

ILR Mitt. 340 (2000)
1.1. 2000

MOONBASE 2015

MODEL OF A NEAR-TERM LUNAR BASE

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MOONBASE 2015 - Model of a Near-Term Lunar Base (H.H.Koelle)

Abstract

The development of a viable concept to return to the Moon remains to be a real challenge for space planners of today. This report is a contribution in this direction. This report builds upon earlier studies^{18,21} and describes in detail a *Lunar Base* growing from 16 to 100 people in 30 years. Nearly 1,000 metric tons of facilities and equipment are installed on the Moon. Average crew duty cycles are nine months. A lunar space transportation system comprised of a heavy lift launch vehicle, a lunar ferry vehicle and a space operations center in lunar orbit is an essential companion project. The systems behaviour, the dynamics of selected parameters and the overall performance and cost-effectiveness of the lunar base, including its logistic system, are analysed on a year-to-year basis. It is shown that the average annual cost of a lunar labor-year is expected to be approximately 37 million (1999) dollars and that the average annual operations cost of this lunar base including a 10 year development phase may be less than 2 billion \$.- Moonbase 2015 is documented as LUBSIM Option 10 and TRASIM Option 14 in the authors electronic files. The results of this study are summarized in 45 tables, 17 figures, 6 appendices, and 26 references comprising 64 pp., excluding five front pages.

Key words: Moonbase, lunar logistics, space transportation systems, cost

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EXECUTIVE SUMMARY:

MOONBASE 2015 - MODEL OF A NEAR-TERM LUNAR BASE

Spaceflight can be considered as a natural, an essential and a logical step of the evolution of the human species. Exploring space, learning to live and work in space, and using its natural resources, will improve the quality of life on Earth and last-not-least enhance the survival chances of our civilization!

Automatic space vehicles are extremely useful in many applications, quite often they are essential. Some satellites are now in operation for more than a decade in near Earth space as well as in interplanetary space, some space probes have even left the solar system. There is no question, that they will also be used heavily in the future. However, it must be realized that roboters have advantages *and* limitations. In may cases they must be supplemented by human skills. For many decades in the past, astronauts and cosmonauts have demonstrated their usefulness in laboratories in orbits about the Earth and in exploring the Moon. However, the space activities we are privileged to witness during the present phase of human development, is just the beginning of mastering a new dimension. It must and will go on, the question to answer is only when and how. Options have to be defined, optimized and to be communicated to those concerned in order to be ready when the time comes to take new decisions^{3,5,7,9,11,12,22,23}.

No later than after the expected completion of the *International Space Station* (ISS) the question will come up and must be answered: SHOULD WE STOP HUMAN EXPLORATION OF SPACE OR WHAT IS NEXT? It appears unlikely that the human exploration of space will be discontinued at that point, because the evolution will not end^{11,12}. A logical choice would be returning to the Moon and to establish an *International Lunar Base* (ILB) .

In so doing, the following primary *objectives* would be -at least partially - achieved^{9,16,17}, a lunar base would:

1. provide a science laboratory in the unique environment of the Moon for experiments which can not be conducted on Earth,
2. improve our knowledge of the Moon and its resources,
3. improve the understanding of our own planet,
4. improve our understanding of our solar system and the Universe,
5. stimulate the development of advanced technology on Earth,
6. demonstrate the potential growth beyond the Earth,
7. establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system beyond our home planet,
8. produce marketable services and products on the Moon for extraterrestrial or terrestrial use,
9. provide a survival shelter in case of global or cosmic catastrophes,
10. provide reliable space transportation systems to the Moon.

Studies and detailed analysis show that an adequately sized lunar facility, providing also commercial opportunities and growth potential, seems to be an attractive and

affordable option for the first half of the 21st century. A detailed model of such a lunar base has the following main characteristics:

**Table ES-1:
Overview of Lunar Base characteristics during a 30 year operational life-cycle -**

year of operational life-cycle	number of total lunar crew members	total lunar facilities (t)	total projected imports (t p.a.)	total output of lunar facilities (t p.a.)	total number of primary lunar missions p.a.
1	17	223	255	107	8
3	28	357	58	195	5
6	38	464	60	301	4
10	48	551	79	403	4
15	64	684	86	467	4
20	86	866	113	559	4
25	91	921	93	607	4
30	100	1,005	103	661	4
30 yr.total	1962	1,005	2640	13,680	125
average	65.4	652	88	456	4

The cost of such an enterprise supported by public funds are summarized in the next table. **The total program costs add up to about 74 billion (1999) U.S.dollar in a 40 year period** , broken down in table below.

Table ES-2: Cost summary of a Lunar Base with a 10 year development phase and a 30 year operational life-cycle - (million 1999 \$ at 0.2 million \$ per man-year)

COST ELEMENT	Life cycle M \$	M \$ p.a.	% of LC total
Development & test of lunar facilities-10 year	9,340	934	12.7
Dev.& test of space transportation system-10year	18,923	1,892	25.7
Subtotal development & test - 10 year	28,263	2,826	38.4
Sustained engineering STS - 30 year	4,146	138	5.6
Productionof space transportation system(STS)	9,911	330	13.5
Operation of space transportation system(STS)	6,620	221	9.0
Operation lunar facilities	24,690	843	33.5
Subtotal operations - 30 years operational LC	45,377	1,532	61.6
Total Lunar Laboratory System - 40 year life-cycle	73,630	1,840	100

Table ES-3: Lunar Base system development and operating cost at selected years during the 40 year life-cycle (million 1999 \$ with 1 direct human labor-year = 0.2 M \$)

oper. life-cycle year	up-front cost lunar facilities	up-front cost space transportation	lunar base total development cost	year of operation	operation cost lunar facilities	operation cost LSTS	lunar base total operating cost
-8	17	0	17	1	441	5,936	6,377
-7	110	0	110	3	615	2,668	3,283
-6	375	1,221	1,596	6	597	361	958
-5	589	2,266	2,855	10	771	507	1,278
-4	1,100	3,210	3,310	15	829	777	1,606
-3	1,300	3,706	5,006	20	937	383	1,320
-2	2,200	3,587	5,787	25	818	327	1,145
-1	2,100	4,621	6,721	30	843	461	1,304
0	1,549	4,508	6,057	program total	34,030	39,600	73,630

The non-recurrent overall system cost and their distribution over the development period (left side of table ES-3) is an important information because this near-term expenditure is a very critical parameter in any decision.

The graphical presentation of the initial investments required versus time (Figure ES-2) is an illustrating example of what it takes to enter a meaningful next phase of lunar development. It should be noted, however, that the investments required in the peak years of about 7 B \$ is merely **one percent** of the current military expenditures on this globe.

It is important to realize that these investments for an initial lunar base would not be required in the next few years! They would have to be budgeted beginning about the year 2005, with a peak after the year 2010. By then, if present geopolitical trends continue, the military expenditures should have come down by more than these amounts.

Considering the critical up-front cost only, their distribution during the nine years of development (beginning about the year 2006) is shown in figure ES-1. operational phase! It also includes shares of vehicle production cost which are in this case distributed over three years, thus smoothing the distribution.

The total cost trend is depicted in the next graph (figure ES-2), to follow the bar-chart. As depicted in the last column of table ES-4 and figure ES-2, there is a major decline of annual cost to be observed after initial beneficial occupancy of the lunar laboratory. This public financial burden can be further reduced by leasing laboratory spaces on the Moon to interested commercial enterprises and also by selling lunar products at the amount of about 100 tons p.a. to the interested companies or persons. This commercial potential could amount to several hundred million dollars per annum.

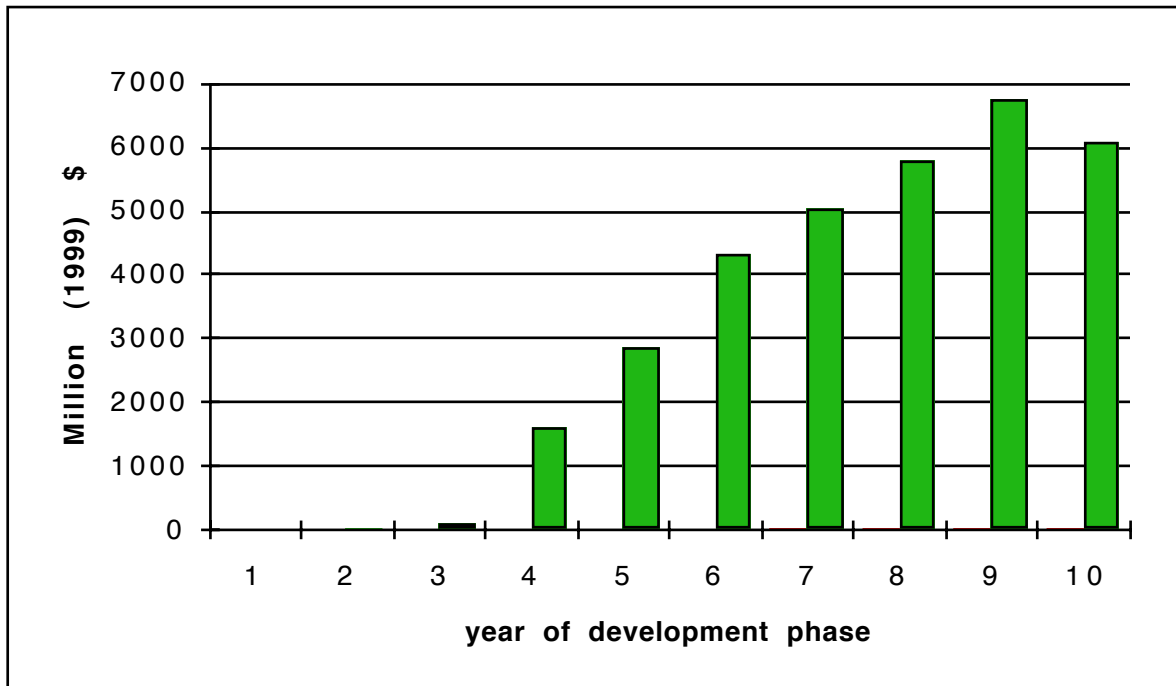


Figure ES-1: Annual distribution of development cost (non-recurrent cost) of the lunar facilities and the logistics system

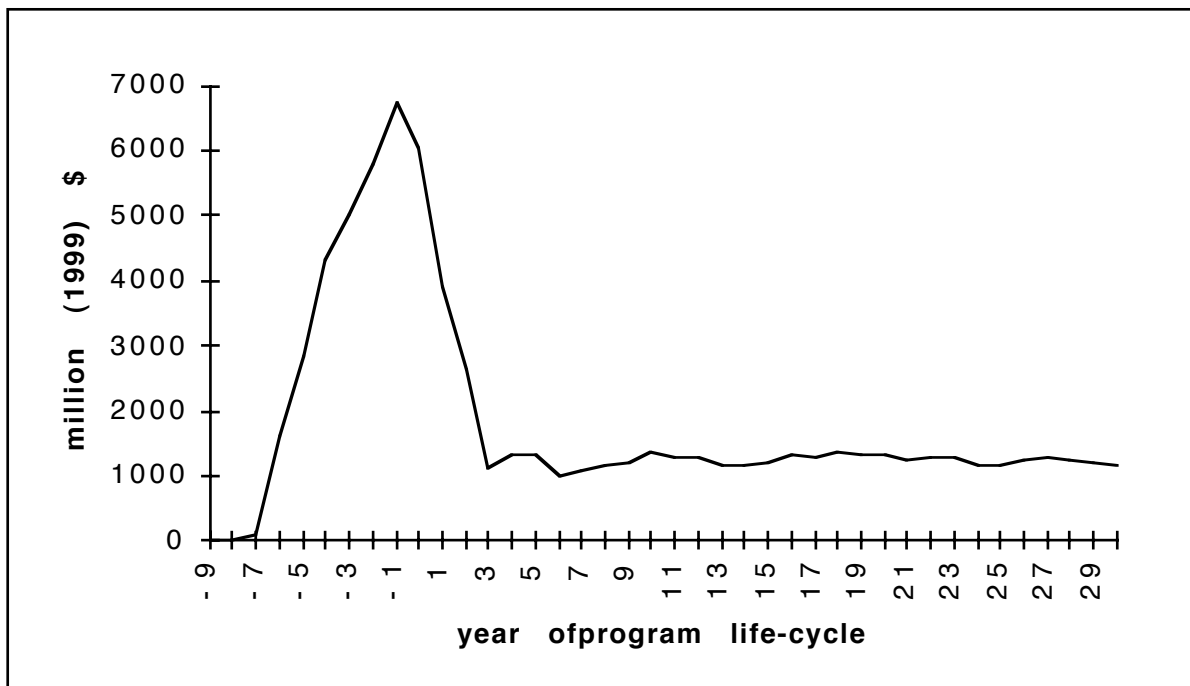


Figure ES-2: Lunar Base total program cost (non-recurrent and recurrent) trend assuming a distribution of hardware cost over three years

In case the lunar space transportation system or elements of it are employed also in other space missions e.g. planetary exploration, the development burden of the lunar space transportation system for the lunar base will be reduced by 1/3 to 1/2. Further details are presented in the full report to follow the Executive Summary!

Study Results :

In the process of analysing and evaluating alternative plans for the next phase of lunar development, several options have been investigated by means of detailed simulation models. These have resulted in annual estimates of the most important system parameters and the system behaviour as a whole. The governing consideration in this analysis can be formulated as follows:

The primary objective in the process of the evolution of the human species is to develop the access to extraterrestrial resources, beginning with the Moon, to learn to live and work in space, use the resources available and last not least, to establish the first extraterrestrial human settlement.

A **representative lunar base development**, modestly extending the present state-of-the-art, has been analysed in some detail to obtain a general overview of the costs and benefits involved. A typical scenario would be a go-ahead in the year 2005, a development phase from 2006 to 2015 and beneficial occupancy in 2016 with a 30 year operational life-cycle. A science and technical development oriented lunar base would start out with a crew of less than 20 people. The lunar population would reach a level of about 50 after ten and 100 after 30 years. Various services are offered to users on Earth and pilot plants would experiment with the manufacturing of lunar products. It could be downsized at any time in the operational phase if the expected benefits are not achieved, or upgraded if new developments require such action.

The development and operation of a modest lunar base could be realized in a 40 year period for less than 80 billion (1999) US dollars, if planned carefully and managed by a competent organization. The peak demands of public funds would reach about seven billion dollars annually at the end of the development phase, an amount which is less than one percent of current global military expenditures. The average annual cost over the 40 year life-cycle would be less than two billion dollar, which is merely one percent of the present annual military expenditures of the United States. Judging from this viewpoint, it certainly appears economically feasible even on a national scale, at least for the United States of America.

A graphical presentation of the growth of the improvement of the cost-effectiveness versus time shows the general trends to be expected. In this context the cost-effectiveness of the program is defined as the ratio of the annual expenditures and

the number of human labor-years available on the lunar surface. The up-front cost are not included in this trend curve.

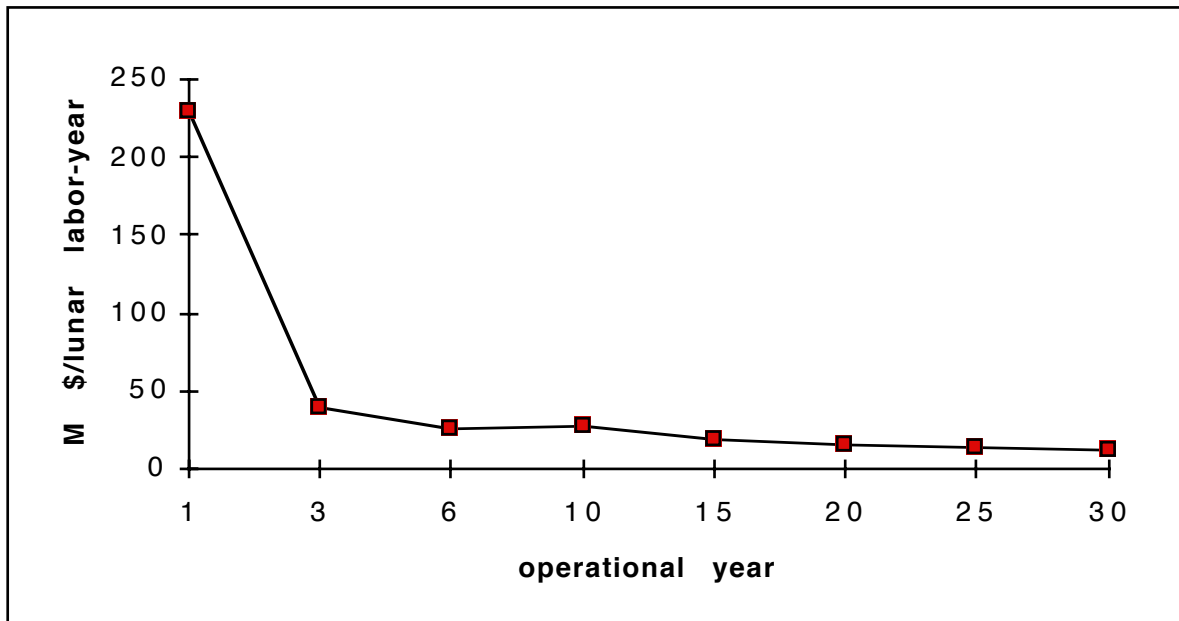


Figure ES-3: Reduction of specific cost per lunar labor-year (M 1999 \$)

CONCLUSIONS AND RECOMMENDATIONS:

- 1.** There is no quick and dirty or cheap solution to return to the Moon soon and to accomplish a meaningful activity of lunar exploration to achieve the defined objectives. Establishing a small lunar outpost with a few people and for a limited time does not appear to be an attractive proposition due to its poor cost-effectiveness (> 1 B \$ per lunar labor-year) and the high risks involved. Even for the smallest outpost, total expenditures can not be held below 50 Billion dollars and moreover, most investments would have to go into an infrastructure that is poorly used.
- 2.** Based on present insights and extending modestly the present state-of-the-art, it is possible to develop technically feasible and attractive concepts of returning to the Moon in order to establish semi-permanent or permanent lunar facilities. This would

allow to continue the lunar exploration early in the 21st century at affordable expenditures and an acceptable risk.

3. The required investments appear feasible and affordable if seen in perspective. The big hurdle of a decision to enter a new phase of lunar development is the fairly sizable up-front investment requiring an average of about \$ 4 billion (1999) and peaks of up to \$ 7 billion for a ten year period. This investment can not come from privat sources, it would probably require the efforts of a group of national governments interested in the exploration and utilization of extraterrestrial resources for the benefit of the present and future generations.

4. It appears quite possible that - after an initial phase - the annual burden to the public for maintaining the operation of this type of a lunar base can - by partially commercializing lunar activities - be held to about one billion dollar which makes this option a very attractive proposition. It would open the door to a development leading to space based solar and/or nuclear energy delivered to the users on Earth and in space, or even expeditions to Mars..

5. Thus, it is recommended to re-open the discussion of returning to the Moon at the time the International Space Station (ISS) is nearly completed, or even before. After a few years of discussion at the international level an agreement among the participating nations should be possible by the year 2005. Development could begin by 2006 and beneficial occupancy of an initial lunar base should then be possible by the year 2016. This planning effort should include the option to continue this line of exploring and utilizing extraterrestrial resources by expeditions to the planet Mars involving human crews.

1. Introduction to the full report

The first phase of lunar development ended with the flight of APOLLO 17 in December 1972. The primary reason for ending this phase of lunar development was the Vietnam war, which was requiring all available resources of the United States, namely 100 billion dollars in the peak year of this engagement! But it was also determined, that after achieving the primary political objective of being there first, the relatively poor cost-effectiveness of continuing the APOLLO program in exploring the resources of the Moon was preventing more lunar excursions of this type¹¹.

