.

Article 5 : Working Operations

1. The Board of Directors shall assign work-packages to the participating task teams indicating the level of effort and the date of completion desired. Decisions shall be taken by majority vote.
2. The Executive Director is responsible for coordinating and issueing a semi-annual report on the progress made and a final report.
3. The work-packages shall include, but not be limited to, the following tasks:

1st priority:

- Identification of additional precurser activities for base acquisition.
- Identification of critical technologies.
- Refined definition and assessment of proposed lunar and Mars base options.
- Preliminary definition of an initial logistics system.

- Identification of preferable locations for initial bases.
- Draft of the most likely scenario and schedule for the acquisition and operation of initial bases.
- Draft of a list for priority lunar and Mars science projects.
- Identification of potential goods and services which may be exported by bases during its operational life.

2nd priority:

- Draft of regulations to protect the local environment.
- Draft of a funding plan for base development and operation.
- Compilation of national capabilities and potential contributions to the development of a lunar base.
- Identification of technical long lead time elements .

3rd priority:

- Draft of a guideline for commercial utilization of local resources.
- Identifications of possibilities for non-governmental organisations to contribute to a Moon-Mars development program.
- Development of organisational plans for the structure of a Moon-Mars Development Agency.
- Proposal for a public relations policy and a distribution list for the communications and reports of the IMM-Planning Office.
- Proposal for a personnel selection procedure and policy in an international scenario.
- Definition of interfaces to other international organisations and institutions.

Article 6 : Effective Date

1. The International IMM-Planning Office shall begin its operations on ....
2. The Executive Office shall be located at ....

Signatures of the Participants

10 . Conclusions and Recommendations

10.1 Conclusions

The crewed space missions and the robot interplanetary probes of the past five decades have defined both the challenges and rewards associated with the exploration of the Moon and Mars. Half a century of study has led to the conclusion that a permanent lunar base could be safely established at an acceptable cost. All that remains is to decide when and how to begin. The long and continuing series of automatic Martian probes should continue for they deepen our understanding of the mysterious, alien, but beguilingly familiar Red Planet. It seems certain that one day during the next century human beings will visit Mars, at first to explore, and then to stay. Exactly when that distant voice will announce to the peoples of the Earth that the next giant leap has been taken for humankind will only be decided after considerable study and a programme of technical development aimed at reducing the risks and cost of interplanetary travel.

Spaceflight has and will continue to enrich the human condition, not only economically, but also in ways, if less easy to count, are very arguably more important, and certainly easier to recognize. We, as a species, have an insatiable urge to explore and understand our environment, for only then can we make it our own, and it is not surprising that curiosity is our outstanding characteristic, for knowledge has, is and will be, the key to our survival and success.

In Sum:

Noting

- the expansive evolution of life on this planet, and especially
the recent evolution of our species; the result has been that
- the confines of this planet now must contain a rapidly growing
human population, and that
- the members of that population harbour a natural desire for a
higher quality of life. However,
- the expanding world economy will demand ever greater supplies
of high quality industrial energy, that will lead to shortages during the
next century; but at the same time
- advances in technology generate new economic opportunities; for
- as populations become richer they demand new and better
products and services. In particular
- humans have a thirst for knowledge and adventure; so
- the highly educated global work force of the future will demand
stimulating, rewarding careers, in spite of the
- challenges inherent in our global civilization's uncertain future.

and therefore:

Acknowledging

The debt we owe to our predecessors and

Recognizing

That we hold the well being of future generations in trust:

We Believe

that, seen by the light of experience, if the world is to surmount the challenges of the coming millennium, the time has come for responsible governments to seize the initiative and unequivocally support an international effort to explore and develop extraterrestrial resources. Consequently a new or an existing multi national organization dedicated to space research and development should be given the responsibility, and allocated the resources needed, to plan for the permanent return of human beings to the Moon, there to exploit its resources for the benefit of humankind, while at the same time preparing for a continuing, aggressive programme to survey the planet Mars using both human explorers and remote systems.

