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A REPRESENTATIVE CONCEPT OF AN INITIAL LUNAR BASE
(Model 4.0 - May 1997)

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Abstract

The proposal of *returning to the Moon to stay* was made by President Bush in July 1989, but the changes in the geopolitical environment since the end of the cold war have prevented a serious discussion of this proposal until now. It is expected, however, that this question of a permanent research facility on the Moon will come up again early in the next decade. Thus concepts and plans have to be ready by that time to be discussed and evaluated. This report is an updated version of an earlier study by the same author entitled:"The Lunar Laboratory"[18]. It describes in detail a *Lunar Base* that is supposed to grow from about 40 to 120 people in 30 years. Some 1,200 metric tons of facilities and equipment are needed on the Moon. Average crew duty cycles are assumed to be six 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 proposed. The systems behaviour, the dynamics of selected parameters and the overall performance and cost-effectiveness of the lunar laboratory are analysed and presented. It is shown that the average annual cost of a lunar man-year is expected to be approximately 42 million (1994) dollars and that the average annual operations cost of this lunar base including a 10 year development phase may be less than 3 billion \$. The results are summarized in 28 tables,17 figures, 20 references comprising 51 pp.

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EXECUTIVE SUMMERY:

A REPRESENTATIVE CONCEPT OF AN INITIAL LUNAR BASE
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H.H.Koelle

Spaceflight is to be considered as a natural step of the evolution of the human species. Exploring space, using its resources, learning to live and work in space will improve the quality of life on Earth and also enhance the survival chances of humankind.

Roboters are extremly useful in many applications and are in operation for several decades in near Earth space as well as in interplanetary space. Some have even left the solar system. There is no question, that they will be used also heavily in the future. However, roboters have advantages *and* limitations, in selected applications they must be supplemented by human skills. For many decades in the past, Astronauts and Kosmonauts have demonstrated their usefulness in laboratories in orbits about the Earth and even began to explore the Moon. However, this 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 and be ready when the time comes to take new decisions[3,5,7,9,11,12].

After the expected completion of the *International Space Station* (ISS) in the year 2002 - or even before - the question will have to be answered: WHAT IS NEXT? It appears unlikely that the human exploration of space will come to an end, the evolution will not stop[11,12]. A likely choice would be returning to the Moon and to establish an *International Lunar Base (ILB)* possibly followed by crewed expeditions to planet *MARS:*
In so doing, the following *objectives* would be -at least partially - achieved[9,16,17]:

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. Stimulate the development of advanced technology on Earth.
4. Establish the first extraterrestrial human settlement as an initial step for expanding human activities in our solar system beyond our home planet .
5. Improve the understanding of our own planet.
6. Produce marketable services and products on the Moon for extraterrestrial or terrestrial use.
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 global or cosmic catastrophes.
10. Provide reliable space transportation systems to the Moon.
11. Improve our understanding of our solar system.
12. Improve our understanding of the universe.

An adequate sized lunar base providing commercial opportunities, 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 characteristics.

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

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

The cost of such an enterprise supported by public funds are summarized in the next table.

Table ES-2: Cost summary of a Lunar Base with a 10 year development phase and a 30 year operational life-cycle (million 1994 $)

COST ELEMENT	Life cycle M$	M$ p.a.	% of LC total
Development & test of lunar facilities-10 year	11,200	1,120	12.3
Dev.& test of space transportation system-10year	28,587	2,859	31.4
Subtotal development & test - 10 year	**39,787**	**3,979**	**43.7**
Sustained engineering STS - 30 year	4,998	167	5.5
Productionof space transportation system(STS)	17,130	571	18.8
Operation of space transportation system(STS)	17,595	587	19.3
Operation lunar facilities	11,640	388	12.8
Subtotal operations - 30 years operational LC	**51,363**	**1,712**	**56.3**
Total Lunar Laboratory System - 40 year life-cycle	**91,150**	**2,280**	**100**

A graphical presentation of the growth of the lunar crew and the improvement of the cost-effectiveness vs time shows the general trends to be expected.