The seventies and the eighties of the 20th century saw a space program concentrating on the development of Earth satellites and space transportation systems, among them the partly reusable Space Shuttle. This space vehicle was designed for crewed transportation missions to the low Earth orbit, originally with the intention to replace all expendable systems. The unfortunate loss of the CHALLENGER vehicle in 1986 changed all this, it caused a big gap in the American space program and a severe cut-back of Shuttle launches. This in turn increased the cost per launch greatly due to the limited use of the available infrastructure. Under these circumstances it was not possible to revive any plans for the immediate continuation of the lunar exploration program.

During the eighties some interest developed again in returning to the Moon in connection with feasibility studies of Space Solar Power Systems (SSPS). Lunar resources were found to be an attractive means to reduce the cost of constructing solar power plants in GEO^{1,2,13}. Also the US Congress demanded in the mid-eighties an answer to the question of how the space program should continue. A *National Commission On Space*, mandated by the US Congress, made a positive recommendation to return to the Moon among other space programs³. Other studies in those years^{4,5,6,7,9,11} supported this recommendation.

These efforts resulted in the recommendation of President Bush in Juli 1989, at the occasion of the 20th anniversary of the first landing of men on the Moon, to return to the Moon to stay. However, three months later, the Berlin wall came down and the dissolution of the Sowjet Union began, leading to the end of the cold war in December 1991. The priorities of all government supported space programs suffered worldwide from this upheaval of the geopolitical scene. Under the heavy burden of the huge national debt at that time, most programs were put on the back burner as the consequence of changing priorities^{11,15}. Contrary to this negativ development trend, some commercial space projects flourished.

In the mid 90s, after some lunar probes of Japan and the United States were quite successful¹⁴, the Japanese and the European Space Agency expressed some interest to take up lunar exploration. This prompted various people to discuss again the pros and cons of returning to the Moon and establishing a permanent facility there. One of these planning activities is sponsored by the International Academy of Astronautics, which re-activated its Subcommittee on Lunar Development¹⁶. Several national and international symposia took place during the last decade, discussing various aspects of robotic and human exploration of the Moon in the future. During 1998 and 1999 the 'Moon-Mars Committee' of the 'International Academy of Astronautics' compiled available data and concepts for an integrated

Moon-Mars development program and presented them to the delegates of the 50th International Astronautical Congress at Amsterdam in October 1999²².

A study concerned with the future of lunar development has to begin with answering the question: WHY? The presently recognized objectives of continuing the exploration and utilization of lunar resources have been summarized as follows^{9,16}:

Table 1-1: Objectives of a Lunar Base

General genuine (primary) objectives of a lunar base:

1. Provide a science laboratory in the unique environment of the Moon.
2. Improve our knowledge of the Moon and its resources.
3. Produce marketable services and space products on the Moon.
4. Establish the first extraterrestrial human settlement.
5. Contribute to the supply of the Earth with space based energy.
6. Provide a focus for the development of space technology.
7. Demonstrate the potential growth beyond the Earth.
8. Enhance the evolution of the human culture into space.
9. Provide a survival shelter in case of a global catastrophe.
10. Provide reliable space transportation systems to the Moon.
11. Provide an isolated depository for high level wastes in case of need.

Secondary objectives of a lunar base:

which could also be achieved or supported by other than space programs:

1. Improve the understanding and control of Planet Earth.
2. Stimulate the development of advanced technologies on Earth.
3. Provide opportunity for international cooperation.
4. Provide rewarding job opportunities.
5. Assist in reducing tensions and conflicts on Earth.
6. Provide the infrastructure and experience for global enterprises.
7. Provide opportunity for involvement in frontier activities.
8. Provide a peaceful outlet for the military-industrial complex.
9. Contribute to the national prestige of participating nations.
10. Improve our understanding of our solar system.
11. Improve our understanding of the universe.

Thus one has to bear in mind, that lunar activities will help to achieve *several* of the identified objectives listed above. Their relative priorities will change as function of time, depending on the current state of the planet. A decision to go back to the Moon with people may become an issue again shortly after the turn of the century¹⁵, after completion of the assembly of the International Space Station(ISS).

Quite a few services and products have been identified already which may be offered by people working on the Moon to users on Earth and in space, such as shown in the following table:

Table 1-2: Services and products of a Lunar Base¹⁷

LUNAR SERVICES:	LUNAR PRODUCTS:
-----------------	-----------------

Knowledge derived from science of the Moon Knowledge derived from science from the Moon Knowledge derived from science on the Moon Engineering development services on materials Engineering development services on processes Engineering development services on equipment Launch services for space transportation systems Maintenance & repair of space transportation systems Waste storage services Administrative services Training services for other space projects Tele-education and Tele-Entertainment Health care to special ailments Space observation and protection of Earth in emergencies Tourism	oxygen and liquid oxygen hydrogen technical gases other than oxygen and hydrogen food raw materials feedstock (benefited minerals) construction material nuclear fuels (Helium 3) thermal and electrical power metallic products ceramic products electric materials pharmaceuticals
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It would be wrong to wait with further planning activities until a situation arises on this planet, in which the return to the Moon develops as a pressing need at the political level. Planners have to prepare for eventualities. For this reason, presently not being under pressure, this is the time to develop attractive options for a new phase of lunar development, so that politicians have a choice of alternatives to select from, if and when a decision is due.

It is obvious that the key question is that of transportation of people and supplies to the Moon, because there is no lunar space transportation available at present time or even in sight. This is the bottleneck: No transportation, no people on the Moon ! - But new space transportation systems have to be matched to program objectives, consequently the size and life-cycle of potential lunar bases are important factors determining the overall program.

To make this relationship transparent is the primary purpose of this report. This analysis begins with discussing the ground rules adopted for developing the program structure, limiting the size and logistic requirements of a lunar base program. The lunar space transportation system is subsequently selected on these assumptions and described in some detail, to be followed by a cost analysis of the entire program. This concept promises to be one of the better options for the next phase of lunar development.

2. Program Structure

An initial lunar base with built-in growth potential would be a logical choice to return to the Moon early in the 21st century with the goal to establish a permanent facility on the lunar surface to explore and utilize lunar resources for the benefit of humankind. This example of a lunar installation is planned on the basis of a ten year development period, a 30 year operational life-cycle and a lunar crew of up to about 100 persons. Its primary objectives are:

- (1) Exploration of the Moon,
- (2) research under lunar environmental conditions on and from the Moon,
- (3) pilot production and manufacturing experiments of lunar products, and
- (4) laying the foundation for further steps of lunar development such as an expansion towards a lunar settlement.

Groundrules and assumptions:

1. - This initial lunar installation and the space transportation system, supporting this lunar enterprise, are government owned. They are financed by public funds through budget allocations of one or several national space agencies. This assumption excludes financing costs and a general profit. However, standard profits for the contractors delivering the hardware and services required, are included. - Leasing of some research facilities to commercial users during the later operational years are envisioned and will reduce the burden on the taxpayers accordingly.

2. - The fully reusable space transportation system serving the lunar installation is designed for growth and multi-mission usage. It could also be employed in other space projects requiring flights to the low Earth orbit, to the geostationary orbit or other extraterrestrial destinations. It is assumed that the lunar logistics activities require initially most of the available launch capacity and thus accepts the development burden. This is an assumption leading to conservative cost estimates! Additional applications of the space transportation system will lead to considerable savings to the lunar program. This, as always, is a choice of either a limited investment and high operation cost or vice versa, offering in addition growth potential.

3. - The first control variable for sizing these science oriented lunar facilities is the number of laboratory spaces to be provided for experimenters involved in public and commercial research and development activities on the lunar surface. - This parameter starts out with only few working places in the early years growing to about 45, equivalent to 45% of all persons on the Moon, in the 30th year of the life-cycle in the selected scenario.

4.- The second control variable of operating a lunar base is the length of the duty cycle per crew member. It impacts heavily the launch rate of the passenger vehicle serving the lunar facility and thus system cost. The average duty cycle for lunar crew members in this science oriented enterprise is planned to be about nine months. Selecting an average duty cycle of six months would increase the passenger

transportation cost markedly, but is within the capabilities of the space transportation system proposed, if required.

5. - The third control variable for sizing lunar facilities is the mass of lunar products to be produced annually. - Typically, the production begins in the first year of the life-cycle processing lunar soil at a rate of about 20 metric tons per day growing to about 50 t per day in due course, producing lunar oxygen and some construction materials. The production activity becomes more effective during the life-cycle by increasing utilization rates of the lunar soil input, which grows in this model run from 1.5 percent initially to about 2.5 percent in the 30th year of the operational life-cycle.

6. - Facilities are sized allowing to produce nearly all the oxygen propellants for the lunar landing and launch vehicle (LUBUS) on the Moon. The return propellants of the HLLV payload stage will use Earth propellants to be onboard at launch, for reasons for crew safety instead using lunar oxygen, but also in the interest of overall economy. Some liquid oxygen may also be imported during the first years by tanker flights from the Earth to the lunar orbit service station (LUO-SOC), in case the production of lunar oxygen will not cover all of the requirements in the first two or three years. This assumption is a compromise, adopted with the intent to increase crew safety, not to overload the production facilities, to keep the operation as simple as possible and to keep the cost down.

7.- Hydrogen propellants are delivered from the Earth by the HLLV throughout the entire life-cycle to lunar orbit for refueling the lunar launch- and landing vehicles(LUBUS) at the lunar orbit space operations center(LUO-SOC). This is practical and cost-effective as has been found in the system analysis.

8. A space operations facility (LUO-SOC) is employed in lunar orbit for storage of propellants, transfer of cargo and passengers. This space based facility is a modified second stage of the heavy lift launch vehicle(HLLV). It is prepared for its mission in LEO, transferred to LUO by its own propulsion system, and will be operational before the first lunar crew arrives at the lunar base site.

A preliminary mass model of the lunar facility applying the groundrules above, must be derived first to determine the logistic requirements. An iterative matching process will follow until a balance is achieved between the capabilities of the space transportation system, the requirements of the lunar facility and the resources considered available for such an enterprise.

3. Lunar Base size and performance

3.1 Concept and layout of lunar base facilities

An existing lunar base simulation model (LUBSIM)¹ was used to derive relevant development trends versus time for the life-cycle of the lunar facilities. This parametric model calculates the annual growth of the respective facilities for the life-cycle planned as a function of the outputs in terms of products and services desired. This lunar base model is science-oriented with a fairly small production capacity and is an updated version of earlier lunar laboratory versions^{18,26}. This concept permits to choose among twenty different facility elements comprising the lunar base. Some of these facility elements could be integrated at small outputs, particularly those elements involved in production.

Operational Concept

Various concepts for the layout of lunar facilities have been proposed and have been published. The lunar laboratory concept discussed in this report is depicted in Figure 3-1.

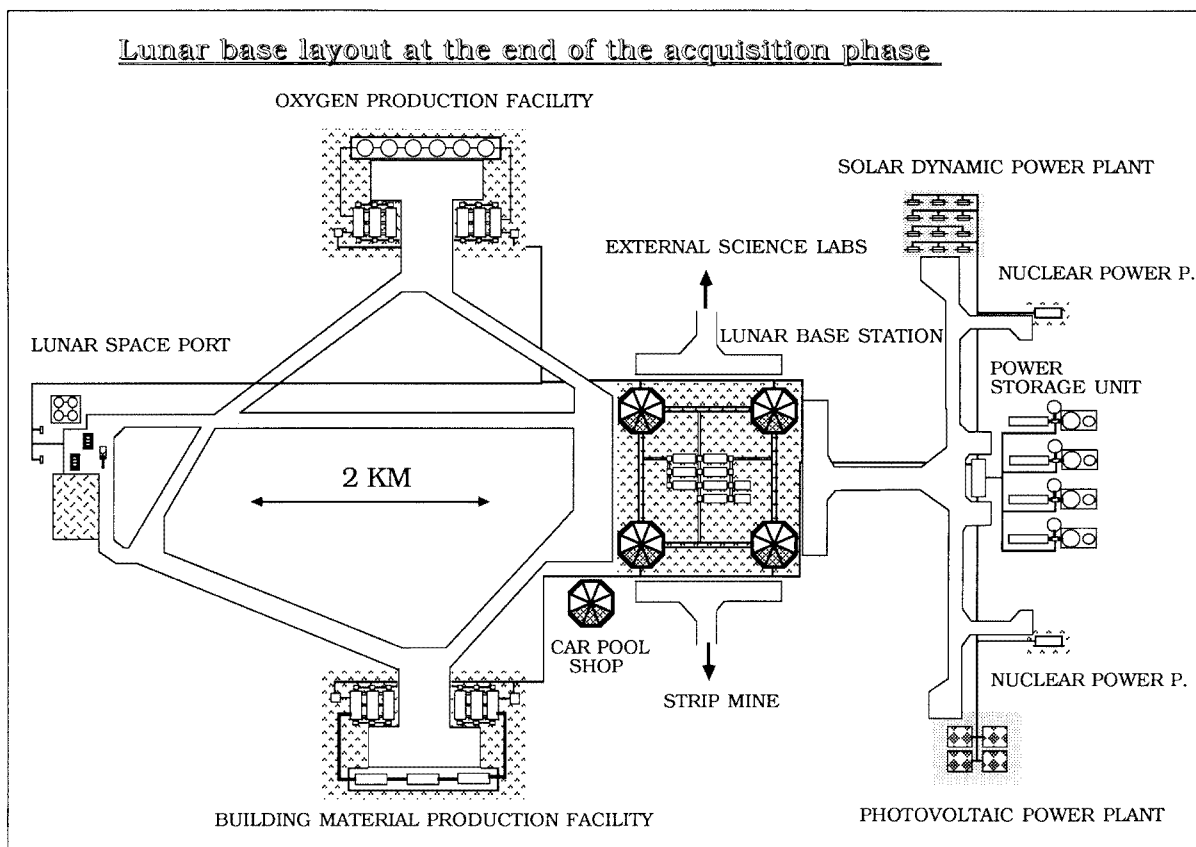


Figure 3-1: Layout of a typical lunar base observing types of facilities, required distances, leaving also room for modest growth.

A short description of the functions, major features and locations of the elements comprising the lunar facility envisioned will help to visualize the operation of the lunar base proposed:

LUO-SOC: The **space operation center**, required in lunar orbit as a transportation node, and an empty lunar bus (LUBUS) are transported into LEO in the last year of flight testing (operational year =0), where the last modifications are made. Then two more flights of the prototype HLLV will refuel the SOC in LEO and a 6 person crew will be put onboard early in the first operational year (year 1). Then it will propel itself into lunar orbit and supervise the landings of the first unmanned lunar lander. The left over propellants in the LUO-SOC(about 200 t) will be used later by the LUBUS.

FAC# 1: This **Strip Mining Facility** comprises a front-end loader (or scraper-loader), a rock-breaking separator and a hauler. The front-end loader scrapes with his shovel about two tons of lunar soil and transports it to the nearby crusher for mechanical processing and screening. The fine grain (e.g. 40 to 100 microns) to be processed further is separated, which may be only 20 percent of the soil. Then it is transported by a hauler to fac.#2. over an average distance of about 3 km for beneficiation. During the first year 6,000 t, and up to 17,000 t of lunar soil in the 30th year might be needed, depending on the local regolith composition as basic feedstock. This activity is controlled from the control center fac.#17. About 100 to 200 m³ of regolith or basaltic material can be processed per shift. The operation during lunar night might be preferable to ease the cooling problem of cooling the equipment. A two-person maintenance crew is sent out during every shift in the first year, increasing to a daily inspection and maintenance of the mining equipment in the last year. (Transportation requirement for people amounts to: $0.3 \text{ t} \times 5 \text{ km} \times 180 / 365 \text{ days} = 275 / 550 \text{ t.km p.a.}$)

FAC#2: This **Beneficiation Module** employs magnetic and electrostatic separation equipment and impact grinding to liberate metals from silicates. Free iron (FeNi), glass and ilmenite are typical products of this beneficiation process. 420 to 2,500 t of refined minerals p.a. are then transported by a conveyor belt over a distance of 0.1 km to the adjacent chemical factory fac #3 for further chemical processing. This beneficiation process is also fully automatic and controlled by fac.#17, and serviced by the crew of fac #3.

FAC#3: This pilot **Chemical Factory** processes about 100 to 650 t p.a. of benefited minerals, ores such as glass, free iron are sorted out. By heating to 900 and 1400 degrees centigrade, volatiles and selected minerals are extracted. Preliminary estimates expect that heating to 700 degrees frees the following volatiles (gram per metric ton): nitrogen 4 ; carbon dioxide 12; water 23; methane 11, hydrogen 43, helium 22. The main product of this facility is oxygen, probably using more than one specific process such as hydrogen reduction, carbothermal reduction and magma electrolysis requiring a furnace and/or reactor. This chemical plant operates fully automatic, but with a maintenance crew in attendance, and is controlled from fac.#17.

Most (3/4)of the products are gases transported over 0.1 km by a pipeline to the gas processing facility for liquifaction(fac #9). The ore (about 1/4) goes to fac #4, over a distance of about 1 km. 2 persons per operating day (1st.year) and 4 persons(last year) are required for maintenance and repairs per day. The distance between habitat and factory is about 5 km. (Resulting transportation requirement for personnel: $= 0.3 / 0.6 \times 5 \times 365 = 550 / 1100 \text{ t.km p.a.}$)

FAC#4: **Mechanical Mill.**- In due course of the 30 year operation about 5 to 205 t p.a. of ore are converted by mechanical machines employing cold and hot forming,

pressing, extrusion, rolling, to raw material. Example products are glass fibers, glass wool, silicon, iron, sintered building blocks and aluminum & titanium powder or slabs. They are transported by truck to the fabrication shop (fac# 5) which is about 1km apart from the chemical factory for safety reasons. A crew of 2 to 4 is in attendance during operation as trouble shooters. This is a one shift and 100 days operation in the first year, and 2 shifts 200 days in the last year. (Personnel transportation requirements : 1st = $0.3 \times 4 \text{ km} \times 100 = 120$ and 30st: $0.6 \times 2 \times 4\text{km} \times 200 \text{ days} = 960 \text{ t.km p.a.}$)

FAC#5: This **Fabrication Shop** is co-located to fac#4. Raw materials to the tune of 2 t to 50 t p.a. are used to manufacture construction materials such as sheets, cables, girders, pipes, and parts in due course possibly solar cells using standard or adapted machine tools. These products are transported to fac#6 for additional work or assembly. The number of people, number of days and distance from the habitat are the same as of fac 4.
(Personnel transportation requirement of 120 and 960 t.km p.a.)

FAC#6: The **Assembly Facility** and the central workshop (fac#15) are co-located in one complex about 1km from the habitat. Here, all products for usage outside of the lunar main camp are assembled and prepared for shipment. This is a small operation in an initial base development scenario, but is tested for future growth. A few 100 kg are processed during the first years, growing only to about 12 t p.a. at the end of the 30 year life-cycle. Due to the limited amounts, this is handled by the central workshop crew and does not need additional human labor. The assemblies are transported over about 3 km to the spaceport or an other point of destination.

FAC#7: Most of the **Development Laboratories** are close to the habitat and can be reached by foot. Some equipment (e.g.telescopes) will be located at some distance. They are operated by remote control, but require some service. An average distance of 3 km is assumed for this portion of the activity. This service amounts to 2 persons, 50 days a year and an average distance of 10 km.
(Personnel Transportation requirement : $0.3 \times 10 \times 50 = 150 \text{ t.km p.a.}$, doubling at the end of the life-cycle.)