Objectives and goals

Extraterrestrial bases generate knowledge, products and services that will help achieve the following goals:

Direct or Primary Objectives of an Extraterrestrial Base:

1. To support a science laboratory in the unique environments of the Moon or Mars
2. To expand our knowledge of the Moon or Mars.
3. To market space derived products and services.
4. To found the first extraterrestrial human settlement.
5. To supply the Earth with space generated energy and fuels.
6. To be a focus for the development of space technology.
7. To support reliable, low cost space transportation.
8. To be an isolated, observable, but accessible depository of long lived, high level, hazardous, wastes.
9. To demonstrate that economic and social growth is possible outside the Earth, and therefore,
10. To stimulate the evolution of human culture.
11. To preserve the best of human culture in the event of a global catastrophe.

Indirect or Secondary Objectives of an Extraterrestrial Base
In concert with terrestrial activities:

1. To advance our understanding of the Earth's biosphere and hence improve our management of this planet's ecosystem.
2. To stimulate the development of advanced technologies.
3. To be an opportunity for international co-operation.
4. To provide satisfying careers for highly educated personnel.
5. To stimulate the education system.
6. To sublimate social and political tensions on Earth.
7. To expand the global economic infrastructure.
8. To be the challenging frontier of human effort.
9. To be a non-military alternative customer for the products of the military-industrial complex.
10. To enhance the prestige of the participating nations.
11. To improve our understanding of the solar system.
12. To improve our understanding of the universe Programme Options.

This study examined programmes that would establish lunar and Martian bases that would cater for various sizes of crew and having a wide range of lifespans. This report has examined many of the most promising concepts within the following categories:

Lunar Programmes:
1. Temporary Lunar Outpost
2. Permanent Lunar Outpost
3. Lunar Laboratory (Base)
4. Lunar Factory
5. Lunar Settlement

Martian Programmes:
1. Single Mars Expeditions
2. Multiple Mars Expeditions

3. Mars Outpost
4. Mars Laboratory
5. Mars Base

The Lunar and Martian base programmes are strongly interdependent and may yield many possible synergies. Out of twenty five programme combinations several may form the basis of a future integrated programme of Lunar and Martian exploration. In the following table those with promising benefit/cost ratios are shaded.

Mars alternatives: **Moon alternatives:**	Single Mars expedition	Multiple Mars expeditions	Mars Outpost	Mars Laboratory	Mars Base
temporary lunar outpost					
permanent lunar outpost	░				
lunar laboratory/base		░	▓		
lunar factory				░	
lunar settlement					░

Two of the most promising combinations have been subject to more detailed analyses that produced representative benefit and cost estimates. The other combinations must also be fully analyzed and the results assembled into a comprehensive data base before government representatives can be expected to approve further action.

General Selection Criteria

Once the potential investors are satisfied with the compiled information, a programme will be selected according to carefully selected criteria. For example:
a: Relative risks of the undertaking.
b: Minimum cost for comparable benefits.
c. Financial regularity.
d. Reliable completion targets
e. Growth Potential.

10.2 Recommendations

A review of the short history of space research and development can only lead to the conclusion that it is incumbent on all nations to support and to participate fully in the further evolution of spaceflight. The rapidly expanding economic and social benefits of space technology clearly justify expanding the exploitation of space and supporting well funded programmes of space research and technology development. Indeed, the real possibility of a catastrophic cosmic impact makes the continued evolution of spaceflight a necessity. The world's politicians carry the responsibility of allocating adequate resources to activities of importance, and in particular, the leaders of the spacefaring nations need to recognize the vital, and increasing relevance of spaceflight and space research.

The Moon and Mars are two large neighbouring celestial bodies that hold clues that may help unravel the mysteries of the evolution of the Solar Systems, and perhaps even of life itself. They offer the best opportunity to exploit the hard to reach, but unlimited resources of space for the benefit of humankind. Consequently this report strongly recommends that planning for an integrated programme of Lunar development and Martian exploration should begin at once, and that any subsequent programme is afforded a high priority.