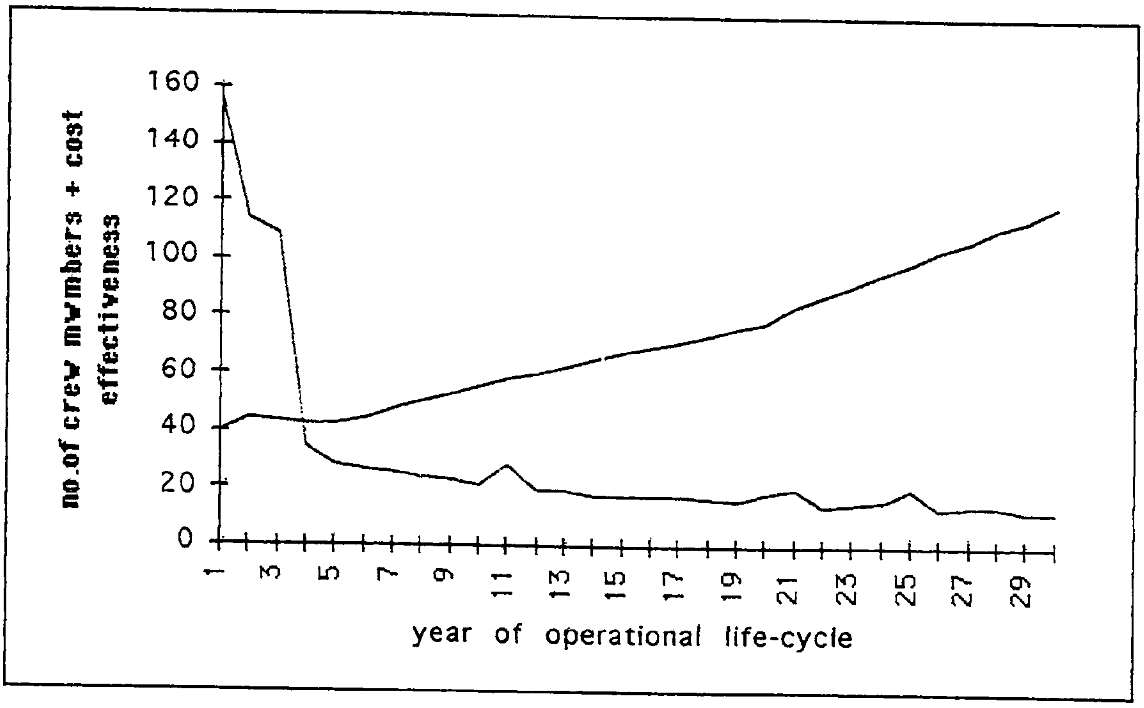


Figure ES-1: Growth of lunar population and reduction of specific cost per lunar labor-year (M 1994 $)

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.

Table ES-3: Lunar Base system development and operating cost at selected years during the 40 year life-cycle (million 1994 $ with 1 direct human labor year = 0.2 M $)

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 cost
-8	10	125	135	1	242	5,974	6,216
-7	290	1,176	1,466	3	290	4,369	4,659
-6	675	2,528	3,203	6	321	851	1,172
-5	1,060	3,340	4,400	10	356	829	1,185
-4	1,300	3,951	5,251	15	384	794	1,178
-3	1,900	4,097	5,997	20	408	1,027	1,435
-2	2,335	4,649	6,984	25	461	1,528	1,989
-1	1,950	5,011	6,961	30	512	937	1,449
0	1,680	5,210	6,890	total	22,843	70,362	93,705
				ann.av.	571	1,772	2,343

The graphical presentation of the initial investments required versus time are 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 7 B $ is merely **one percent** of the present military expenditures on this globe. The investments would not be required now, but begin no earlier than ten years from now with the peak after year 2010. By then the military expenditures are expected to come down by more than these amounts.