FAC.8: Gas mining operations. - Not activated in this phase

FAC#9: This **Gas Processing Facility**, also controlled by fac#17, is co-located with the chemical plant where the gas is produced (fac#3) and connected to it by a pipeline. The gases extracted in fac#3 are cleaned, separated and liquified where applicable. This is a fully automated process with a throughput of about 100 to 400 t p.a., the liquids are going to fac#10 by pipeline. A maintenance crew of two is required one to twice a week arriving from the habitat 5 km away.
(Personnel transportation requirement : $0.3 \times 5\text{km} \times 50\text{days} = 75 \text{ t.km}$ in the 1st year and doubling to 150 t.km last year.)

FAC#10: The **Propellant Storage** is located near the lunar spaceport about 3 km away from the habitat and 2 km from fac#9. It is fully automated and controlled from fac #17. Some 70 to 350 t of lunar oxygen is flowing through this facility p.a. A weekly check and maintenance job of this facility by one crew member is considered satisfactory. (Personnel transportation requirement of: $0.2 \times 50 \times 5 \text{ km} = 50 \text{ t.km p.a.}$)

FAC#11: This is a lunar surface **Power Plant** located about 1 km away from the habitat and about 4 km away from the chemical factory. It is connected with power lines or pipelines with all users of electrical or thermal energy (average distance 2 km). It is fully automated, but requires maintenance twice a week in the 1st year and one a day in the last year by a two person crew. (Transportation requirement: $0.3 \times 1 \times 100 = 300$ and $0.3 \times 1 \times 360 = 1,080$ t.km p.a. in the 30th year.)

FAC#12: The lunar **Dump** will be near the strip mine or chemical factory where most of the unused lunar soil will be dumped, and near the main camp for the other wastes not being recycled. No service other than biweekly inspections are required. (Transportation requirement : $0.2 \times 25 \times 5 \text{ km} = 25 \text{ t.km p.a.}$)

FAC#13: The lunar **Spaceport** is located about 2 km away from the habitat for reasons of safety. It handles a heavy load in the first few years during the initial acquisition phase and about 100 t of cargo transported to the central storage and the exchange of the lunar crew. This amounts to about 6-8 landings and launches in the early years, going down to about 4 p.a., and going up again to about 5 p.a. at the end of the 30year life cycle. A total of about 120 flights have to be serviced. (Personnel transportation requirement: 4 missions p.a. * 7 workdays p.mission * 5 * 0.2 t service crew * 2 km + 50 days, once a week, maintenance 2 * 0.15 t crew * 2 km + $40/100 * 0.15\text{t passengers @ } 6/15 \text{ t} * 2(\text{to \& from}) * 2 \text{ km} = 96/132 \text{ t.km.}$)

FAC#14: The **Central Storage** facility is co-located with the habitat(fac#18) and handles about 30 to 130 t of imported supplies, spares and construction material. Most of this material will be brought to the central workshop(fac #15) about 1 km away. It is fully automated but may require 1 crew member in attendance during a one shift operation. (Transportation requirement: $0.15 \times 365 \text{ days} \times 1 \text{ km} = 55 \text{ t km}$)

FAC#15: The **Central Workshop** takes care of all repair activities and the extensions of existing facilities with materials either produced on the Moon or imported from the Earth. It handles the initial assembly of about 200 t and all repairs, altogether it processes 15 to 65 t of components and parts annually. This requires nominally one shift, but temporarily also two or three 8 hour shifts per Earth-day. They have to go back and forth to various facilities increasing the average daily distance to about 5 km in addition to the trip to the habitat. (Transportation requirement: $2/4 \text{ people} = 0.3 \text{ to } 0.6 \text{ t} \times 1+5 \text{ km} \times 365 \text{ days} = 660/1320 \text{ t km p.a.}$)

FAC#16: This **Car Pool** is a big inflatable facility that houses all surface vehicles and their operators and/or drivers. It is connected by gangways with airlocks with the habitat. It has also an airlock big enough for most surface vehicles stationed on the Moon. 2 - 4 people are stationed here and take care also of all maintenance and smaller repairwork. It is attached to the habitat and can be reached by foot. If the drivers go to other facilities with their vehicles, this will result in additional transportation requirements. 2- 4 people (0.3-0.6 t) will make 6 trips per day, each over 5 km. (Transportation requirement: $0.3/0.6 \times 5 \text{ km} \times 360 \text{ days} = 540/1080 \text{ t.km} + \text{vehicles.}$)

FAC#17: The **Central Control Facility** operates around the clock, supervises by remote control the status and functions of all elements of the lunar installation which are highly automated. It is co-located or part of the habitat. In case of irregularities,

the respective specialists assigned to these facilities or of the central workshop are sent out for maintenance and repairs.

FAC#18: The **Habitat** houses the crew accommodations and all equipment required to take care of the personnel. It is operated by a crew of about 2 to 10 people, including general personnel for housekeeping, health and other services. They normally do not leave the habitat, possibly for some recreation purposes or in case of emergencies. (Transportation requirement: 0.3 to 1.5 t x 5 km x 50 days = 75/150 t.km p.a.).

FAC#19: This **Recycling Facility** recycles 10 to 50 t of air, water, food and biological wastes p.a. Also some pilot experiments to grow food, such as grain and potatoes, are carried out. This activity is kept simple in the early years, such as water and air recycling, to keep the required facility and equipment small and to save cost. One to 10 people are taking care of the recycling and farming activities. They are living within the habitat and have probably only modest transportation requirements. (They are estimated to be close to those of the housekeeping personnel of fac#18, = 75/150 t km p.a.).

FAC#20: A **Space Power Plant** in Lunar orbit is not planned to be available in this early lunar facility, thus there are no personnel transportation requirements.

A functional barchart is shown below to illustrate the dynamic character of this simulation model.

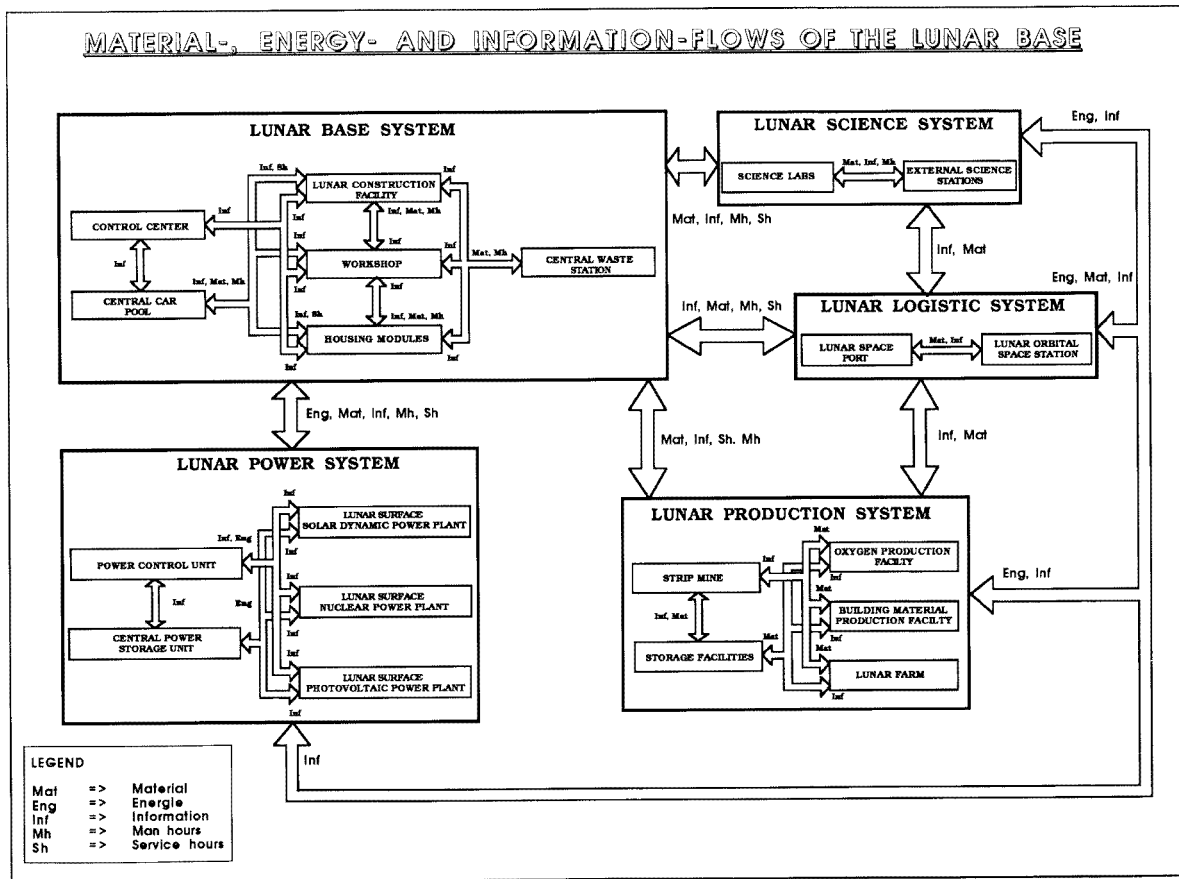


Figure 3-2: Dynamic model of typical lunar facility illustrating the flow of masses, information and energy between the elements, also indicates where lhuman labor is required.

Simplified mass data of the lunar facility analysed in this report are presented in table 3-1, summarized in the following categories:

- lunar laboratories and scientific equipment
- habitat including life support system
- production facilities
- infrastructure facilities.

Table 3-1 belowlists the theoretical growth rates as projected by the mathematical model on the basis of the relations and assumptions comprising the model. In reality however, these facilities will not grow incrementally in the early years. The base will grow rather in way of a step-function, because entire modules, not fractions of them, must be transported to the Moon. This is particularly the case in the beginning of the acquisition period. The selected model of system acquisition is determined by the capabilities of the transportation system and the available human labor at the base site. This will require a very careful planning of the manifest of the logistic system. In this process it will also effect the annual cost diistribution during the acquisition phase.

Table 3-1: Typical Growth of lunar population and facilities (metric tons)
Numbers in () indicate the individual facilities of the basic model summarized as a group .

year	lunar science crew p.a.	total lunar crew p.a.	laboratories & science equip.(7)	habitat + farm elements (18+19)	pilot prod.fac & equip. (1-6,9)	infrastructure facility & equip. (10-17)	total lunar facilities
1	3	16,6	9	60	40	116	223
2	4	31,4	12	118	49	158	337
3	6	28,4	18	119	61	160	357
4	8	32,6	24	129	71	166	391
5	10	40,2	30	161	82	179	455
6	11	38,3	34	162	86	180	464
7	12	39,9	37	166	92	180	476
8	14	43,0	41	181	95	184	501
9	15	45,4	44	193	99	187	524
10	16	48,4	48	208	104	190	551
15	25	63,9	75	288	116	205	684
20	37	86,0	111	401	125	227	866
25	41	90,7	123	434	135	230	921
30	45	100,0	135	490	140	239	1005
sum	780	1962	135	490	140	239	1005
av.	26	65.4	78	300	109	203	690

The production-oriented facilities on the Moon are considered to be at best 'pilot plants' for various production experiments, such as raw materials, feedstock, and some more complex products, such as construction materials converted to components in a mechanical workshop. The lunar oxygen production plant is an exception, it has to produce propellants for the LUBUS flights. Because this is difficult during the early years, the difference has to be imported from Earth by extra refueling flights to lunar orbit. This capability exists also during the later years if needed to provide operational flexibility.

The consumables produced on the Moon include recycled water, the gases (CO₂) and the biological wastes of the crew, but also some food produced in the biological laboratory (experimental farm), including oxygen gas using part of the waste material. The spare parts listed in table 3-2 are either handmade parts in the workshop or reworked parts which have failed in the past.

The defined facilities allow a certain production rate of various products for lunar use and export (or extending the lunar infrastructure) as a function of their size and mass. The outputs resulting from these production activities grow with size and lifetime in a modest rate and are shown in Table 3-2.

As shown in tables 3-1 and 3-2, the initial facilities are improved and extended as required by the projected production rates, partly by imported subsystems and partly by lunar produced components. The lunar produced components have to be subtracted from the total mass for extension to obtain the imports required. With increasing share, also the size of the facilities and the amount of human labor required will grow, suggesting that an optimum can be defined.

Table 3-2: Projected average annual outputs of defined lunar base facilities

- (kW or metric tons per annum)

year	lunar power produced (kW)	lunar produced spares & extensions	lunar produced consumables	products for external usage	lunar oxygen propellants	total mass output of lunar facilities
1	490	1	22	3	81	107
2	914	27	44	1	109	181
3	894	7	40	8	140	195
4	1091	11	48	11	170	240
5	1353	20	61	12	199	292
6	1318	5	58	26	212	301
7	1401	7	61	30	224	322
8	1517	11	66	31	235	343
9	1602	11	72	36	246	365
10	1704	13	76	40	257	386
15	2132	14	104	62	287	467
20	2715	26	144	75	314	559
25	2877	14	155	107	331	607
30	3179	21	172	122	346	661
average	2123	15	108	63	270	456

Table 3-3 : Projected imports required by the operational lunar base on the lunar surface as projected by the model (metric tons p.a.)

year	production supplement materials	spare-parts	new equipment	life support & consumables	lunar produced spares & consumables	total projected imports
1	2	8	223	22	23	255
2	2	14	88	35	71	139
3	2	12	14	30	47	58
4	3	14	24	32	59	73
5	3	17	46	37	81	103
6	3	16	6	35	63	60
7	4	16	8	35	68	63
8	4	17	17	36	77	74
9	4	18	15	37	83	74
10	5	18	18	38	89	79
15	6	21	15	44	118	86
20	6	24	26	57	170	113
25	7	25	6	55	169	93
30	7	25	13	58	193	103
sum	150	600	510	1368	3240	2640
average	5	20	17	46	108	88

The initial facilities have to be transported to the Moon before or shortly after the arrival of the first crew are listed in line year 1 in table 3-3. A detailed assembly analysis will result in a better distribution of the imports during the first 3 to 5 years. In due course of development, all complex facilities and equipment will have to be imported, also most of the food. In general it can be expected that the import rate of supplies per crew member will decline during the life cycle due to increased use of lunar products. The selfsufficiency remains limited, a consequence of keeping the

initial investments low. There is plenty of room for increasing the selfsufficiency, but this would require a different base concept.

Taking the data from the above tables a comparison of the masses produced on the Moon for lunar purposes and the total projected imports is possible.

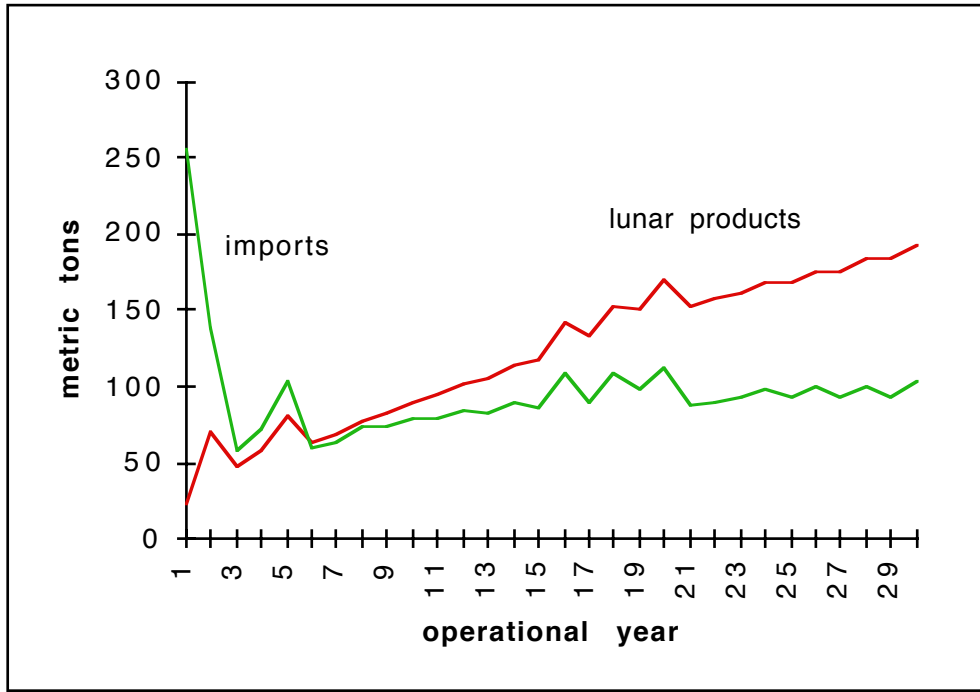


Figure 3-3 : Development trends of lunar products mass for lunar use and the mass of imports to the lunar surface (metric tons p.a.)

This frame of reference for the crew size, the mass of the lunar facility, their output and input requirements must be the basis for selecting a suitable space transportation system. This vehicle program, to be discussed in chapter 4, has to be sized and structured with respect to performance and capacities required by the lunar and other space programs. In this case study it is assumed, that the initial lunar base program would be the driver of the space transportation system under consideration.

Generally, in planning a logistic system such as a lunar space transportation system, one has already a fairly good picture of the space transportation system that may or should be available to size the lunar propellant production facility accordingly, otherwise, an iteration process between lunar facility and lunar space transportation system will be unavoidable. However, before the space transportation system is discussed, the cost estimates of the lunar facilities are presented.

3.2 Acquisition and operating costs of lunar facilities

Non-recurring cost:

The program structure shown above is the basis for estimating program cost. To estimate costs and distribute these over the calendar years is the next task to be accomplished. This cost estimate begins with the non-recurring costs of the program,

to be carried out during an eight to ten year development and test phase of subsystems and total system compatibility. These costs are primarily the development costs, first unit costs and cost of system testing.

Table 3-4: Overview of preliminary estimates of the upfront costs of lunar facilities (1 direct labor-year = 0.2 M 1999\$)

no.	Facility designation	development cost M \$	first unit cost M \$	system integration cost M \$	total upfront costs M \$
1	strip mine	10	11	0	21
2	beneficiation facility	50	18	12	80
3	chemical processing facility	600	130	31	762
4	mechanical processing facility	500	87	17	605
5	fabrication plant	600	41	21	662
6	assembly shops	300	17	18	335
7	laboratories	150	63	22	235
9	gas processing facility	70	11	19	99
10	propellant storage	40	25	20	85
11	power plant	500	464	46	1,011
13	space port	160	35	29	225
14	central storage	30	14	12	57
15	central workshop	750	44	17	811
16	carpool	100	46	14	160
17	control center	1,000	374	187	1,561
18	housing facility	1,000	748	249	1,997
19	biological processing facility	500	100	25	625
sum	million (1999) \$	6,370	2,229	741	9,340

These costs have to be distributed over the duration of the development phase. The program resources required start have a peak towards the end of the development period which will be over 2,000 M \$. If a ten year development phase is assumed, there will be little demand for resources in the first three years concentrating on detailed planning, system analysis and preliminary design,

Table 3-5: Annual distribution of of non-recurrent cost of lunar facilities (M \$)

year	Development	1st unit cost	systems integration	total cost
-8			17	17
-7	70		40	110
-6	300		75	375
-5	500		89	589
-4	1,000		100	1,100

-3	1,200		100	1,300
-2	1,400	700	100	2,200
-1	1,200	800	100	2,100
0	700	729	120	1,549
totals	6,370	2,229	741	9,340

Recurrent cost of lunar base facilities

The "recurrent cost" during the operational phase are presented next, first of the lunar facilities and equipment. Table 3-6 presents the direct operating costs associated with the lunar facilities proper. This includes the imports such as equipment and consumables. It indicates the estimated level of supporting effort required back on Earth in the areas of sustained engineering for facility extensions and improvements, but also administration, science support, training of lunar crews and their salaries. All this adds up to the operating cost of the LULAB facilities, however, it does not include transportation cost! The LULOX cost and lunar STS services are included in this list, but could also be charged to the space transportation system, if a different accounting system is preferred. The alternatives available are discussed and presented in Appendix C.