Stages in the Proposed Programme

As presently envisioned an integrated programme of Moon-Mars exploration and development would entail the following stages.

Near Term:
1. Preparatory Stage (less than $100 million)
2. Enabling Stage (approximately $1 billion per annum)
2.1 Extraterrestrial Facilities and equipment
2.2 Logistic Infrastructure

Medium and Longer Term:
3. Systems Development Stage (approximately $5 billion per annum)
4. Primary Systems Acquisition Stage (TBD)
5. Initial Operations Stage (TBD)
6. Extended Operations Stage (delayed TBD)

Preparatory Stage :

The establishment of an *International MM Planning Office* to operate for two years that will:
(1) Prepare a detailed proposal to create a coordinated multi - national programme that would support the enabling stage to develop technologies critical to the success of the overall programme.
(2) Present a wide range of planning options that will form the foundation for later executive actions. The collective history of past missions to the Moon and Mars will be the point of departure for studies that will review and verify the objectives of the joint programme. Some studies will concentrate on lunar activities, others on the exploration of Mars, but the planning office will select the most promising scenarios and compile realistic schedules, cost and benefit estimates and risk assessments for each. The results will, in turn, be used to create organisational models of each programme stage.

Within 18 months of the start of the planning process, the planning teams will submit a draft of the proposed integrated programme to representatives of the participating governments and associated non-governmental sponsors. A final report will be completed within two years.

Proposed Action:

The next stage in lunar development would follow the signing of a *Memorandum of Understanding* to establish an officially recognised effort that would prepare detailed plans for a permanent return to the Moon. This would involve five hundred person-years of work extending over two years and at a total cost of not more than $100 million. A legal regime that would recognize the development of the Moon already exists under the provisions of previously signed space treaties. A draft Memorandum of Understanding which could act as the first formal step towards an international effort to establish a lunar base is available for further consideration. This draft proposes the following tasks:

The work-packages shall include, but not be limited to, the following tasks:
- Preliminary definition and assessment of a Moon and Mars base.
- Identification of preferable locations for initial bases.
- Draft of regulations to protect the local environment.
- Draft of a list for priority lunar and Martian science projects.
- Identification of additional precurser activities for base acquisition.
- Identification of potential goods and services which may be exported by bases during its operational life.
- Preliminary definition of an initial logistics system.
- Draft of a guideline for commercial utilization of local resources.
- Draft of the most likely scenario and schedule for the acquisition and operation of initial bases.
- Draft of a funding plan for base development and operation.
- Compilation of national capabilities and potential contributions to the development of a base.
- Identification of technical long lead time items.

- Identifications of possibilities for non-governmental organizations to contribute to a Moon-Mars development program.
- Development of organizational plans for the structure of the proposed Moon-Mars Development Agency.
- Proposal for a public relations policy and a distribution list for the communications and reports of the IMM-Planning Office.
- Proposal for a personnel selection procedure and policy in an international scenario.
- Definition of interfaces to other international organizations and institutions.

Program Enabling Phase - Four years

If the final report of the planning team justifies continuing the programme, work will begin on developing the relevant technologies and infrastructure. If approved, the programme will conform to the goals, level of effort, and schedule set down for the second stage of the integrated international Moon-Mars programme and be supervised by an International MM-Mission Office. This office will also prepare for the establishment of an International Agency that will take responsibility for the subsequent stages of the programme, if they are approved.

The programme will only continue after the results of the first and second stages have been fully reviewed.

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APPENDIX A:

NASA‘S ENTERPRISE FOR THE HUMAN EXPLORATION AND DEVELOPMENT OF SPACE - (January 1996)

This strategic plan is a guideline for the long range activities expected by NASA in the area of the human exploration of space. It deliniates among other things the goals and objectives of primary importance to lunar development and Mars exploration.