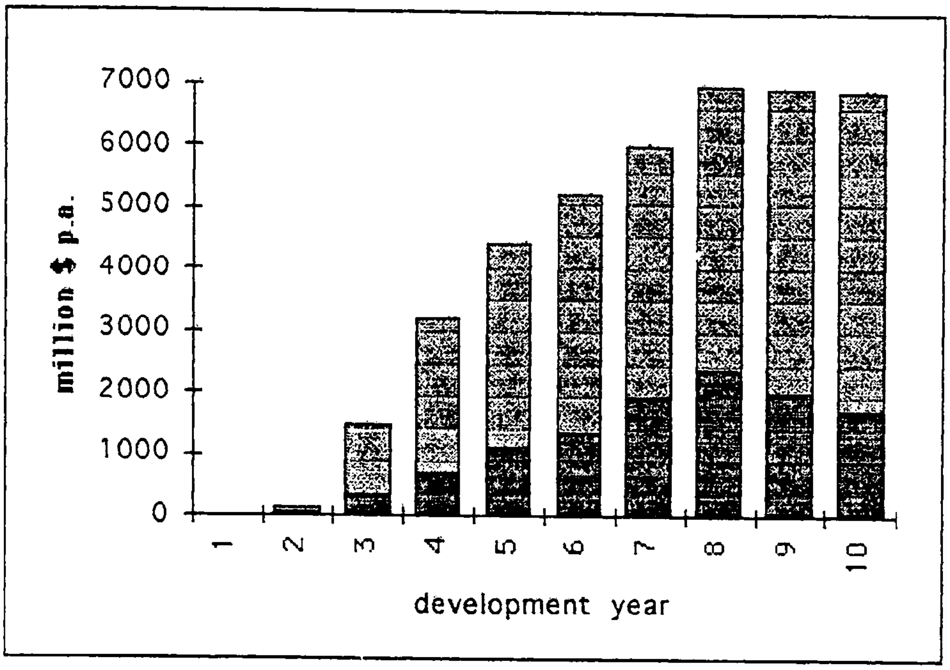


Figure ES-2: Annual distribution of development cost (non-recurrent cost) of the lunar facilities (lower bar) and the logistics system (upper bar)

There is a major decline of annual cost to be observed after initial beneficial occupancy of the lunar base as seen in figure ES-3. This public financial burden can be 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. If half of the available laboratory spaces could be leased at a rate of 20 M $ p.a. and half of the available export products can be sold at 1,000 $/kg, then 250 x 30 = 7.5 B $ + 1,230,000 kg x 1000 $/kg = 1,23 B $, or a total between 5 and 10 billion dollars is the commercial potential of this particular lunar base concept.

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. Additional cost reductions are possible, e.g.by increasing the crew duty-cycle as the lunar base grows and provides more comfortable living conditions.