Table 3-6: Direct operating cost of Lunar Base (million 1999 \$ p.a.)

year	total imports suppl.& equipment	sust. eng , admin., science support, crew training	crew salaries	total recurrent lunar base costs
1	93	327	21	441
2	1085	327	32	1,444
3	259	327	29	615
4	577	327	33	937
5	589	327	36	953
6	234	327	35	597
7	349	327	36	713
8	386	327	38	751
9	385	327	39	752
10	403	327	41	771
15	450	327	51	829
20	545	327	65	937
25	421	327	70	818
30	441	327	75	843
av	443	327	53	823

3.3 Specific costs of lunar products and services

As a consequence of these investments and activities the lunar base is producing values by offering services, such as laboratory spaces, or products, such as construction material, lunar propellants and feedstock. The mass flows and services as projected have been presented in tables 3-1 and 3-2 in absolute terms, but not their specific costs. If the overhead costs of the lunar base operation are prorated on the bases of mass flows, human labor and energy consumed over all products and services offered, then their specific cost are obtained.

If a market can be found for some of these, the expenditures to be provided by public funds in the beginning of this extraterrestrial human activity would be reduced accordingly. The following table presents the respective cost data on the basis that the transportation costs are paid by the public agencies involved and thus are *not* prorated over the individual products and services. Thus the specific costs presented are theoretical minimum direct costs only, since they do not yet take into consideration transportation costs, interest, taxes and profits. In a commercial environment the transportation cost would have to be included. Consequently commercial prices would be higher than shown in the next tables. Alternative accounting models are presented in Appendix C.

Table 3-7: Specific direct costs of lunar products and services excluding logistic costs, financing and profit

year	lunar oxygen (\$/kg)	laboratory (M\$/MY)	workshop (M\$/MY)	habitat (M\$/MY)	recycld. products (\$/kg)	control center (M\$/MY)	power plant (\$/MWh)	port services (\$/kg)	export goods average (\$/kg)	av.tot. lunar output (\$/kg)
1	3,540	28	57	15	12,104	48	17,262	79	17,957	4,100
2	13,306	176	476	111	82,321	195	112,246	1,039	12,099	13,295
3	2,275	35	40	12	11,168	40	11,185	98	8,590	2,605
4	2,835	43	75	24	19,762	51	27,198	113	8,322	3,118
5	2,298	36	69	21	16,302	46	22,293	98	7,017	2,619
6	1,163	17	38	9	7,620	33	8,777	55	5,060	1,587
7	1,301	21	52	13	10,369	37	11,508	62	4,724	1,674
8	1,267	21	55	13	10,266	37	12,503	61	4,397	1,636
9	1,160	19	53	12	9,597	35	11,542	58	4,075	1,537
10	1,103	19	51	12	9,402	35	11,337	56	3,818	1,478
15	833	16	44	10	8,033	30	9,298	43	2,720	1,162
20	701	14	38	9	7,368	26	8,452	36	2,107	980
25	532	10	34	6	5,568	23	6,242	29	1,684	808
30	478	10	32	6	5,347	22	5,829	27	1,466	737
av	1,058	14	70	10	8,220	35	10,049	66	2,339	1,298

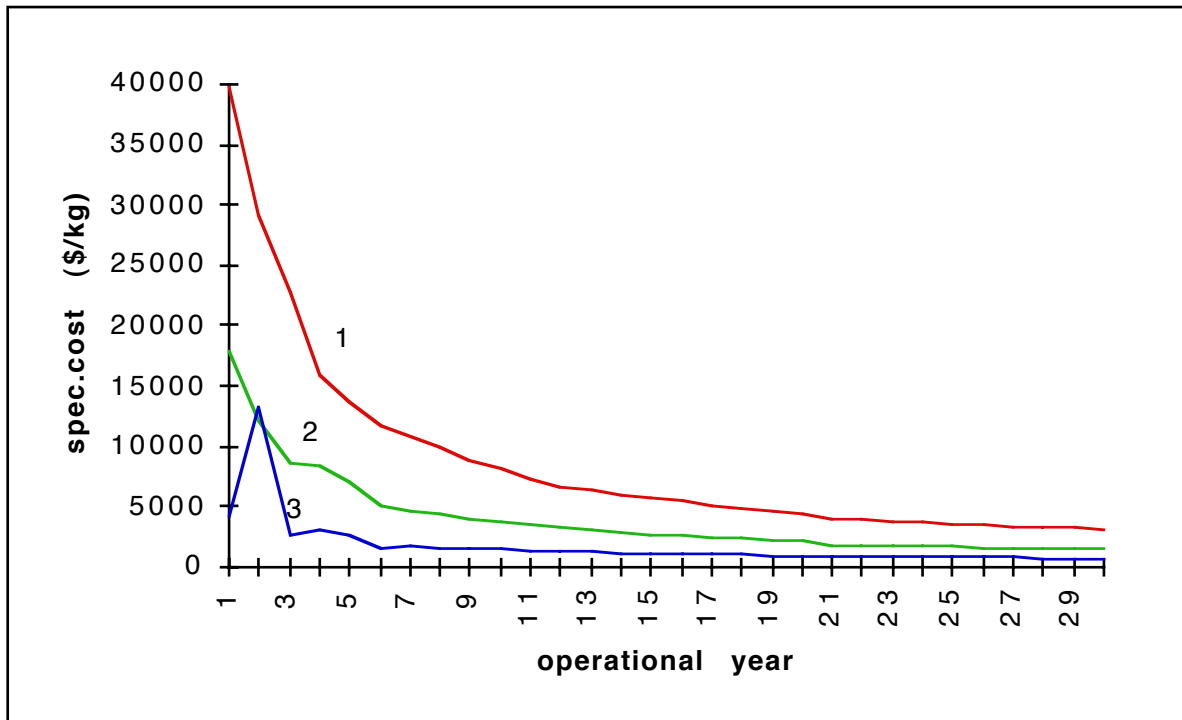


Figure 3-4: Trends of specific cost of selected lunar products excluding space transportation cost -1 = all lunar products for local lunar use, 2 = products for commercial use or infrastructure build-up on the Moon, 3 = average cost of all lunar products including Lulox

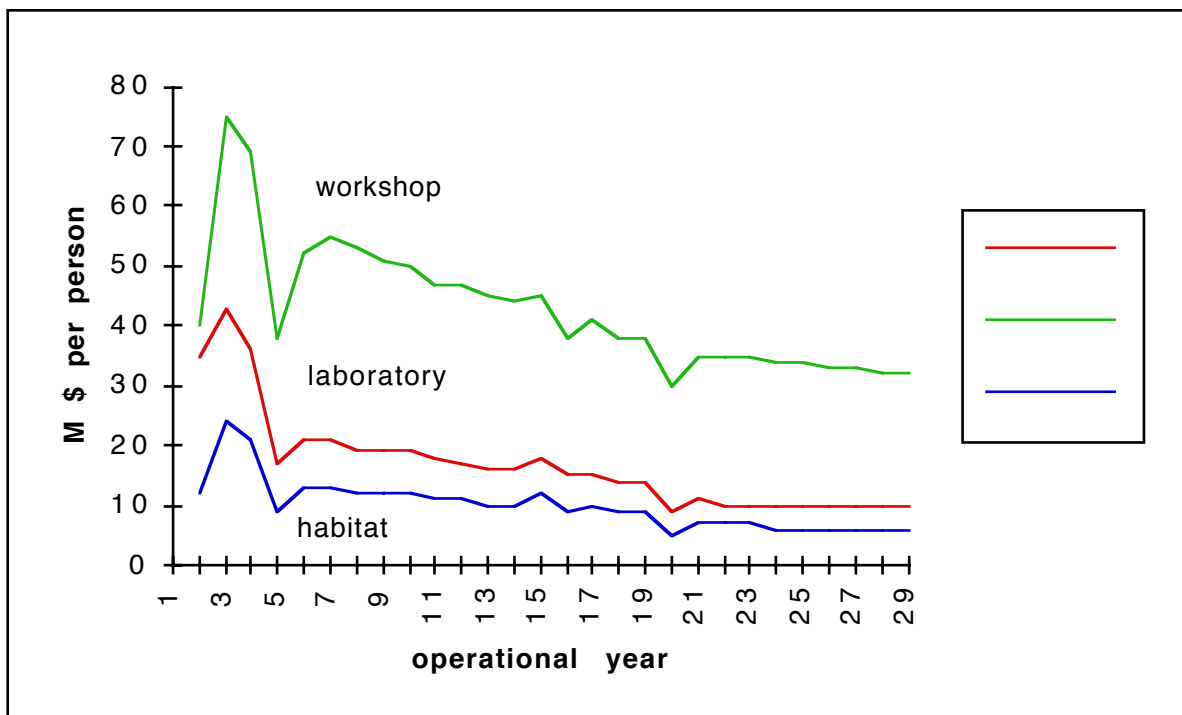


Figure 3-5: Trends of specific costs of selected lunar facilities (M \$ per labor-year) excluding transportation cost

In general, these figures show that it is expensive to produce lunar goods and services within the frame of a *small* lunar facility as described in this scenario, because the production volume of this science oriented operation is quite low.

Of particular interest (of the items listed) are the specific cost of lunar produced oxygen, listed in the first column of table above. The life-cycle average price is 1,058 \$/kg, which is an equivalent of about 5.2 labor-years. This value would have to be entered into the TRASIM model as the minimum price to be paid for using lunar oxygen propellants to obtain the total transportation cost including the Lulox refueled on the Moon.

Also of special interest is the next column, illustrated in figure 3-5, indicating that a working space in the laboratory research and development facilities could be leased for an *average* of 14 M \$ p.a. , excluding the roundtrip cost of the research scientist.

Multiplying the specific cost of lunar products and services with the annual amounts (mass, labor years, kWh) yields the annual "sales" to be realized in terms of million (1999) \$, if they are to cover the cost of the operation. The lunar laboratory would have - under these assumptions - the sales potential presented in table 3-8.

Table 3-8: Projected total annual sales potential (million \$ p.a.) with transportation cost not charged to the Lunar Base

year	exports or infra-structure	pro-pellants	port services, and maintenance of Lulox	laboratory spaces leased	sales of all products and services	products used by lunar base
1	59	288	13	85	445	82
2	131	454	109	706	2283	733
3	66	320	10	210	606	233
4	77	483	18	346	923	297
5	102	460	17	362	941	280
6	131	247	10	201	590	119
7	130	292	14	270	705	155
8	138	298	15	292	743	158
9	149	286	14	295	744	148
10	157	284	14	309	764	147
15	165	240	13	405	823	136
20	165	221	12	535	932	149
25	176	176	11	450	814	109
30	181	166	11	482	839	110
av	147	286	16	398	846	162

4. The Lunar Space Transportation System (LSTS)

4.1 System definition

The governing factor for the conceptualization, acquisition process and operation of the lunar laboratory specified above, is the payload capability and launch rate of the **Lunar Space Transportation System (LSTS)** to be employed. It determines the size and the growth rate of the lunar installation. The cost of the Logistics operation is the prime parameter of the entire life-cycle system cost. Generally, pre-fabricated modules with large dimensions and masses transported to the Moon are preferred, because they lead to reduced requirements of expensive human labor on the Moon. On the other hand, if the average flight frequency is less than four flights p.a. then the operational flexibility may suffer. Furthermore it must be assured that enough reserve payload capability will be available^{10,20} for unforeseen emergencies and companion space programs.

The logistic support system for the lunar base selected in this case study is a near state-of-the-art fully reusable space transportation system, using high energy chemical propellants and available subsystems from the Shuttle and other existing programs^{9,10,20}. After a nine to ten year carefully planned development and flight-test period, the system is expected to offer an initial operational capability by about the year 2016. This could be done in a shorter time but at increased peak cost! The system selected offers considerable growth potential for other Earth orbital, lunar and planetary programs. Aside from spaceports on the Earth and the Moon, the **Lunar Space Transportation System (LSTS)** conceived is comprised of three elements :

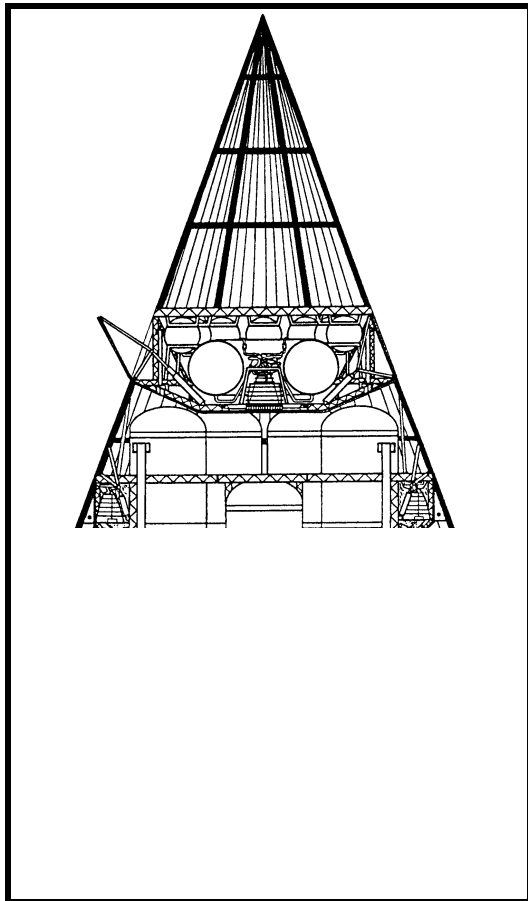
- (1) A three stage **Heavy Lift Launch Vehicle (HLLV)** for passenger and cargo transportation between the Earth spaceport and a space operations center in lunar orbit, or direct flights to the lunar surface respectively,
- (2) a **Space Operation Center (LUO-SOC)** in a low lunar orbit (100 km) - or possibly in L2 - , being used during standard operations for the transfer of passengers and cargo payloads, but also as propellant storage and maintenance facility, and
- (3) a **Lunar Bus (LUBUS)** for local transportation of passengers and cargo between the lunar spaceport and the LUO-SOC.

4.2 The Heavy Lift Launch Vehicle (HLLV)^{10,20}

The **HLLV** employed in this scenario has a launch mass of 6,000 tons, allowing a payload capability of **110 metric tons (t) to lunar orbit** and of about **50 t to 60 t** to the lunar surface. This payload capability is the average performance during the entire life cycle. It could be somewhat lower in the early years and should grow during the life-cycle resulting from regular product improvement efforts. To keep the model simple, the payload capability is kept constant throughout the life-cycle of the lunar laboratory. This assumption does not change the overall life-cycle performance of the conclusions..

Figure 4-1:
Longitudinal cross-section of
the **NEPTUNE -2015**
HEAVY LIFT LAUNCH VEHICLE

Technical University Berlin



This three stage heavy lift launch vehicle, based on the NEPTUN concept shown in this picture, has been developed by the Aerospace Institute of the Technical University of Berlin during the last two decades for an employment in a multi-mission global space program^{4,9,10,20}.

Among other applications, it can either transport cargo, passengers (or in a mix passengers with some cargo) to the lunar orbit. The dry mass of the payload stage is 47 metric tons and the net mass is 52 t. The return flights with a 50 mt passenger or cargo module require a mass ratio of 1.30, thus a gross mass of 132 t including 30 mt of return propellants, which it brings along from the Earth in its early lunar logistics job. Subtracting these from the 110 t nominal payload results in an **effective payload delivered to the lunar orbit of 80 t** for the passenger version, and **95 t** for the cargo version of this launch vehicle, aside of the return requirements. -

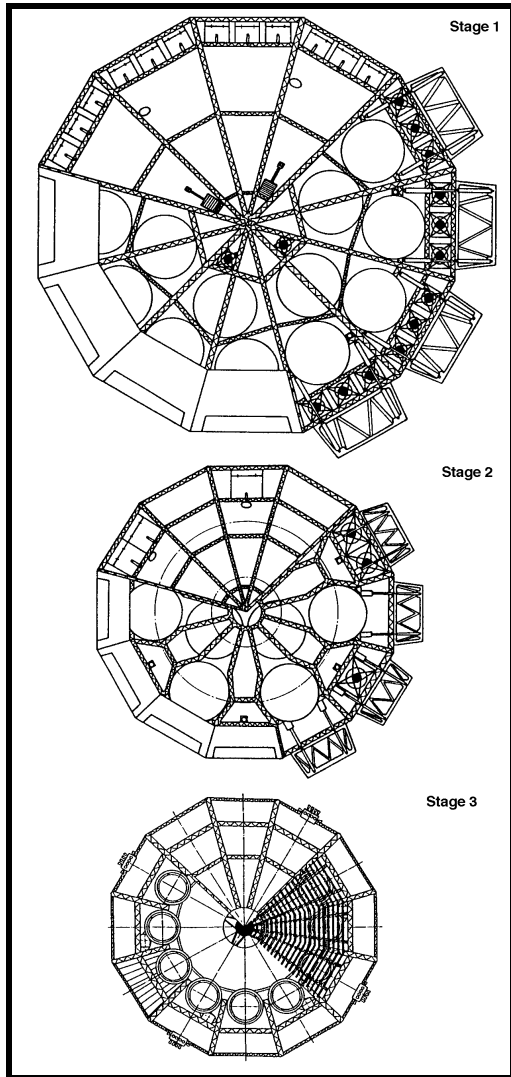
The dimensions of this three stage NEPTUNE launch vehicle are 40 meters wide and 72 m high. Payload dimensiones can be up to 17 x 24 m.

The HLLV passenger version carries a 50 ton crew cabin including **40 passengers**. It is attached to the 3rd stage and is capable of returning to the Earth from the LUO-SOC without refueling. With a 50 t module, a 30 t propellant capacity for the return flight and about 12 t of hydrogen for the LUBUS a total of 92 t are required, which leaves up to 18 t of equipment or propellants delivered to support the lunar SOC. This excess of payload capability can also be considered as a design and/or performance margin.

Figure 4-2:

Horizontal cross section of the three stages of the NEPTUNE -2015 heavy lift launch vehicle

Aerospace Institute
Technical University Berlin



Cargo vehicles can either return empty to the Earth or with a cargo of lunar products or equipment up to 50 t. In addition, the 3rd stage carries also the hydrogen required for the continuing flight of the LUBUS roundtrip between LUO and lunar base as a standard operational procedure in this analysis. The HLLV standard cargo version would thus have a capability to carry a **63 t cargo** module, 15 mt of propellants for return to Earth, 15 t for refueling the LUO-SOC and 17 t liquid hydrogen propellants for LUBUS operation, adding up to 110 t nominal HLLV payload capability.

The payload platform of the 3rd stage has a diameter of about 17m, which must be made compatible with the LUBUS which has a core platform with only a diameter of about 7 m. Thus supporting struts will ne needed for stability. Additional payload containers can be placed between the engines of the 3rd stage if required .

Several **direct flights of the HLLV** with the LUBUS as a 4th stage to the Moon may be needed during the early acquisition phase to transport the initial facility modules to the lunar base site before or shortly after the arrival of the first crew. These flights will then be scheduled in addition to the regular flight plan, considering only the supply and crew rotation demands. The empty landing stage, a slightly modified LUBUS, would remain on the Moon and be available for storage of liquids and gases, or as back-up vehicles for the standard LUBUS .

4.3 The lunar orbit service center

The lunar orbit operations center (LUO-SOC) has an empty mass of about 250 t and it is a modified second stage of the HLLV²⁰. This space facility is scheduled to be activated in lunar orbit, before the first lunar crew arrives. Under standard operational conditions, the LUO-SOC has a maintenance crew of 3-6 astronauts depending on the traffic. An average crew duty cycle of six months is assumed resulting in additional secondary missions.