THE STRATEGIC PLAN

Goals, Objectives, and Strategies

Goal 1: Increase human knowledge of nature‘s processes using the space environment

Goal 2: Explore and settle the Solar System

Objective 1:

Enable Human Exploration through Space Science Enterprise Robotic Missions

Objective 2:

Expand human presence in Space by assembling and operating the international Space Station

Objective 3:

Develop biomedical knowledge and technologies to maintain human health and performance in Space

Objective 4:

Establish a human presence on the Moon, in the Martian System, and elsewhere in the inner Solar System

Objective 5:

Develop opportunities for commerce in Space as a basis for future settlements

Goal 3: Achieve routine Space travel

Objective 1:

Sustain Space Shuttle operations at improved levels of safety and efficiency

Objective 2:

Ensure the health, safety, and performance of space flight crews through space and environmental medicine

Objective 3:

Develop requirements, demonstrate and implement advanced propulsion systems, and other advanced space transportation systems and capabilities to enable exploration

Goal 4: Enrich life on Earth through people living and working in Space

Objective 4: *Join with other nations in the international exploration and settlement of Space*

Of particular importance for those who support future Moon-Mars exploration and development is the Objective 4 of Goal 2 which reads:

Objective 4: Establish a human presence on the Moon, in the Martian System, and elsewhere in the inner Solar System

We will establish a lunar base for scientific research and development of the Moon‘s resources. Scientists, engineers, and entrepreneurs from around the world will be able to use the Moon for research and to test new technologies not only for their commercial possibilities, but also for their application on Mars. As the enterprise progresses, we will eventually send the first international team of explorers to the planet Mars and return them safely to Earth. Research and sustained presence on Mars will increase our understanding of nature‘s processes on our own planet, yield insights into the origin and evolution of life, and equip us for more ambitious human missions deeper into the Solar System.

Strategy: *Explore revolutionary architectures and advanced systems to radically reduce the cost of human exploration*

We will aggressively pursue studies of breakthrough advanced systems and architectures which will yield revolutionary performance enhancements and dramatic reductions in cost. These studies should reveal initial feasibility assessments from which further technology development activities can be judged.

Strategy: *Develop life support and other human support technologies and advanced systems to achieve exploration goals*

We will accelerate research and technology development for advanced life support systems, intent upon developing a reliable closed loop system. A closed, long duration life support system can be validated on the international Space Station or on the Moon. Research and technology efforts will focus on advancements in regenerative physical, chemical and biological technologies. Understanding the behavior of fluids in low gravity, as well as understanding plant growth and maturation from “seed to seed” in low gravity will help guide the design of future systems. Additionally, we will develop a wide range of systems for human support, local transportation, and health maintenance, as well as research and development laboratories. These systems will be developed and tested to demonstrate long-term reliability and dramatically lower operating costs.

Strategy: *Develop innovative advanced technology to support human exploration*

A critical requirement for HEDS is to establish a productive, safe, long-term human presence on the Moon and Mars at a fraction of the cost of employing today‘s technologies. This breakthrough will occur, in part, by the aggressive development and use of advanced technology, including totally new approaches and concepts. HEDS will work with the Space Technology Enterprise (STE) to identify, define and develop these enabling technologies. Topics will include use of local planetary resources for the production of propellants, life support gasses and surface structures; efficient surface power generation and storage, including solar and, possibly, nuclear systems; teleoperation and robotics; advanced propulsion technologies; and cryogenic fluid systems. HEDS will provide overall system performance goals and architectures to the Space Technology Enterprise to guide technology research and development. The STE will work with the HEDS Enterprise to identify revolutionary means to accomplish the HEDS mission and to develop technology implementation plans. The STE will subsequently develop and deliver technology products to HEDS for mission-focused advanced development.

Strategy: *Conduct prototype, advanced-development demonstrations to ensure feasibility of the exploration strategy*

We will strive to bring technologies which are of high leverage to human exploration missions to levels of maturity which give us confidence in their readiness and cost estimates. For example, we will advance the state of extraterrestrial resource extraction and utilization through subscale pilot plants, reduced gravity testing, and space experiments. These demonstrations of technical options will be performed on a schedule to support timely decisions for the integrated strategy of Moon and Mars exploration.