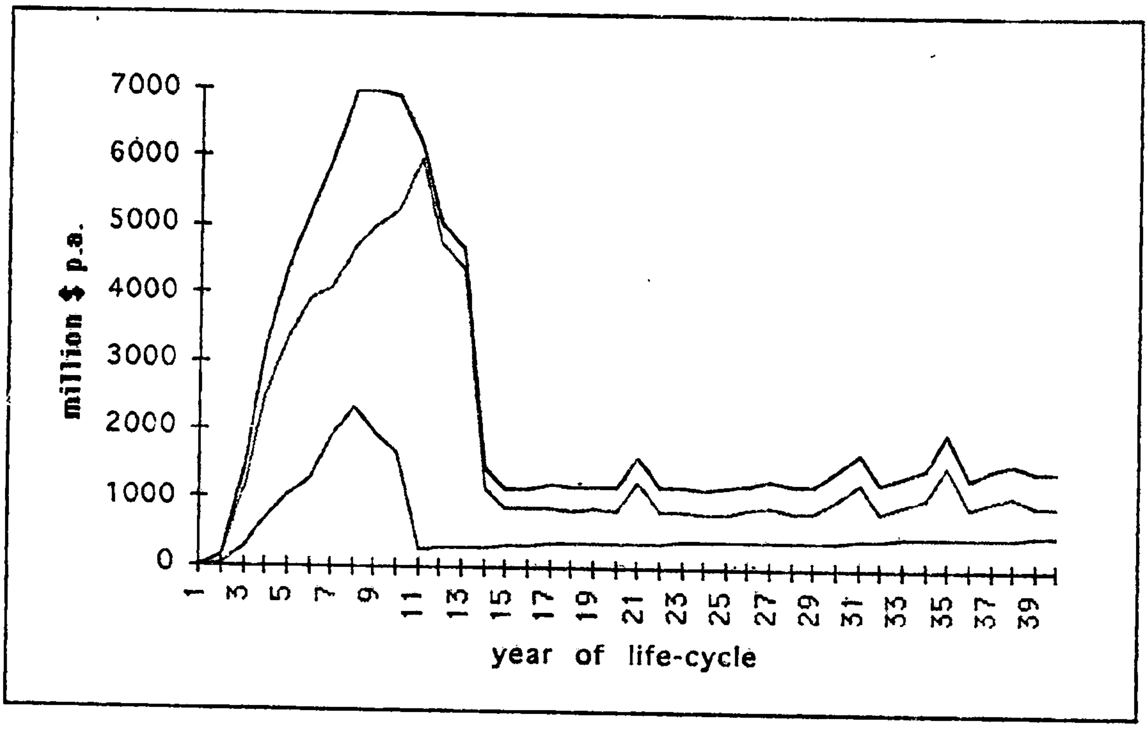


Figure ES-3: Lunar Base Sytem total cost trend (upper curve) with lunar faciliy costs (lower curve) and space transportation costs (middel curve)

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. The construction and operation of a small lunar outpost for a limited time can not be recommended at this time due to its poor cost-effectiveness and high risks involved. 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 next century at affordable expenditures and an acceptable risk.

3.The big hurdle of a decision to enter a new phase of lunar development is the sizable up-front investment requiring an average of about 4 billion (1994$) $ and peaks of up to 7 billion $ for a ten year period.This investment can not come from privat sources, it would have to be made by 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 come down in due course by partially commercializing lunar activities from 2.2 billion $ p.a. to about one billion dollar which makes this option a very attractive propositon. 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.

5. It is recommended to reopen the discussion of returning to the Moon at the time the International Space Station (ISS) is fully operational, presently planned in 2002. After a few years of discussion at the international level an agreement among the participating nations should be possible by 2005. Development could begin by 2006 and beneficial occupancy of an initial lunar base should then be possible by the year 2016. This planning 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

The first phase of lunar development ended with the flight of APOLLO 17 to the Moon in December 1972. The primary reason for ending the first phase of lunar development was the Vietnam war, which was requiring all available resources of the United States, 100 billion dollars in the peak year of this engagement! But it was also determined, that - after achieving the political objective of being there first - the relatively poor cost-effectiveness of the APOLLO program in exploring the resources of the Moon was preventing more lunar excursions of this type[11].

The seventies ot 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 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. Under these circumstances it was not possible to revive any plans for the immediate continuation of the lunar exploration program.

In the early 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 Congress, made a positive recommendation to return to the Moon among other space programs[3]. Other studies in those years [4,5,6,7,9,11] supported this recommendation.

The result of these efforts was the recommendation of President Bush in Juli 1989, 20 years after 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. All government supported space programs suffered from this upheavel of the geopolitical scene and most of them were put on the back burner as the consequence of changing priorities[11,15]. On the other hand commercial space projects in the telecommunication area flourished.

In the mid 90s the European Space Agency expressed an interest to take up lunar exploration after some lunar probes of Japan and the United States were quite successful[14]. Thus it is encouragement enough to discuss again the pros and cons of returning to the Moon and establishing a permanent facility on the lunar surface. This planning activity is sponsered also by the International Academy of Astronautics, which re-activated its Subcommittee on Lunar Development[16]. Several national and international symposia took place during the last decade to discuss various aspects of robotic and human exploration of the Moon in the future.