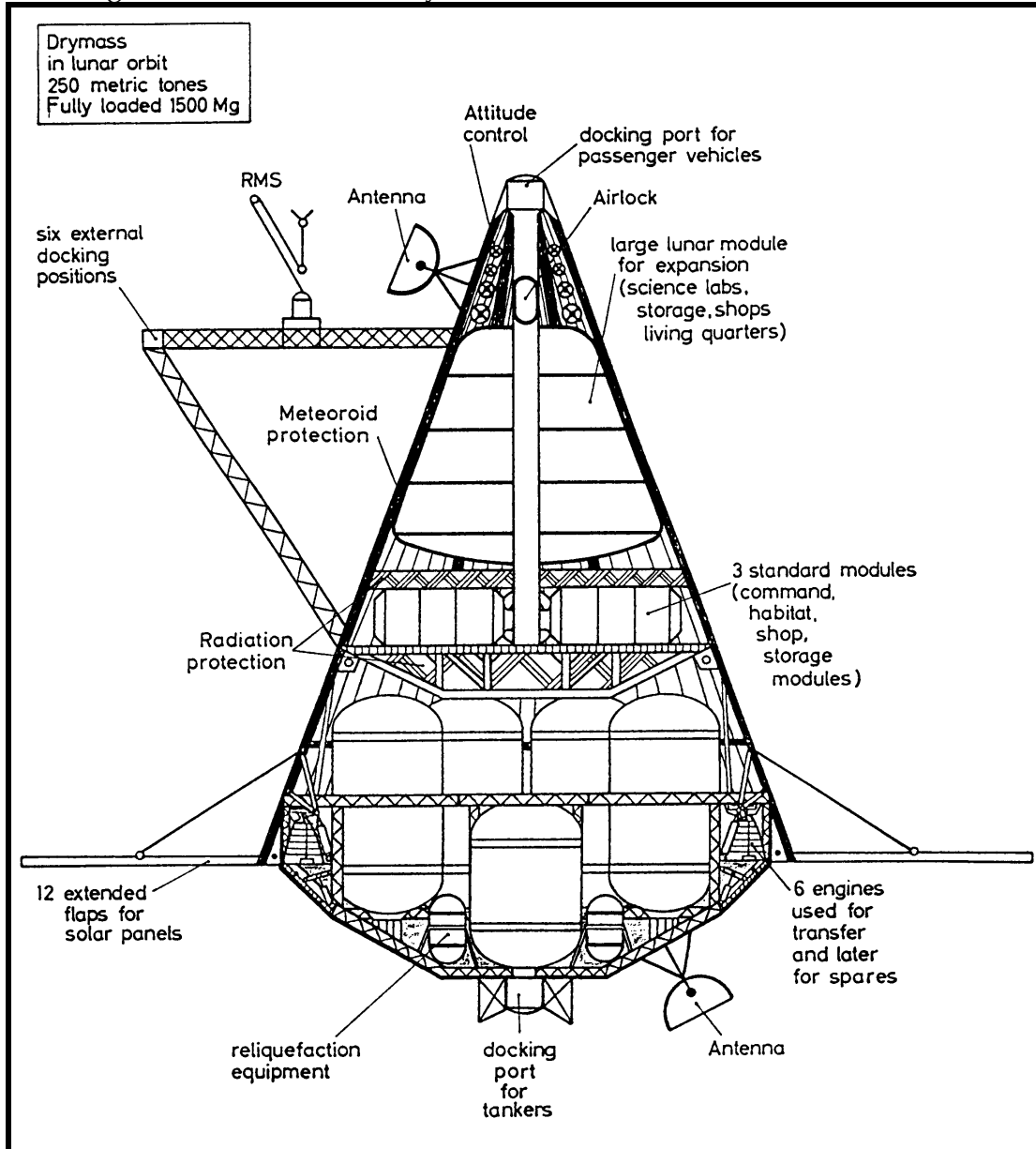


Figure 4-3: Space Operations Center(SOC) derived from the second stage of the NEPTUNE HLLV

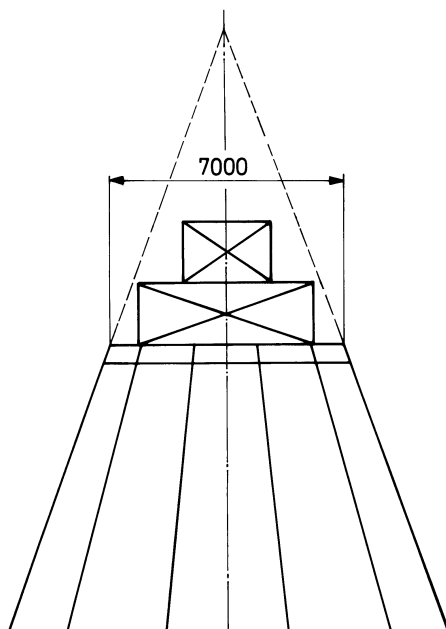
It transports itself during the first operational year in an extra flight to the lunar orbit, after modifications, refueling and checkout have been completed in low Earth orbit.

The transfer of the LUO-SOC from the low Earth orbit to lunar orbit requires a velocity increment of 4,165 m/s, with an effective exhaust velocity of $c = 4,500$ m/s this results in a mass ratio

requirement of $r = 2.523$. The LUO-SOC with a dry mass of 250 t arrived in LEO with 300 t residual propellants to be modified for its lunar orbit mission. After refueling 2×300 t in LEO, its take-off mass is $250 + 900 = 1,150$ t. The required mass ratio of 2.523 leads to a SOC mass at arrival in LUO of $1,150 : 2.523 = 456$ t or 250 t hardware, some 26 t unusable residuals and about **180 t** of propellants for later use by the LUBUS. Thus two secondary refueling flights to low Earth orbit (LEO) with about 300 mt are required by the HLLV to make this transfer of the LUO-SOC facility into lunar orbit by using its own propulsion system, feasible. Some propellants remain onboard of the SOC after arrival in lunar orbit, if completely fueled in LEO before departure. These propellants are needed for supplying the initial LUBUS flights due to a limited LULOX production capability on the Moon in the early years.

4.4 The lunar launch- and landing vehicle (LUBUS)

Figure 4-4:
The lunar launch and landings vehicle - LUBUS



Dimensions:

Diameter max: 17 m,

height: 24 m,

cargo platform: 7 m.

The lunar launch- and landing space vehicle is a single stage vehicle. It is a modified third stage of the heavy lift launch vehicle with a 7 meter loading platform on top and other payload locations at the bottom. Using a characteristic velocity requirement for a single flight between the lunar orbit and the lunar spaceport of 2,000 m/s and an exhaust velocity of 4,500 m/s, the resulting minimum mass ratio becomes 1.56. These assumptions lead to the mass- and performance data given in the table below, determining the lunar landing- and launch vehicle (LUBUS) design. The masses specified are then used for estimating the additional development and production costs.

There are several modes of operation, depending from the location where the refueling takes place.

Table 4-1: LUBUS Flight performance

Mode 1: Refueling on the lunar surface

LUBUS Passenger Flights:

DOWN LEG from LUO-SOC:

empty stage	20 t
crew cabin with crew	25 t (40 passengers for 1 hr flight time)
<u>hydrogen for ascent</u>	<u>7 t</u>
<u>stage at cut-off</u>	<u>52 t</u>
usable propellants required	30 t (5t LH ₂ + 25 t Lulox)
<u>take-off mass in LUO</u>	<u>82 t</u>
ASCENT of the Passenger LUBUS from LUS to LUO:	
empty stage mass	20 t
cabin with crew	25 t (max.capacity 40 persons for 1 hr)
<u>Lulox for down leg</u>	<u>25</u>
<u>cut-off mass</u>	<u>70 t</u>
usable propellants required	40 t (7 t LH ₂ + 33 t Lulox)
<u>Take-off mass on the Moon</u>	<u>110 t</u>

LUBUS Cargo flights:

DOWN LEG from LUO-SOC:

empty stage mass	20 t
cargo incl.packaging	63 t
<u>hydrogen for ascent</u>	<u>10 t</u>
<u>cut-off mass on the Moon</u>	<u>93 t</u>
usable propellants required	52 t (7 t LH ₂ + 45 t Lulox)
<u>Take-off mass in LUO</u>	<u>145 t</u>
ASCENT of Cargo-LUBUS:	
empty stage mass	20 t
Lulox for down-leg	45 t
return cargo	50 t
<u>cut-off mass</u>	<u>115 t</u>
usable propellants required	64 t (9 t LH ₂ + 55 t Lulox)
<u>Take-off mass on the Moon</u>	<u>179 t</u>

ONE WAY cargo down from lunar orbit without refueling:

<u>Take-off mass in LUO</u>	<u>100t</u>
propellants used	36t
cut-off mass on the Moon	64 t
empty stage mass	18 t
cargo and residuals	46 t

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

Mass-balance of HLLV cargo-flights : 15- 30 t return propellants or propellants delivered to the SOC + 16 t + 1 t losses hydrogen for LUBUS,+ **63 t cargo** container = 110 t total payload delivered to LUO, used as *nominal* payload capability for this scenario.

Lunar LOX-requirements at the lunar spaceport:

Passenger flights : 25 + 33 + 2 losses = 60 t per flight
Cargo flights: 55 + 45 =100 t per flight

It has to be noted that the LUBUS propellant tanks have to be sized allowing the refueling of both propellants for the entire roundtrip. All hydrogen is fueled in lunar orbit, all oxygen is fueled on the Moon! This requires a large tank volume and explains the relatively large dry mass of this vehicle.

Mode 2: Refueling in lunar orbit

The reduced production of Lulox in the early years requires special propellant flight to the LUO-SOC to insure that enough propellants are available for refueling in lunar orbit instead on the lunar surface. A second mode of operating the lunar bus must be introduced, leading to a modified mass model for those missions which can not refuel on the lunar surface, as follows

LUBUS mass model for missions with Earth LOX/LH2, refueled in lunar orbit:

Mass ratio: 1.56, $\Delta v = 2000 \text{ m/s}$, $C = 4600 \text{ m/s}$

Passenger flights:

DOWN:

empty stage	20t
crew cabin	25t
propellants up	25t
cut-off	70t
propellants down	40
launch mass	110t

UP:

empty stage	20t
crew cabin	20t
cut-off mass	45t
propellants up	25t
launch mass	70t

total LUO propellants down and up = **65 t per mission (of this 35 t refueled in LUO)**

Cargo flights:

DOWN:

empty stage	20t
cargo	55t
propellants up	17t
cut-off	92t
propellants down	53t
launch mass	145t

UP:

empty stage	20t
cargo	10t
cut-off mass	30t
propellants up	17t
launch mass	47t

total LUO propellants down and up = **70 t per mission (of this 35 t refueled in LUO)**

Mass ballances HLLV Earth- Lunar Orbit:

HLLV passenger missions:

50 t crew module + 30t return propellants + **65t** Lubus propellants required = 145t needed. 110t of these are available in 3rd stage for delivery to LUO-SOC. Thus **35t**

additional propellants to the **30t** brought by the HLLV must be refueled by the LUBUS from LUO-SOC on passenger flights.

HLLV Cargo missions:

20t return propellants + **70t** Lubus propellants + 55t lunar cargo = 145t.

110t total are available at LUO arrival. **35t** additional propellants to be refueled by the LUBUS from LUO-SOC on cargo flights to the 35 t brought along by the HLLV.

4.5 Space Transportation System Schedule and Performance

4.51 STS - Mission Plan

In the early years the number of logistic missions from the Earth spaceport to the lunar spaceport will be limited. This does not allow the transportation of all facilities in the first year. However, propellants are required for the return of the lunar bus to lunar orbit which would have to be imported if not available on the Moon. This requires an optimization and leads to a limited number of refueling flights to the lunar orbit service station during the first 4 or 5 operational years. A detailed analysis presented in table 4-3 leads to the following total requirements:

Table 4-2. Summary of the logistic requirements:

43 cargo missions @ 60 t = 2,580 t imports

+7 cargo missions @ 50t = 350t imports

total = 50 cargo missions with 2,930 t.

43 cargo missions (mode 1) require 100t Lulox each on LUS = 4,300 t

7 initial cargo missions (mode 2) require 35 t propellants each in LUO = 245 t

5 refuelling missions @ 100 t bring to LUO = 500 t total

1 LUO-SOC arrives with 200t residuals in lunar orbit

47 passenger missions (mode 1) leave 18t residuals propellants in LUO = 846 t

47 passenger missions (mode 1) require 60t propellants each on LUS = 2,820 t

23 passenger missions (mode 2) require 35t propellants each in LUO = 805 t

A total of 8,103 t or an average of 270 t p.a. lunar oxygen are produced

with 983 t remaining in store on the Moon in at the end of the LC

also 496 t of LOX remain in the LUO-SOC at the end of the LC

At 1,968 lunar person-years and a passenger transportation capacity of

$70 \times 38 = 2,660$ roundtrips, this leads to an average duty cycle of

$1,962/2,660 = 0.74$ years or nearly 9 months.

A control calculation of the propellants available at the depots in lunar orbit and on the lunar surface from year to year must thus be made. It is presented in table 4-3 and illustrates the mass balances of the logistic system in lunar orbit and on the lunar surface.

Table 4-3: Mass balances of propellants and imports, and determination of number of missions required during the 30 year operational period

	no . pass. flights mode 1 (18 imp.) mode 2 (35 luolox)	im- port req. (t)	cargo miss. mode 1(60) 2(50)	car- go capa- city t	luolox req. / luolox req.	Luolox pro- duced and - used	lox impor- ted to LUO	HLLV missions to LUO	propellants available in LUO (200 in SOC)
1	0+1	255	0+5	250	0/ -210	81-0=81	200	1+7	200+200 -210= 190
2	0+1	139	1+1	110	-100/ -70	81+109 -100=90	100	1+3	190+100 -70=220
3	1+1	58	1+1	110	-160/ -70	90+ 140 -160= 70	100 +18	2+3	220+100 +18 -70=268
4	1+1	73	1	60	-160/ -35	70+170 -160=80	100 +18	2+2	268+100 +18 -35=351
5	0+2	103	2	120	-200/ -70	80+200 -200= 80	0	2+2	351-70 = 281
6	1+2	60	1	60	-160/ -70	80+212 -160=132	18	3+1	234+18 -70=182
7	1 +1	63	2	120	-260/ -35	132+224 -260=96	18	2+2	182+18 -35 =165
8	1+1	74	1	60	-160/ -35	96+235 -160=171	18	2+1	165+18 -35=148
9	1+1	74	2	120	-260/ -35	171+246 -260=157	18	2+2	148+18 -35 = 131
10	2+1	79	1	60	-220/ -35	157+257 -220=194	36	3 +1	131+36-35 =132
11	1+1	79	2	120	-260/ -35	194+263 -260=197	18	2+2	132+18-35 =115
12	2+1	84	1	60	-220/ -35	197+270 -220=247	36	3+1	115+36-35 =116
13	1+1	83	2	120	-260/ -35	247+275 -260=262	18	2+2	116+18-35 =99
14	2+1	89	1	60	-220/ -35	262+280 -220=322	36	3+1	99+36-35 =100
15	1+1	86	2	120	-260/ -35	322+288 -260=350	18	2+2	100+18-35 =83
16	2+1	109	1	60	-220/ -35	350+293 -220=423	36	3+1	83+36-35 =84
17	2+0	90	2	120	-320/0	423+300 -320=403	36	2+2	84+36 =120
18	3+0	109	1	60	-280/0	403+305 -280=428	54	3+1	120+54 =174
19	2+0	98	2	120	-320/0	428+310 -320=418	36	2+2	174+36 =210
20	3+0	113	1	60	-280/0	418+315 -280=453	54	3+1	210+54 =264
21	2+0	88	2	120	-320/0	453+320 -320=453	36	2+2	264+36 =300
22	2+0	90	1	60	-220/0	453+322 -220=555	36	2+1	300+36 =336
23	2+0	93	2	120	-320/0	555+325 -320=560	36	2+2	336+36 =372
24	2+0	99	2	120	-320/0	560+328 -320=568	36	2+1	372+36 =408

25	2+0	93	2	120	-320/0	568+332 -320=580	36	2+2	408+36 =444
26	2+1	100	1	60	-220/ -35	580+335 -220=695	36	3+1	444+36-35 =445
27	2+1	94	2	120	-320/ -35	695+338 -320=713	36	3+2	445+36-35 =446
28	2+1	101	1	60	-220/ -35	713+340 -220=833	36	3+1	446+36-35 =447
29	2+1	94	2	120	-320/ -35	833+344 -320=857	36	3+2	447+36-35 =448
30	2+1	103	1	60	-220/ -35	857+346 -220=983	36	3+1	448+36-35 =449 (496)
av		88				270			
tot	70	2873	50	2930	7120	8103	+1346	120+5F	1546 -1050

With the number of missions known, the cost of the space transportation system as specified can be calculated by the TRASIM code. This is done on an annual basis, but for an overview, it is sufficient to present first the average values for the entire life-cycle.

4.6 Acquisition and operating cost of space transportation system

4.6.1 Overview

With the number of missions known, the cost of the space transportation system as specified can be calculated by TRASIM. This is done on an annual basis, but for an overview it suffices to present the average values for the entire life-cycle. The hardware available at the end of the arbitrary life cycle is not fully used thus it has a residual value. This is the difference of the total cost and the cost based on a standard amortization of the flight hardware using the design life time of the vehicles as a reference and not the number of missions flown till the end of the assumed life cycle.

Table 4-4. Summary of STS total life-cycle cost (M \$)

Initial research and development	18,923	
product improvement		4,146
vehicle production	9,911	
mission operations	6,620	
total including residual value		39,600
annual average over 40 year LC	990	

Table 4-5: Overview of average LC cost per prime mission (M \$)

	-ES-LUO passengers	-ES-LUO cargo	ES-LUS passengers	ES-LUS cargo
direct cost	110	115	129	127
amortization	133	107	170	120
total cost per flight	243	222	299	247

Table 4-6: Average LC specific cost - (passenger: 1000 \$/passenger ; cargo: \$/kg)

	-ES-LUO passengers	-ES-LUO cargo	ES-LUS passengers	ES-LUS cargo
direct cost	2,911	1,908	3,398	2,119
amortization	3,501	1,782	4,469	2,004
total cost per flight	6,412	3,690	7,867	4,123

Table 4-7: Life cycle cost on the basis of mission cost (M \$)

70 passenger missions to LUS
50 cargo missions to LUS + 5 to LUO

Million \$ (1999 value)	-ES-LUO cargo	ES-LUS pass	ES-LUS cargo	total
direct	575	9,030	6,350	15,955
amortization of development	535	11,900	6,000	18,435
total	1,100	20,930	12,350	34,390
remaining value at LC end				5,210
40 year total cost of STS				39,600

4.62 Annual non-recurring cost:

The program structure of the space transportation system as described above is the basis for estimating program cost. The next task to be accomplished is to distribute them over the calendar years.

This estimate begins with the non-recurring costs of the program to be carried out during an eight to ten year development and test phase, before the operational phase can be initiated. These costs are primarily development costs and first unit costs derived by cost estimating relationships developed using relevant data on past experience during the last decades and entered into the TRASIM code^{10,23}.

This cost estimate of the up-front costs (= non recurring costs) summarized in table 4-8 is followed by an estimate of the recurrent cost of the logistic system during its operational phase (table 4-9). Knowing the vehicle flights required, it is possible to derive at preliminary cost estimates for the various elements of the space transportation system.