A great deal of the information presently available has been compiled in a 400 page Lunar Data Base[17], a 200 pag: summary "Prospects and Blueprints for Future Lunar development" of which is available on the INTERNET: http://vulcain.fb12.tu-berlin.de/ILR/personen/hh_koelle.html
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

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:

(these 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 opportunies.
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. These will change their relative priorities as function of time, depending on the current state of the planet. While a decision to go back to the Moon with people can not be expected in this decade, it may become an issue shortly after the turn of the century[15].-

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

Table 1-2: Services and Products of a Lunar Base

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 Maintenence & 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 Tourism Space observation and protection of Earth in emergencies	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

Now 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 or in sight. But new space transportation systems have to be matched to program size and 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. 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

A 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 base is planned on the basis of a ten year development period, a 30 year operational life-cycle and a lunar crew up to about 120 persons. Its primary objectives are :
(1) exploration of the Moon,
(2) research under lunar environmental conditions on and from the Moon,
(3) pilot production experiments 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, e.g. financed by public funds through budget allocations to national space agencies. This assumption excludes financing costs and a general profit. Standard profits are permitted, however, for the contractors delivering the hardware and services required.

2. - The space transportation system serving the lunar installation 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.

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 40 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 six months due to its experimental character.

5. - The third control variable for sizing lunar facilities is the mass of lunar products to be produced anually. - Typically, the production begins in the first year of the life-cycle processing lunar soil at a rate of about 10,000 metric tons per year producing lunar oxygen and some raw materials. The production activity becomes more effective during the life-cycle by increasing utilization rates of the lunar soil input.

6. - In this scenario it is further assumed that nearly all the oxygen propellants for the lunar landing and launch vehicle (LUBUS) will be produced on the Moon. The return propellants of the HLLV payload stage will use Earth propellants to be onboard at launch for reasons fo crew safety instead using lunar oxygen. Some liquid oxygen must also to be imported during the first years by tanker flights from the Earth to the lunar orbit service station (LUO-SOC), because the production of lunar oxygen will probably not cover all of the requirements initially. 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 keep the cost down.

7.- Hydrogen propellants are delivered from the Earth by the HLLV throughout the life-cycle to lunar orbit for refueling the lunar launch- and landing vehicles(LUBUS) at the lunar orbit space operations center(LUO-SOC). This space based facility is a modified second stage of the HLLV. It is prepared for its mission in LEO, transfered to LUO by its own propulsion, and will be operational before the first lunar crew arrives at the lunar base site.

A preliminary mass model of the lunar base facilities 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.

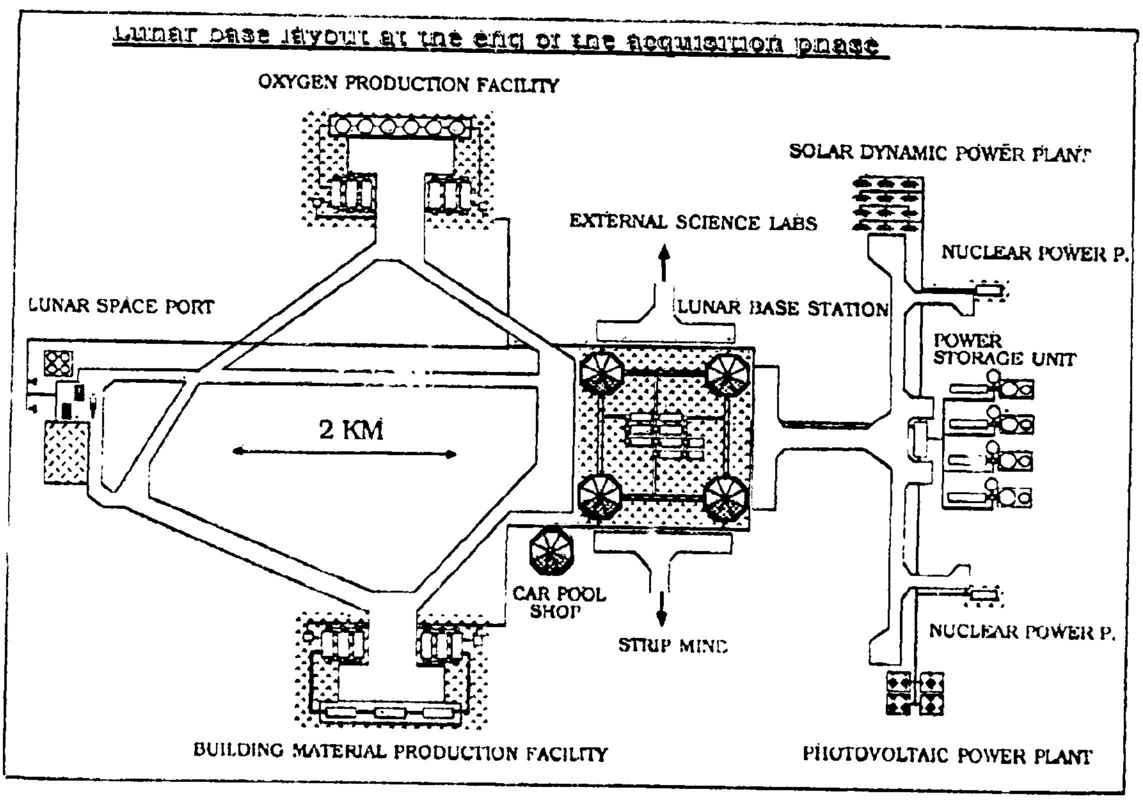
3. Lunar Base size and performance

3.1 Sizing of the lunar base facilities

An existing lunar base simulation model (LUBSIM)[1] was used for deriving 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 very small production capacity and is an updated version of an earlier lunar laboratory version (model 3.0 of 1996)[20]. This simplified concept permits to reduce the number of base elements from 20 (see table 3-4) allowed by the model, by grouping the production oriented elements as well as those comprising the infrastructure into one each.
Thus the simplified mass data presented is shown in table 3-1 in the following categories:

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

Figure 3-1 is a layout of a typical lunar base observing types of facilities,required distances, but leaves also room for modest growth.