Table 4-8: Non-recurrent cost of space transportation system (million 1999 \$)

year	HLLV+LUBUS development including 1st units	crew modules & payload development	LUO-SOC development excluding 1st unit	total up-front investment
-8	50	0	0	50
-7	150	20	20	190
-6	968	60	33	1,061

-5	1,803	289	75	2,167
-4	2,291	825	94	3,210
-3	2,513	1,091	102	3,706
-2	2,343	1,150	94	3,587
-1	1,874	960	75	2,909
0	1,322	645	53	2,020
totals	13,314	5,040	546	18,900

4.63 Annual recurrent cost of space transportation system

The lunar space transportation system is comprised of the two vehicles HLLV and LUBUS plus the LUO-SOC as described above. A total of about 120 HLLV primary flights comprise this 30 year program. These vehicle costs are estimated with the TRASIM model of the Aerospace Institute of the TU Berlin (1990)^{10,23} and are presented in tables 4-9 and 4-10.

Table 4-9: Overview of space vehicle direct operations cost per mission and specific transportation costs of cargo and passenger transportation of primary flights during the operational phase excluding Lulox cost and cost of lunar services - (million 1999 \$, M \$ per seat and \$/kg respectively)

year	total direct cost of passenger missions ES-LUS	total direct cost of cargo missions ES-LUS	direct cost per passenger seat ES-LUS -1000 \$	direct cost of cargo ES-LUS \$/kg
1	210	183	5,538	3,036
3	135	120	3,566	1,995
6	136	120	3,581	2,012
10	135	119	3,532	1,990
15	129	115	3,387	1,909
20	123	109	3,230	1,815
25	124	111	3,277	1,850
30	113	100	2,982	1,668
av	123	134	3,398	2,119

Table 4-10: Overview of sustained engineering, production, operations and total cost during the operational phase (million 1999 \$; 1 MY = 0.2 M \$)

year	sustained engineering cost	production cost	operations cost	total recurring cost
1	138	5,138	782	6,058
2	138	2,323	214	2,676
3	138	218	268	625
4	138	31	214	384
5	138	32	214	385
6	138	27	223	389
7	138	10	208	357
8	138	54	162	355
9	138	25	204	367
10	138	249	213	601
11	138	24	199	362

12	138	431	209	778
13	138	8	195	343
14	138	22	206	366
15	138	24	193	355
16	138	21	203	363
17	138	45	190	375
18	138	23	201	362
19	138	237	188	564
20	138	7	198	344
21	138	22	186	347
22	138	184	146	470
23	138	384	184	707
24	138	19	184	341
25	138	21	183	342
26	138	7	193	338
27	138	43	230	411
28	138	230	191	560
29	138	20	228	387
30	138	18	190	347
total	4,150	9,900	6,600	20,650
average	138	330	220	688

It should be noted, that calculations of this type are based on the assumption that the vehicles will fly as often as their design life will allow, e.g. that their production cost are prorated over their design life-time. In this scenario, however, this design life-time is not fully used up in the 30 year period at the launch rates scheduled. Consequently, at the end of the life-cycle assumed the vehicles will have a residual value, which is not pro-rated over the missions actually flown! - In this model, the production cost of the individual vehicles as listed in column 3, table 4-10, is paid fully in the year of delivery. Consequently the distribution of annual expenditures is irregular as can be seen in column 5 of table 4-10. In reality the peaks will be lower because it is common practice to pay one third of the cost when the vehicle is ordered, one third in the second year and the last third upon delivery. - The next two graphs illustrate these trends.

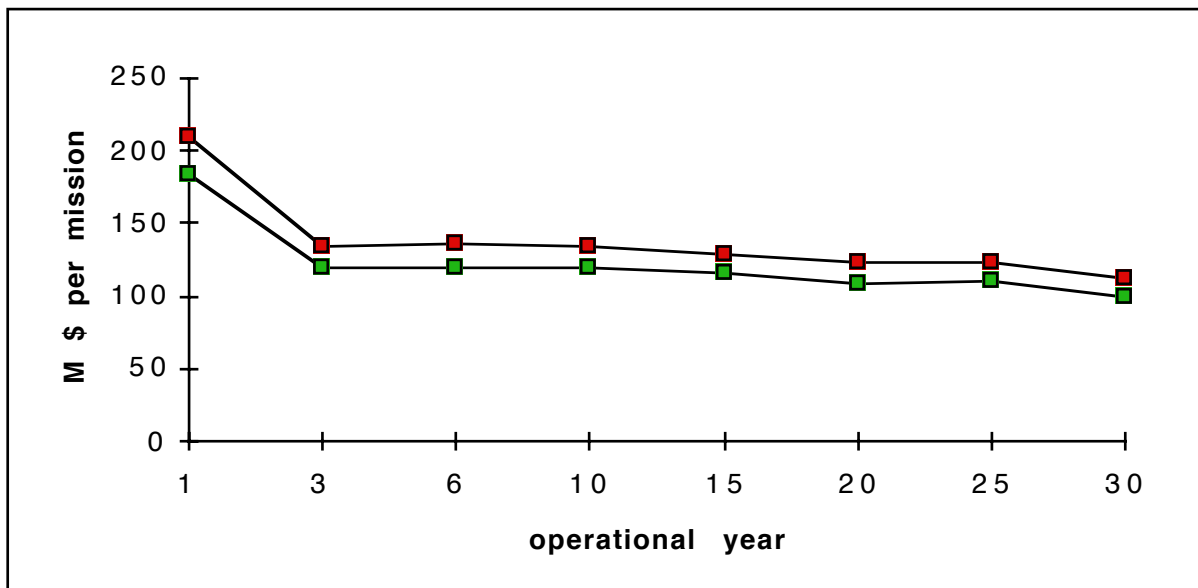


Figure 4-5: Mission cost for passengers (upper curve), and for cargo - all without lulox cost (lower curve) - (million 1999 \$)

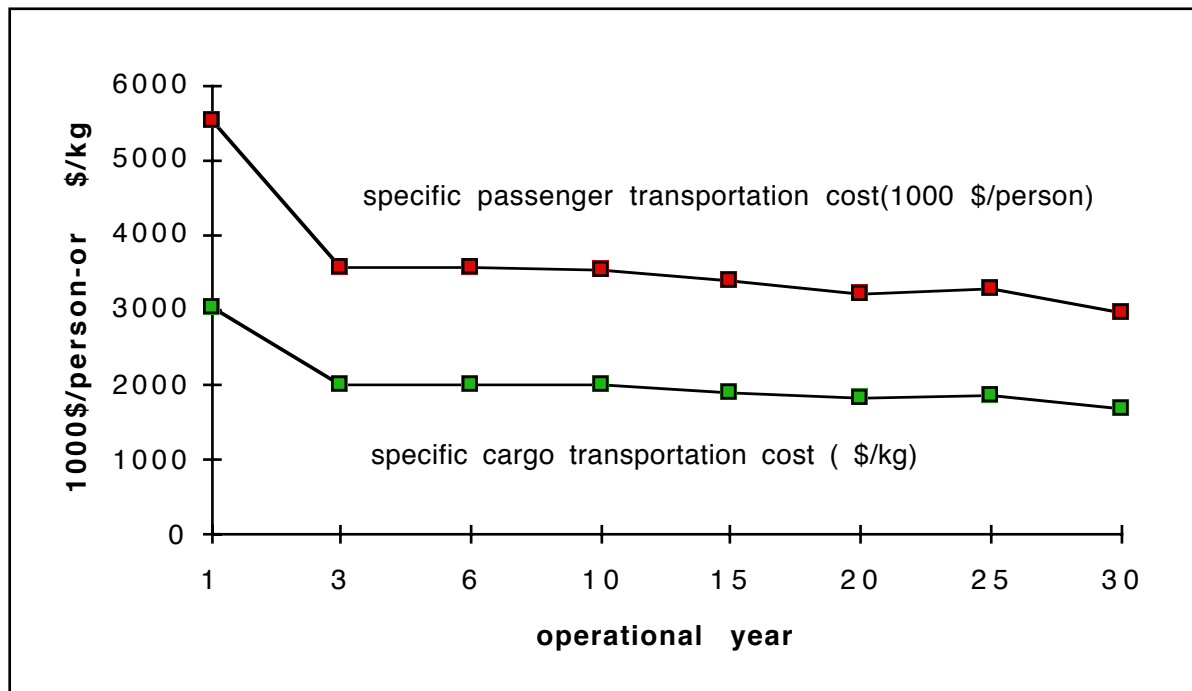


Figure 4-6: Specific direct (recurrent) transportation cost for passengers 1,000 (1999) \$/seat and for cargo transportation \$/kg to the Moon taking into account secondary flights supporting the LUO-SOC, but not the cost of Lulox

This concludes the description of the space transportation system employed to support logistically the lunar base concept conceived.

5. Program Schedule, - Cost and System Effectiveness Summary

A typical lunar base with its facilities has been structured and analysed with respect to mass flows, energy and human labor requirements in sufficient detail to allow fairly realistic cost estimates for the up-front and operational costs. These have to be combined with the attributes and performance of the entire lunar base system including its logistics during the entire life cycle, which was assumed to be 10 years for development and 30 years of operation.

5.1 Project schedule

Previous programs have demonstrated that the development phase is the most critical one with respect to technical feasibility, operational feasibility and financial acceptability. Consequently, it is necessary to develop detailed plans for the total system, particularly for the development and transition period. This requires a breakdown of the program activities and milestones on a quarterly basis from the time of program initiation up to the first flight test to develop a better understanding of the development sequence and time periods involved. This phase has been studied extensively, however, detailed tables can be omitted from this report at this stage of the discussion. An overview of the acquisition schedule should suffice at this point and is illustrated in table 5-1.

Table 5-1: Initial Lunar Base Program Development Schedule

year x = year of first development flights

year & Quarter	activity or flight mission
x-10	Program planning activities are initiated
x-9	program definition and specifications completed, memorandum of understanding (MOU) signed by partners
x-8	program approval, industrial competition for contracts
x-7/2nd Qtr	begin of vehicle and facility developments
x-7/3rd Qtr	design begin of crew capsule for HLLV, crew cabin of LUBUS, and of lunar facilities; construction begin of launch facilities
x-6/1st & 2nd Qtr	design reviews of HLLV elements, the lunar power plant module and the lunar LOX production module
x-5/2nd Qtr	design reviews of crew cabin for LUBUS and the HLLV system
x-4 /1st Qtr	design review of LUBUS stage, lunar habitat module
x-4/2nd Qtr	design review of lunar workshop module, lunar spaceport & mobility equipment
x-4/3rd Qtr	design review and approval of LUBUS system
x-4/4th Qtr	design review and approval of SOC modifications
x-3/1st Qtr	design review of lunar base control system
x-3/2nd Qtr	begin of component testing of new elements
x-2/3rd Qtr	begin of prototype production of all vehicles and lunar facility modules
x-2/4th Qtr	begin of subsystem testing
x-1/1st Qtr	begin of assembly of prototype vehicles
x-1/2nd Qtr	begin of ground testing of prototype vehicles
x-1/3rd Qtr	completion of launch facilities
x-1/4th Qtr	acceptance test of prototype HLLV and LUBUS

5.2 Lunar Program Cost Summary

To obtain the total cost of the program, one has to estimate the two major elements of the system separately, the *space transportation system* and the *lunar base facilities*. This has been done in the respective chapters above. The total cost of the program described in this report have been summarized in table ES-2 of the executive summary. It added up to about 73.6 B (1999) \$ during a 40 year period, e.g. an average expenditure of less than 2 billion dollars per year.

Table 5-2: Annual total system/program cost - Lunar Base plus Logistics
(M 1999 \$, 1 labor year = 0.2 M \$)

year system LC	LSTS cost p.a.	Lunar facility cost p.a.	total system cost p.a.	year	LSTS cost p.a.	Lunar facility cost p.a.	total system cost p.a.
-9	0	5	5	12	501	788	1,289
-8	0	12	12	13	352	812	1,164
-7	0	110	110	14	367	806	1,173
-6	1,221	375	1,596	15	362	829	1,191
-5	2,266	589	2,855	16	371	941	1,312
-4	3,210	1,100	4,310	17	431	852	1,283
-3	3,706	1,300	5,006	18	428	925	1,353
-2	3,587	2200	5,787	19	416	898	1,314
-1	4,621	2,100	6,721	20	408	937	1,343
0	4,508	1,549	6,057	21	522	726	1,248
1	3,481	441	3,922	22	481	809	1,290
2	1,211	1,444	2,655	23	464	807	1,271
3	501	615	1,116	24	338	820	1,158
4	383	937	1,320	25	345	818	1,163
5	376	953	1,329	26	425	827	1,252
6	393	597	990	27	467	824	1,291
7	376	713	1,089	28	419	835	1,254
8	410	751	1,161	29	379	830	1,209
9	441	752	1,193	30	334	843	1,177
10	586	771	1,357	total	39,600	34,030	73,630
11	492	798	1,290	40 year average	990	850	1,840

A graphical illustration of these trends (as shown in figures ES-2 and ES-3) in the executive summary brings out clearly that there is a peak demand of financial resources during the development phase and a sharp drop after the initial beneficial occupancy of the lunar base.

The simulation of the entire system life-cycle on an annual basis has resulted in additional insights into the behaviour of this system and its subsystems. Therefore some factors illustrating the system-effectiveness are presented in chapter 5.3.

5.3 Program cost- effectiveness

The results of system simulations such as done in this analysis allow to design and select a number of indicators for the behaviour and cost-effectiveness of the lunar laboratory. The ten most important ones are presented below. Program objectives, program structure and program cost are the elements required to determine program effectiveness. This effectiveness is the most important criteria for a go/no-go decision. Ratios presented in table 5-3, depicting the annual trends, give a more complete insight into the behaviour of the system analysed than cumulative values. The primary parameters selected are:

- (1) Systems life-cycle cost per lunar labor-year (M 1999 \$/labor-year)
- (2) Systems life-cycle cost per lunar science year (M 1999 \$/ lab.-year)
- (3) Systems life-cycle cost per unit mass produced on the Moon (M 1999 \$ /kg)
- (4) Lunar habitat + farm mass per lunar crew member (t/ person)
- (5) Imports per lunar crew member (t p.a./ person)
- (6) Lunar manufactured products per lunar crew member (t p.a./person)
- (7) Import mass per unit mass of lunar products (-)
- (8) Mass of lunar products per unit mass of lunar facilities (t p.a./t)
- (9) Installed power per unit mass of lunar products (kW/ t p.a.)
- (10) Installed power per lunar crew member(kW/crew member)

Table 5-3: Development trends of primary system-effectivness ratios

year	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	230	1307	36654	3.53	15.0	35	2.38	0.48	4.58	29
3	40	186	5723	4.25	2.07	39	0.30	0.55	4.58	32
6	26	90	3289	4.26	1.58	43	0.20	0.65	4.38	35
10	28	85	3367	4.33	1.65	43	0.20	0.73	4.23	36
15	19	48	2550	4.50	1.34	41	0.18	0.68	4.56	33
20	16	36	2402	4.66	1.31	38	0.20	0.65	4.86	32
25	13	28	1916	4.77	1.02	38	0.15	0.66	4.74	32
30	12	26	1780	4.90	1.03	38	0.16	0.66	4.80	32

The change of of the facility mass per lunar crew member with time, and the specific output per mass facility as a function of time are typical outputs of a simulation run. The reason that the production efficiency is not greatly changing with time is the fact, that the production of hardware on the lunar surface is deliberately kept down to save mass and manpower. The fairly strong increase of the laboratory and scientific equipment mass does not contribute to the mass output, thus it is of no help to improve the efficiency of the production process. This shows clearly that this is a laboratory with only limited production efforts. It is an experimental facility that concentrates on developing the technology rather than efficiency. Larger lunar facilities with higher outputs would show a more favourable trend!

5.4 Expected Benefits

Benefit models do allow a preliminary assessment of the benefits to be expected if a planned space program, such as a lunar base, is actually implemented. Studies of this type employing benefit estimating relationships have resulted in some insights where benefits can be derived by lunar installations^{25,26}. Benefits in this case are defined as relative degrees of goal achievement.

The following table summarizes and compares the relative benefits of a temporary lunar outpost and a permanent lunar base. A lunar base with a 30 year operational lifecycle can contribute about 43% of the benefit potential on the basis of the goals set for the end of the 21st century. A lunar settlement that reaches a population of several thousand people in year 2100 would achieve nearly 100 percent of the potentials defined in this benefit model.

Table 5-4: Expected benefits of extraterrestrial facilities on the Moon

	Options	tempo- rary lunar outpost	lunar base
A	HUMANISTIC OBJECTIVES	131	218
a.1	enhance the evolution of the human culture in space	6	39
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
a.3	enhance the educational system and motivation to learn	10	10
a.4	provide a survival shelter for artifacts, documents and some elements of the human race in case of a global catastrophe	32	57
a.5	assist in reducing tensions and conflicts, thus contributing to peace on Earth	9	11
a.6	provide opportunity for involvement of a broad spectrum of people in exciting frontier activities	12	17
B	POLITICAL OBJECTIVES	140	177
b.1	demonstrate the potential growth existing beyond the limits on Earth	41	72
b.2	provide more opportunities for international cooperation	25	22
b.3	extend the infrastructure and experience for global enterprises	29	22
b.4	provide a peaceful outlet for national, competitive high technology urges and a useful employment of existing industrial-military capabilities	26	30
b.5	enhance the national pride and prestige of participating nations	18	31
C	SCIENTIFIC OBJECTIVES	160	343
c.1	improve the understanding and control of our own planet	2	26
c.2	improve our knowledge of the Moon and its resources	37	69
c.3	improve our understanding of the solar system beyond the Earth-Moon double planet	32	32
c.4	improve our understanding of the universe beyond our own Solar System	49	41
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	117
D	UTILITARIAN OBJECTIVES	160	343
d.1	provide rewarding job opportunities and thus stimulate the economy on Earth in general	14	12
d.2	stimulate the development of the educational system and of advanced technology on Earth	20	30
d.3	produce marketable products for extraterrestrial and for terrestrial use	1	16
d.4	contribute to the supply of space based energy to the Earth	34	68

d.5	provide an isolated extraterrestrial depository to store high level wastes	27	72
d.6	enhance the development of safe and economical space transportation systems providing access to other celestial bodies and space resources	43	95
d.7	provide thrust and focus for continued development of space technology other than in the area of space transportation systems	41	50
	total benefit expected with respect to Quality-of-life	679	1023
	Percent of maximum potential theoretical achievable within the constraints of the model used	28%	43%

According to this preliminary valuation the upper ten objectives benefiting most from the establishment of a lunar base are the following.

Table 5-5: Ranked list of objectives benefiting most from a lunar base program

1. Providing a science laboratory in a unique environment for experiments in physics, chemistry, biology, geology, physiology and sociology which can not be conducted on Earth.
2. Enhancing the development of safe and economical space transportation systems providing access to other celestial bodies and space resources.
3. Establishing 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.
4. Demonstrating the potential growth existing beyond the limits on Earth.
5. Providing an isolated extraterrestrial depository to store high level wastes.
6. Improving our knowledge of the Moon and its resources.
7. Contributing to the supply of space based energy to the Earth.
8. Providing a survival shelter for artifacts, documents and some elements of the human race in case of a global catastrophe.
9. Providing thrust and focus for continued development of space technology other than in the area of space transportation systems.
10. Improving our understanding of the universe beyond our own Solar System.

The following table describes the life-cycle performance of the lunar laboratory program by listing the most important state-variables and parameters. These data are suitable to compare options for lunar development. While this summary allows neither a complete picture nor a very accurate data base, it is the best set of representative data presently available, but awaits further improvements.

5.5 Program Summary

Table 5-6: Life-cycle performance and cost summary of a Lunar Base program - (cost in million 1999 dollars ; 1 labor year = 0.2 million \$)

lunar facilities available at the end of the life-cycle	1,005 t
total imports	2,640 t

total lunar products available	13,620 t
---- LC lunar propellants used for space vehicles	8,100 t
---- LC lunar products for infrastructure extension or export	1,890 t
---- LC lunar products used directly by the lunar laboratory	3,630 t
total lunar labor-years available	1,962
---- laboratory years available for lease	780
cost of planning and program integration activities	740 M \$
initial development cost of lunar facilities	6,370 M \$
production cost of initial facilities	2,230 M \$
lunar facilities acquisition	9,340 M \$
cost of engineering support during expansion of lunar facilities, administration and training	9,810M \$
salaries of lunar crew	1,590 M \$
cost of imported spares, equipment & consumables	13,290 M \$
operations cost of lunar facilities	24,690 M \$
subtotal lunar laboratory acquisition and operation	34,030M \$
total space transportation system development cost	18,923M \$
product improvement during operation	4,150 M \$
total production cost	9,900 M \$
total operations cost	6,600 M \$
total recurring cost lunar space transportation system	20650M\$
subtotal logistic system acquisition and operation	39,600 M\$
total LULAB system cost for 40 yr life-cycle	73,630M \$
annual average during the 10 dev.+ 30 oper. = 40 year life-cycle	1,840 M \$
cost per lunar labor-year	37.5M \$/y

It is clear that this model can be adapted to any desired performance and more efforts can lead to more economies of the laboratory concept presented! -

Conclusions and Recommendations resulting from this study have been summarized in the Executive Summary in front of the report !

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APPENDIX A: Lunar Surface Transportation Requirements

The production activities on the lunar surface require seizable transportation activities for lunar soil, feedstock, construction materials, but also of lunar personnel participating in these efforts. Thus distances, frequencies and masses to be moved are entering the simulation model. It is necessary to keep track of these inputs because they are often the cause of an interruption of the simulation process. Representative inputs, as used in this laboratory scenario, are summarized in this appendix.

Table A-1: Surface transportation requirements for lunar (equivalent) personnel (labor-years) and products (t p.a.) - Case Moonbase 2015

facility	crew year 1st year	crew last year	mass flow 1st year	mass flow last year
01 = strip mine	0.6	0.9	6 000	16,000
02 = beneficiation facility	0.4	0.8	420	2,240
03 = chemical processing facility	1.3	4.8	94	533
04 = mechanical processing facility	0.2	3.4	4	126
05 = fabrication shop	0.5	4.7	2	38
06 = assembly facility	0.2	1.5	0	7
07 = laboratories and scientific equipment	3	45	0	0
08 = gas mine and equipment	0	0	0	0
09 = gas processing and liquefaction facility	0.2	0.7	86	363
10 = propellant storage for rocket propellants	0.1	0.5	81	347
11 = power plant system on lunar surface including power lines	0.2	1.9	0	0
12 = lunar dump	0	0	0	0
13 = lunar spaceport and equipment	0.4	1.5	256	213
14 = central storage facility other than for rocket propellants	0	2.6	33	135
15 = central workshop for maintenance, repair & facility extensions	1.8	5.4	9	67
16 = central carpool and surface transportation facilities	2.3	4.0	0	0
17 = control center for all lunar facilities and activities	2.5	3.7	0	0
18 = housing facility & offices, incl. health & recreation facilities	1.7	10	0	0
19 = biological facilities, incl. waste recycling and food production	0.7	8.6	7	54
20 = lunar solar power satellite in space serving lunar facilities	0	0	0	0
total	16.6	100		

Table A-2: CARGO volume on lunar surface (t.km)

facility	1st year s=1 km	last year s=3 km	mass flow 1st year	mass flow last year	t.km 1st year	t.km last year
01 = strip mine	3	3	6 000	16,000	18,000	48,000
02 = beneficiation facility	0.1	0.1	420	2,240	42	225
03 = chemical processing facility	1	1	94	533	94	533
04 = mechanical processing facility	0.1	0.1	4	126	1	13
05 = fabrication shop	2	2	2	38	4	76
06 = assembly facility	3	3	0	7	0	21
07 = laboratories and scientific equipment	3	3	0	0	0	0

08 = gas mine and equipment	0	0	0	0	0	0
09 = gas processing and liquefaction facility	2	2	86	363	172	726
10 = propellant storage for rocket propellants	2	2	81	347	162	694
11 = power plant system on lunar surface	2	2	0	0	0	0
12 = lunar dump	1	1	0	0	0	0
13 = lunar spaceport and equipment	2	2	256	213	512	426
14 = central storage facility (excludg.propellants)	6	6	33	135	198	810
15 = central workshop for maintenance, repair & facility extensions	1	1	9	67	9	67
16 = central carpool & surface transportation facilities	5	5	0	0	0	0
17 = control center for all lunar facilities and activities	0.1	0.1	0	0	0	0
18 = housing facility & offices, incl. health & recreation facilities	0.1	0.1	0	0	0	0
19 = biological facilities, incl. waste recycling and food production	0.1	0.1	7	54	1	5
20 = lunar solar power satellite in space serving lunar facilities	0	0	0	0	0	0
total					19,100	51,600

Table A-3: Distances of output mass and departing personnel mass flow to next facility (t.km x days) with 150kg per person over average distances between habitat and duty station

facility	1st year s=1 km	last year s=3 km	1st year t km	last year t km
01 = strip mine	3	3	275	550
02 = beneficiation facility	0.1	0.1	1	1
03 = chemical processing facility	1	1	550	1100
04 = mechanical processing facility	0.1	0.1	120	960
05 = fabrication shop	2	2	120	960
06 = assembly facility	3	3	0	0
07 = laboratories and scientific equipment	3	3	150	300
08 = gas mine and equipment	0	0	1	1
09 = gas processing and liquefaction facility	2	2	75	150
10 = propellant storage for rocket propellants	2	2	50	50
11 = power plant system on lunar surface including power lines	2	2	300	1080
12 = lunar dump	1	1	25	25
13 = lunar spaceport and equipment	2	2	96	132
14 = central storage facility other than for rocket propellants	6	6	55	55
15 = central workshop for maintenance, repair & facility extensions	1	1	660	1320
16 = central carpool and surface transportation facilities	5	5	540	1080
17 = control center for all lunar facilities and activities	0.1	0.1	1	1
18 = housing facility & offices, incl. health & recreation facilities	0.1	0.1	75	150
19 = biological facilities, incl. waste recycling and food production	0.1	0.1	75	150
20 = lunar solar power satellite in space serving lunar facilities	0	0	0	0
total passenger surface transportation requirement (t.km p.a.)			3,169	8,065
or with 0.15 kg/person = passenger.kilometers			21,100	53,800

APPENDIX B: Life Support system

The life support system becomes the dominating element of a lunar base which has only small pilot production capacities. It determines the sensitivity of the entire model and also the limit of its application. Consequently, it is important to understand the interrelationships of the primary input parameters. The present analysis is far from an optimization. To do that, a detailed analysis must be performed at the subsystem and component level. The following tables describe the present status and can be used as a point of departure.

Table B-1:
Parameters used in model sizing and impacting the Life Support System

Basic facility (fac 19)-1st year - last year:

facility and equipment mass	1.5 - 4.0 (t per t /y throughput)
average power demand	15- 25 (kW / t/y throughput)
human labor demand	0.1- 0.17 (persons/ t/y throughput)
workshop labor burden	0.02- 0.05 of operational labor
surface transportation demand	75 t*km - 150 t*km

Current assumptions:

Cost:

development cost total subsystem (M \$)	500
specific development cost (\$/kg) @ 55 t	10,000
first unit cost (M \$)	100
specific production cost(\$/kg)	10,000
system integration (M \$)	25
specific integration cost (\$/kg)	2, 500
specific cost consumables (\$/kg)	300

Requirements of crew:

4318 0.40 0.35 total consumables other than LS demand for habitat / man (t/y/person)

Facility demands:

2519 0.01 0.04	spareparts for repair & replacement of equipment/facility mass of fac.19
2619 0.01 0.20	salvaged parts/spare part demand
5719 0.15 0.10	lunar construction material for repair/sparepart/demand
5819 0.01 0.14	lunar fabricated products for repair /spare part demand
5919 0.01 0.13	lunar assemblies for repair / spare part demand
5419 0.20 0.30	lunar construction material for extension /total facility extension mass
5519 0.10 0.20	lunar fabricated products for extension /total facility extension mass
5619 0.0 0.25	lunar produced assemblies for extension /total facility extension mass

Imports for life support subsystem:

4218 1.20 0.60	total life support (organic supplies) demand /person (t/y/person)
4219 0.10 0.10	imported organic matter (farm supplies)/ air & water & food output of farm
4118	imported nitrogen from fac, 14 to fac 18- calculated remnant

Relevant Lunar Products:

5307 0.03 0.05	lunar fabricated products supporting R&D / laboratory crew
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5208	0.001	0.001	lunar consumable materials / gaseous products leaving fac 08
5209	0.001	0.001	lunar consumable materials/ Gox output 09
3618	0.25	0.75	organic waste to farm fac 19/ food input habitat fac 18
5318	0.08	0.12	lunar produced consumables other than food to fac 18 / crew member
3718	lunar produced food from fac 19 to fac 18- calculated from inputs		
4718	organic waste of habitat for dump from fac 18 to fac 12 - calculated remnant		

Relevant Gas inputs:

2907	0.37	0.37	lunar Gox input / air leakage of laboratories a/c 07
2918	0.37	0.37	lunar Gox input / air used of fac 18 & 19
3918	0.12	0.12	lunar hydrogen input / water leakage fac 18 & 19

Relevant Gas outputs:

2703	0.21	0.16	gaseous products of chemical plant / beneficiated soil
2909	0.98	0.99	Gox output / gaseous input to gas processing facility
2919	0.80	0.80	regenerated Gox output / CO2 input of farm
3001	0.99	0.99	Lox output / Gox input to liquefaction facility
3518	0.30	0.30	total CO2 production / person

Gas/air/water leakages:

3210	0.03	0.02	Lox leakage / Lox input of propellant storage
4410	0.03	0.02	propellant leakage / propellant imports to propellant storage
4603	0.01	0.01	gas leakage / input of chemical plant
4604	0.005	0.002	air leakage / input to mechanical plant
4605	0.01	0.01	air leakage / imported products for fabrication shop
4607	0.05	0.05	air leakage / laboratory crew (t/y/person)
4609	0.01	0.005	gas leakage / total input of gas processing facility
4611	0.5	0.3	gas leakage / consumables input to power plant
4615	0.01	0.005	air leakage / output of central workshop
4618	0.05	0.05	air leakage of habitat, farm & vehicles/ surface crew (t/person-y)
4619	0.10	0.08	water leakage of habitat and farm / surface crew (t/person-y)

Table B-2: Results of the reference simulation run - mass & power flows

operational year	mass output fac 19 (t)	imported spares & extentions (t)	human labor rqrd. for fac 19 (persons)	imported consumables-for 19 (t)	M43 imported anorganic supplies	power required for fac 19 (kW)
1	7	0.1	0.7	0.7	6.4	100
2	13	9.5	1.5	1.3	10.9	218
3	13	0.9	1.5	1.3	10.3	218
4	15	4.6	1.8	1.5	11.9	265
5	18	7.0	2.3	1.8	14.3	342
10	24	4.6	3.2	2.5	17.2	480
15	36	5.2	4.7	3.6	22.7	693
20	44	8.9	6.7	4.4	30.4	995
25	50	5.1	7.5	5.0	31.6	1,100
30	54	7.6	8.6	5.4	34.1	1,265
AV.	34	5.4	4.9	3.3	23.0	727

Table B-2 continued

	M39 lunar H2 for H2O (t)	M 41 imported N2 for air (t)	M29 lunar Gox for air & H2O (t)	M35 crew produced CO2 (t)	M36 recycled organic waste (t)	M42 imported organic suppl. (t)	M37 rqrd.lun. food from 19 (t)
1	0.2	0.6	5.8	5.0	5.0	14.0	6.7
2	0.4	1.1	10.8	9.4	10.1	21.3	13.3
3	0.3	1.1	9.8	8.5	9.6	16.8	12.5
4	0.4	1.3	11.2	9.8	11.3	17.4	14.7
5	0.4	1.6	13.8	12.0	14.2	19.6	18.5
10	0.5	2.0	16.5	14.5	18.4	17.3	23.7
15	0.7	2.8	21.8	19.2	25.4	18.2	32.5
20	0.9	3.9	29.3	25.8	35.2	20.4	44.9
25	0.9	4.1	30.9	27.2	38.0	18.1	48.3
30	1.0	4.6	33.9	30.0	42.7	17.0	54.1
AV.	0.7	2.9	22.3	19.6	26.2	18.1	33.5

Table B-3: Cost without amortization of acquisition cost and without transportation cost

year	cost of equip.& extensions for 19	cost of consumables for 19	Earth support cost of fac 19	fac 19 crew salary	total recurrent cost of 19
1	1	1	24	1	26
2	95	1	24	2	121
3	9	1	24	2	36
4	46	1	25	2	73
5	70	1	25	2	98
10	46	1	25	3	75
15	52	1	26	4	82
20	89	1	26	5	122
25	51	2	26	6	84
30	76	2	26	6	110
AV.	54	1	25	4	84

Table B-4: Specific cost of products and services

year	specific cost of lunar oxygen (\$/kg)	specific cost of port services (\$/kg)	spec. cost of recycled products (M \$/t)	specific cost of electric power (\$/kWh)
1	3,532	79	11.8	16.9
2	18,600	1491	114	14.8
3	2,239	95	9.09	11.0
4	2,277	93	15.7	18.0
5	2,780	112	20.6	28.0
10	1,152	57	9.80	11.8
15	805	42	7.50	8.50
20	774	38	8.30	9.60
25	510	29	5.06	5.50
30	523	30	6.00	6.60
AV.	1,137	80	8.70	10.6

The study puts also some light on an other important issue of lunar base development: Does it pay off to produce food on the Moon? - While the lunar produced food will be expensive in this small facility, there is an important interdependence here that should be taken into account. The pleasures from growing part of their own vegetables and have some green about the facility, will enhance the well being of the lunar crew considerably and allow longer duty cycles on the Moon, thus saving passenger transportation cost. A more detailed analysis of such trade-offs is thus recommended for a specific scenario and life-cycle.

Appendix C: Lunar Laboratory Cost Accounting Alternatives

1. Introduction

The lunar development program, analysed in this study, envisions an early acquisition (in years 2006/2015) and a 30 year operational phase of a lunar base including a small pilot production facility. These allow the manufacturing of modest amounts of lunar products and services for use by commercial users, however, at very high cost due to high investments and extremely low production rates.

Furthermore, it is important to note, that this initial lunar development program is assumed to be an isolated enterprise and not a partial program of a larger global space program. Thus the total cost are estimated under very unfavourable conditions, neglecting all synergic-effects. The average annual cost of this 40 year baseline program are estimated to range between 2 and 1 billion US 1999 dollars per annum. Several alternatives for different accounting methods are shown for the purpose of comparisons.

2. Cases of primary interest for comparison of average life-cycle costs:

A. *Baseline*: Separate partial programs are assumed for the lunar base and logistic system, each comprised of an acquisition and an operational phase. These partial programs are budgeted by the participating governments, thus financing costs are not included. Also, no other users of the same hardware within a possible *global* space program are assumed. Costs of lunar products and services are based on recurrent lunar base costs only, excluding logistic costs. The year 1999 is used as the reference year for converting labor-years in U.S.Dollars.

B. Same as model A, but the amortization of laboratory acquisition costs within the first ten operational years (using a 3% interest rate), is now included. The full space transportation system(STS) acquisition cost are listed separately, but are not introduced as a burden to the lunar operation! No financing costs are assumed for this STS because it is still financed by public funds. Costs of lunar products and services are based on non-recurrent and recurrent laboratory costs without a transportation burden.

C. This alternative is based on an *integrated* lunar development program, it considers *recurrent* costs of the laboratory and logistic system. The cost of lunar produced propellants are charged to the logistic system, and thus increasing its share of the total cost. This is leading to a different distribution of the same costs shown for A, but it reduces lunar operations cost accordingly and does not result in higher specific cost of lunar products and services.

D. The theoretical upper limit of the specific cost of lunar services and products can be estimated as follows:

The acquisition costs of the space transportation system are paid initially by the governments, but have to be repaid during the operational life-cycle, however, without interest charges. Due to the architecture of the simulation models, the Number of missions must be adjusted in case actually scheduled missions are higher than those required by the LUBSIM code. The specific transportation costs are based on direct plus amortization costs.

The total acquisition cost of the lunar facilities are financed by loans and amortized over ten years at a 3 percent interest rate. The cost of the lunar products and services are then calculated by entering the total specific transportation costs into the LUBSIM model as a burden to be carried.

3. Assumptions pertaining to all four cases analysed:

The overall performance of this lunar development program is kept constant and represented by the following characteristic parameters:

Table C-1: Constant program performance parameters

1. Duration of acquisition phase (years)		10
2. Duration of operational life-cycle (years)		40
3. Maximum crew size (persons)		100
4. Average crew size (persons)		65
5. Average R&D or commercial crew (persons)	26	
6. Accumulative number of lunar labor years (years)		1,962
7. Accumulative number of labor years available for lease(years)		780
8. Passenger seat capacity per lunar flight		38
9. Accumulative number of lunar passenger missions		70
10. Accumulative number of passenger roundtrips Earth-LUS		2,660
11. Passenger roundtrips to LUO-SOC		293
12. Average duration of crew duty cycle(months)		8.5
13. Mass of facilities at end of acquisition (5th year)		455
14. Mass of lunar facilities and equipment at end of LC(t)		1,005
15. Power installed at end of acquisition -kW(5th year)	1,350	
16. Output of power plant at end of LC(kW)		3,180
17. Accumulative lunar soil processed(1000 t)		400
18. Accumulative mass of lunar products used by the laboratory(t)		3,867
19. Accumulative mass of products available for sale(t)		1,887
20. Accumulative mass of lunar produced propellants (t)		8100
21. Accumulative mass of imported propellants from Earth(t)	700	
22. Available mass of habitat + life support facility/ lunar crew member-yr30(t)		4.9
23. lunar products for sale /pilot production facilities - yr 30 (t /t)		0.42
24. Available mass(t) of R&D laboratories & equip./R&D crew members -yr 30		3
25. Payload capability of space transportation system per lunar flight(t)		60
26. same, if refuelled in lunar orbit(t)		50
27. Accumulative number of lunar cargo flights	50	
28. Accumulative import mass required(t)		2640
29. Accumulative import mass scheduled(t)		2930
30. Total number of HLLV missions incl.secondary missions		140
31. Specific cost of imported spares and equipment w.o. transp.(\$/kg)		11,380
32. Specific cost of lunar produced spares w.o.transportation burden(\$/kg)		6,315
33. Specific cost of lunar produced extensions w.o.transportation burden(\$/kg)	8,625	

General assumptions:

1. An improved model Moonbase 2015, with reduced Lulox production in early years - as presented in the body of this report - will be used for the baseline (case A), to ease the ramp-up operation of the laboratory.
2. In this experimental lunar facility operation only 7 to 15% of the lunar soil, entered into the production process at facility 1, is selected for further processing by facility 2. -In this process, which is primarily designed for Lulox production, only 21 and 22 % of beneficiated soil is the feedstock for the production to follow in the

other facilities. Thus the technology chosen allows to convert about $0.07 \times 0.21 = 1.5\%$ to $0.15 \times 0.22 = 3.3\%$ of the total mass to manufacture lunar products.

3. The STS and the Lunar Laboratory have separate accounts in Cases A and B only.

4. Comparison of Accounting alternatives

Table C-2: Program Cost Overview - Accounting alternatives
(rounded figures including value of residual hardware about 5 B \$)

Program cost overview	A	B	C	D
1. Laboratory R&D costs (B \$)	9.4	9.4	9.4	9.4
2. Financing costs (M\$)	0	2.4	0	2.4
3. Laboratory recurrent cost (B \$)	24.9	24.8	15.3	24.9
4. Laboratory total cost(B\$)	34.3	36.6	24.7	36.7
5. Acquisition cost of STS	18.9	18.9	18.9	18.9
6. Recurrent cost of STS	20.6	20.6	30.2	27.6
7. Logistic system (STS) total cost (B\$)	39.5	39.5	49.1	46.5
8. total program R&D cost (B\$)	28.3	30.7	28.3	30.7
9. total program recurrent cost(B\$)	45.5	45.4	45.7	52.5
10. Total program costs (B\$)	73.8	76.2	74.0	83.2
11. Av. program cost -40 yrs (B \$ p.a.)	1.85	1.90	1.86	2.08
12. Cost /lunar labor year (M\$)	37.6	38.8	37.6	42.4
13. Cost/ lunar R&D year (M\$)	94.6	97.7	94.6	107

Table C-3. Potential cost reductions of a Program in referece scenario

1. 50 percent of commercially available products sold at cost	3
2. 50 percent of commercially available laboratory places at cost	6
3. amortization of vehicle production cost over design life	5
4. amortization of R&D cost over total vehicle life in global program	9
<u>4. reduced operations cost due to higher launch rates in global program</u>	<u>1</u>
Total potential reduction of cost to the public (B \$)	24
Remaining cost to be financed by the public (B \$)	50

Table C-4: Performance parameters of the space transportation system (STS)
(if fully charged to this lunar development program, Alternative D not included, because integrated program)

	A/B	C #
1. average annual cost (B\$)	0.99	1.23
2. Total life-cycle cost	39.5	49.1
3. Development cost	18.9	18.9
4. Production cost share	9.9	9.9
5. Operations cost including sys. improvment	10.7	10.7
6. Lunar propellants	0	9.6
7. Financing cost	0	0

8. direct cost HLLV flight -cargo/ pass.(M\$)	100/105	100/105
9. direct cost Lubus flight - cargo/ pass.(M\$)	11/16	113/78
10. total cost p. pass. mission (M\$)	300	361
11. total cost p.cargo mission(M\$)	249	351
12. tot.spec.cost/pass.roundtrip(M \$)	7,912	9.54
13. tot. spec.cargo cost (\$/kg)	4,141	5,844

with 1160 \$/kg for Lulox & port services = 5.80 MYrs/t

Table C-5: Comparison of specific cost of lunar products and services

	A/C*	B**	D#)
raw material(\$/kg)	955	1,592	2,590
construction material+feedstock(\$/kg)	2,458	3,683	6,040
selected products(\$/kg)	7,085	11,630	18,270
selected assemblies (\$/kg)	15,670	24,000	38,620
lunar propellants(\$/kg)	1,136	1,949	3,134
recycled life support products(\$/kg)	2,827	12,600	20,100
laboratory use (M \$/lab.yr)	15	21	48
workshop use(M \$/lab.yr)	67	1,112	177
habitat use(M \$/person .yr)	12	18	30
control center use(M \$/lab.yr)	39	73	103
surface transportation (\$/t.km)	1,470	2,400	4,410
port services (\$/kg)	80	134	216
power plant use (\$/kWh)	11	15	21
av. cost all export products(\$/kg)	2,394	3,298	5,756
av. cost all lunar used products(\$/kg)	7,320	12,328	19,164
av.cost tot.lunar output(\$/kg)	1,372	2,200	3,623

*) no amortization of acquisition cost

**) with amortization of acquisition cost over 10 years @3 percent interest

#)The specific cargo transportation costs resulting for alternative D had to be increased by 11 percent due to a larger number of cargo missions than estimated as minimum values by the LUBSIM code, using incremental missions without reserves. A multiplier of 1.145 had to be applied to include the residual cost of the flight hardware at the end of the life cycle, assuming that there is no follow-on program.

APPENDIX D:

On The Influence of the Earth Support Staff Size on the Cost of the Lunar Base (LULAB 2000 Model)

One parameter that has a great influence on the total operating cost of an extraterrestrial facility is the degree of support it requires on Earth after initial operational capability is achieved. This is currently also subject of discussion among the participants for the International Space Station. This will lead to a prototype mode of operation of great importance for future lunar and Martian exploration activities with a human crew in-situ.

In general, one would prefer a fairly stable Earth support staff, but it is also certain that the ratio of Earth support personnel/ number of extraterrestrial crew members will decrease with increasing crew size of extraterrestrial operations. One also knows, that the project participants will always want to have plenty of support and those financing it, will attempt to put the brakes on.

A good point to begin with modelling this activity is a list of functions the Earth support staff has to fulfill. Here is a preliminary list:

- Program overview and control
- system engineering
- organization of logistic support
- trouble shooting
- safety in space and on Earth
- product improvement (assumed to be 2% of R & D cost of subsystems)
- science program planning and support
- marketing
- public affairs
- budgeting and long range planning
- training of space personnel (assumed to be 300 professionals + overhead)

Due to lack of a detailed model of this operation, a preliminary assumption to cover these activities must be made when simulating the life-cycle of a lunar facility. The present concept and the implications of this assumption is presented below.

The crew size of the lunar laboratory analysed (Model LULAB 2000) is 32 in the first year and growing to 100 in year 30, accumulating a total of 2,029 lunar work-years. The 30 year - 100 people(max) Laboratory analysed is based on the preliminary assumption that the lunar laboratory is supported by a Earth crew of 1,000 people and a training organization with 300 people. These numbers are assumed to stay level over the life-cycle leading to a decrease of the ratio Earth Support Crew/Lunar Crew from 120 to 12. The cost per support staff member was assumed to 180,000 \$/work-year for the scientific staff and 160,000 for the training staff. In this model 2% of R&D cost for product improvement are $7100 \times 0.02 = 142$ an equivalent of 710 professional people at 0.2 M \$/R&D person.

A sensitivity analysis is now performed with respect to this assumption to obtain a better appreciation of the relative importance of this assumption. The Earth support staff(without product improvement and training) is varied between 1000, 2000 and 4000, the training staff between 300, 600 and 1,200. Acquisition cost (including 7.1 B \$ for subsystems R&D) are a fixed number approaching the ten billion dollar mark,

and there are no interest charges assumed for the initial hardware set to be purchased.

The percentage and total change of the Lunar Lab recurring cost without and with the recurrent cost of logistics, as well as the average specific labor-year cost will be analysed. The cost data are plotted versus average Earth-/lunar Crew ratio and life-cycle respectively.

Table D-1: Influence of size and cost of Earth support staff for a lunar laboratory

Earth support staff + training staff	1,000 +300	2,000 +600	4,000 +1200
cost of Earth support crew (M \$ p.a.)	370	598	1,054
average recurrent cost (M \$ p.a.)	727	955	1,411
Earth -/lunar crew: 1 st year (32 crew)	41	82	163
same : 30th year (100 crew)	13	26	52
same: LC average for 67.6 crew members	19	38	77
cost share of Earth crew (%) of laboratory cost	51	63	75
tot.recurrent cost incl.logistics (M \$ p.a.)	1,509	1,737	2,193
cost share of Earth crew (%) of recurrent lunar laboratory system cost	25	34	48
average specific recurrent cost per lunar crew member (M \$ p.a.) incl.logistics	22.3	25.7	32.4

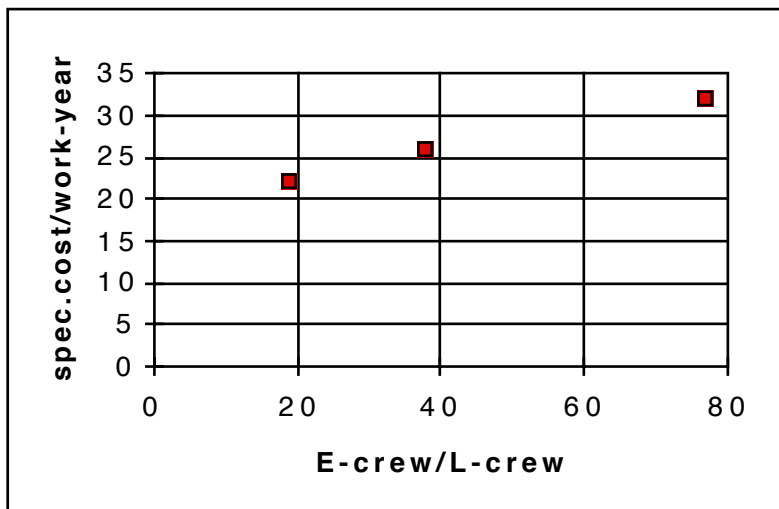


Figure D-1:
Specific cost of a lunar labor-year plotted versus the ratio:
number of Earth support staff members/average number of lunar crew

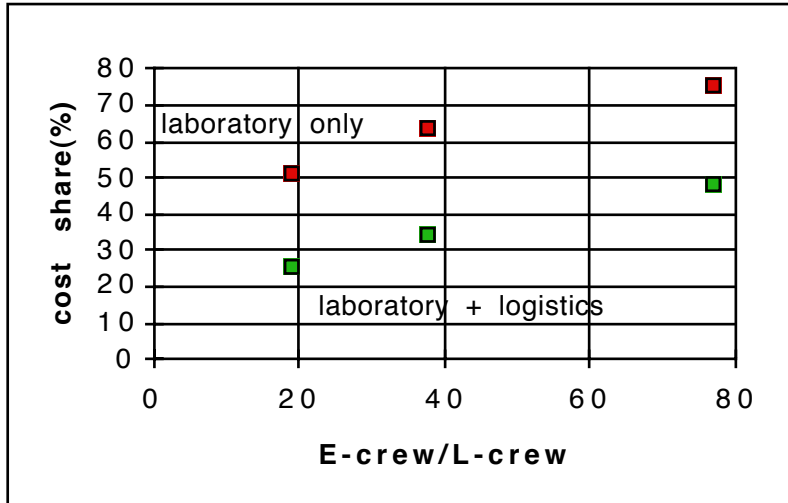


Figure D-2:
 Cost share of the Earth support staff with respect to recurrent laboratory cost and total recurrent cost (laboratory + logistics) plotted versus the average ratio of no. Earth support crew/no. of lunar crew

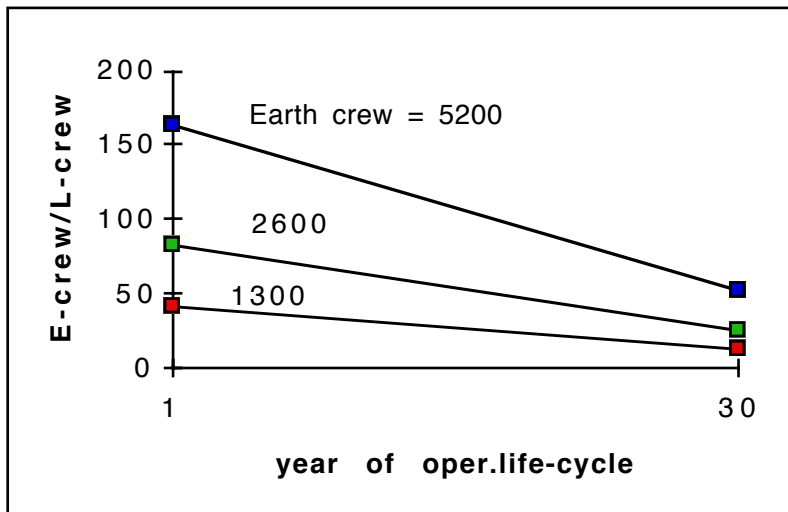


Figure D-3:
 Ratio of Earth support staff/ lunar crew as a function of time with total number of (constant) Earth support staff as a parameter valid for a 30 to 100 person lunar laboratory

APPENDIX E: LEAN LUNAR LABORATORY (LLL) Option

It is conceivable that a scientific oriented laboratory not making use of lunar resources can be less costly than the reference model. Some of the production facilities can be saved, the production personnel is greatly reduced, power demands and other infrastructure requirements are also reduced. This leads to a reduction of passenger flights, but it increases the number of cargo flights.

Obviously the value of such a reduced lunar operation in a slender facility, concentrating on research and development activities and cutting out most of the production, would be less than the value of a full fledged laboratory. This question of a smaller and simpler lunar laboratory will certainly be asked some time and thus this alternative is analysed and compared with the reference case in this appendix.

Table E-1: Comparison of lean lunar laboratory with reference lunar base	Reference case	lean facility
Technical Data:		
LC av. Number of lunar R & D crew members	26.0	26.0
accumulative scientific lunar labor-years	780	780
LC average total number of crew members	65.4	46.2
accumulative lunar labor-years	1962	1380
LC average facility mass	690	397
LC average power plant capacity (kW)	2,123	895
LC average import requirements (t)	88	107
- spares and extensions	37	31
- consumables	51	76
LC average products for own usage (t)	123	63
LC average products available for lunar users or export(t)	63	23
Cost data lunar operation (M \$) :		
initial development	6,370	5,310
initial equipment	2,229	1,594
system integration	741	519
Total acquisition w.o.interest	9,340	7,423
LC average p.a. equipment imported during operation	432	356
LC average p.a. consumables imported during operation	15	23
LC average p.a. Earth support	327	267
LC average p.a. lunar personnel salaries	53	38
LC average p.a. total recurrent cost	823	742
Total recurrent 30 year operational LC	24,690	22,260
System total cost 40 years LC	34,030	29,683
Specific cost data(M \$/ person):		
Use of laboratories and R&D equipment	14	18
use of habitat	10	13
use of central workshop	70	67
electrical power (\$/kWh)	10.5	12.8
Logistics:		
Number of primary passenger missions	70	50
number of primary cargo missions	50	60
number of refueling missions	5	40
Total cost of logistic support (incl. residual value)- (M\$)	39,600	40,755

Program totals:		
Program cost (M\$)	73,630	70,438
specific cost per scientific lunar labor-year (M\$/labor-year)	94.4	90.3
specific cost of lunar labor-year (M\$/labor-year)	37.5	51.0

In conclusion, a "Lean Lunar Laboratory (LLL)" could possibly reduce the life-cycle cost by about 3 B \$ or nearly 5 %, but at a heavy loss of experience and severe reduction of lunar outputs. This does not look like an attractive scenario, but demonstrates on the other hand a considerable flexibility of the entire program.

This brings also up the question whether it is possible to change the LUBUS mission mode for cargo transportation to the lunar spaceport. An expendable LUBUS could become the payload of the HLLV and land directly in a one-way flight on the Moon with about 45t payload. It would cost close to 150 M \$ per unit to manufacture the expendable landing stage stage.

The passenger mission mode with refueling in lunar orbit would not change, because round trips are a must for this part of the logistics operation.

The number of cargo missions would increase by 12 (due to the reduced payload per mission), resulting in additional cost of $12 \times 127 \text{ M \$} = 1,542 \text{ M \$}$.

However, the number of refueling missions to lunar orbit would be reduced by 20, resulting in a saving of $20 \times 115 = 2,300 \text{ M \$}$.

On the other hand, a total of 72 landing stages would have to be manufactured and would end up on the lunar surface for cannibalizing. These would cost an additional $72 \times 150 \text{ M \$} = 10,500 \text{ M \$}$.

Thus, the total cost would increase by about 9,742 M \$, an increase by about 14%, which does not make this alternative an attractive proposition.

APPENDIX F :

**DATA BASE AND BLUEPRINTS FOR THE DEVELOPMENT
OF LUNAR RESOURCES**

A Lunar Base Planning Guide

**A comprehensive compilation of the deliberations of the Subcommittee of Lunar
Development of the International Academy of Astronautics in the period of 1985
through 1999**

**compiled by H.H.Koelle
(as of December 31st , 1999)**

Table F-1: LUNAR DATABASE - LEVEL 1: List of Sections

(56 documents, 490 pages, 342 tables, 40 figures, 422 references)

0. - Basic Data	(10/71/41/2/14)
1. - Lunar Market	(05/25/21/2/43)
2. - Lunar Base Program	(06/46/23/2/26)
3. - Lunar Science	(05/23/09/ -/29)
4. - Lunar Facilities	(09/73/37/1/179)
5. - Lunar Logistics	(04 /19/10/ 1/2)
6. - Lunar space transportation systems	(06/55/59/17/43)
7. - Lunar cost and benefits	(05/48/36/3/21)
8. - Blueprints for Program Alternatives	(06/130/106/22/65))

Table F-2: LUNAR DATABASE - Level 2

0. DATABASE : (71 pp.,41 tabs.,2 figs.,14 refs.)

Doc-L01: Definitions

Doc-L02: Milestones of Lunar Development

Doc-L03: Lunar Data and Environment

Doc-L04: Subjects and Issues

Doc-L05: The Force Field of Lunar Development

Doc-L06: Lunar Development Programatics

Doc-L07: Lunar Base Systems State Variables and Performance Indicators

Doc-L08: System Comparisons

Doc-L09: Legal Aspects

Doc-L10: Declarations

1. PRODUCTS and MARKETS: (25/21/2/43)) .

Doc-L11: Lunar Market Prospects and Structure

Doc-L12: Lunar Services

Doc-L13 : Lunar Products

Doc-L14 : Cost and Prices for Lunar Products

Doc-L15 : Commercial Activities in Progress

2. LUNAR BASE PROGRAM: (46/23/2/26)

Doc-L21 : The Justification for a Lunar Base
Doc-L22 : Representative Lunar Development Program Timeline
Doc-L23 : Lunar Development Strategies
Doc-L24 : Building-block Scenarios
Doc-L25 : Skills and Activities
Doc-L26 : Program Uncertainties

3. LUNAR SCIENCE and HUMAN FACTORS: (23/9/0/29)

Doc-L31 : Lunar Science Fields
Doc-L32 : Specifications required of Experiments
Doc-L33 : Provisional Lunar Science Program
Doc-L34 : List of typical experiments
Doc-L35 : Current and Planned Projects

4. LUNAR FACILITIES : (73/37/1/179)

Doc-L41 : Functions
Doc-L42 : Lunar Facilities and Equipment (LF)-
Doc-L43 : List of Mass-categories
Doc-L44 : Combined Mass-flows
Doc-L45 : Mass-flow Balances for the individual Facilities
Doc-L46 : Simulation of Lunar Base Infrastructure Models
Doc-L47 : Facility Models
Doc-L48 : Preliminary Description of Infrastructure Facilities
Doc-L49 : Preliminary Description of Production Facilities

5. LUNAR LOGISTICS : (19/10/1/2)

Doc-L51 : Definitions , Selection Criteria, Requirements, Ground Rules
Doc-L52 : State-variables, control-variables and performance-parameters
Doc-L53 : Options for Lunar Transportation Systems
Doc-L54 : Comparison of Early Lunar Logistic Studies

6. LUNAR SPACE TRANSPORTATION SYSTEMS (LSTS)-(55/59/17/43)

Doc-L61 : State-of-the-art
Doc-L62 : CLASS 1 LSTS
Doc-L63 : CLASS 2 LSTS
Doc-L64 : CLASS 3 STS - SSTS
Doc-L65 : CLASS 3 LSTS - SPACE FERRIES
Doc-L66 : CLASS 4 LSTS

7. LUNAR COST and BENEFITS (48/36/3/21)

Doc-L71 : Cost Modeling
Doc-L72 : Cost Assumptions
Doc-L73 : Case studies
Doc-L74 : Benefit Modeling
Doc-L75 : Case Studies of Benefits of Lunar Development Programs

8. BLUEPRINTS FOR PROGRAM ALTERNATIVES (130/106/22/65)

Doc-L81: Lunar Development Program-OPTION I "Lunar Outpost"
Doc-L82: Lunar Development Program-OPTION II "Lunar Laboratory "
Doc-L83: Lunar Development Program-OPTION III "Lunar Base "
Doc-L84: Lunar Development Program-OPTION IV "Lunar Factory"
Doc-L85: Lunar Development Program-OPTION V "Lunar Settlement"
Doc-L86: Overview of Lunar Development Options