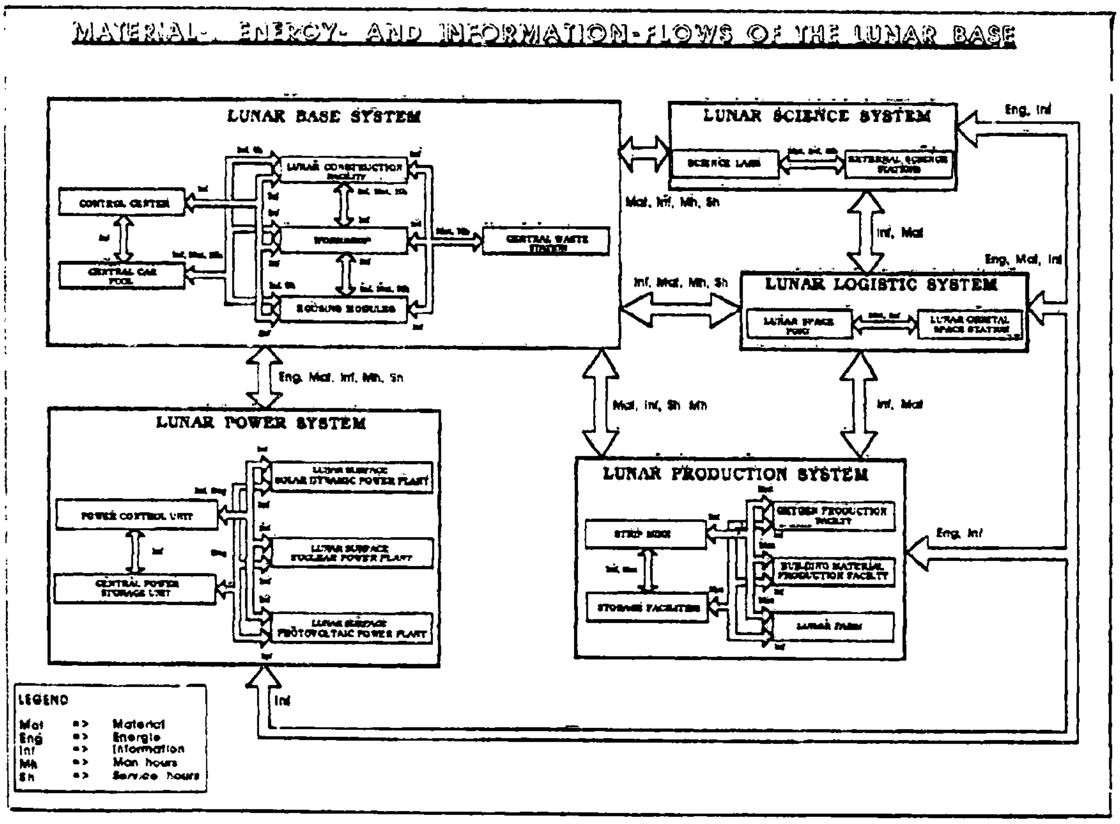


Figure 3-2 illustrates the flow of masses, information and energy between the elements of a typical lunar base, but also indicates where lhuman labor is required.

Table 3-1 lists 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. A detailed annalysis of this problem is part of the acquisition planning discussed in chapter 5 .

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. This early oxygen plant has to produce enough propellants for the LUBUS flights. If it does not initially, the difference has to be imported from Earth by extra flights.

The consumables produced on the Moon include recycled water, the gases (CO_2) and the biological wastes of the crew, but also the food produced in the biological laboratory (experimental farm) including some oxygen using part of the waste material.- The spare parts listed 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 as a function of their size and mass. The outputs resulting from these production activities are shown in Table 3-2.

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.	labora-tories and sci. equip. (7)	habitat + farm elements (17-19)	pilot prod.fac & equip. (1-6,9)	infra-structure facility & equip. (10-16)	total lunar facili-ties	actual annual facility & equip. growth
1	2	40	8	109	101	142	361	361
2	3	44	11	139	118	180	448	87
3	4	43	15	142	122	180	459	11
4	4	42	18	146	124	180	467	8
5	5	42	22	149	124	180	474	7
6	6	44	27	157	124	180	488	14
7	7	48	31	173	127	181	512	24
8	8	50	36	187	128	183	536	24
9	9	53	41	200	131	186	558	22
10	10	56	46	214	133	189	580	22
11	11	58	50	227	134	192	602	22
12	12	60	55	240	135	194	623	21
13	13	63	60	253	136	196	645	22
14	14	65	65	266	136	199	666	21
15	15	68	70	279	138	201	688	22
16	16	70	75	294	139	202	709	21
17	17	72	80	306	139	204	731	22
18	18	74	85	320	140	207	752	21
19	19	77	90	334	140	209	774	22
20	20	79	95	348	141	211	796	22
21	22	85	105	379	142	217	843	47
22	24	88	115	397	143	220	873	30
23	26	92	124	418	143	223	909	36
24	28	96	134	441	143	227	945	36
25	30	100	144	463	144	230	982	37
26	32	104	154	485	144	234	1,018	36
27	34	108	164	509	145	237	1,055	37
28	36	112	174	532	145	241	1,092	37
29	38	115	184	555	146	245	1,129	37
30	40	120	194	579	146	248	1,167	38
sum	523	2,170	-	-	-	-	-	1,167
av.	17.4	72.3	82	308	135	195	700	39

Table 3-2: Projected average annual outputs of defined lunar base facilities (kW and metric tons per annum)

year	lunar power produced (kW)	lunar produced spares & extensions	lunar produced consum-mables	total lunar products for direct lunar use	products for export or use TBD	lunar oxygen produced for LSTS	total output of lunar facilities
1	1,176	22	48	70	27	238	335
2	1,593	25	60	86	42	341	468
3	1,677	17	62	79	53	382	514
4	1,729	16	62	78	58	397	533
5	1,745	16	61	78	60	398	535
6	1,871	20	64	84	64	420	568
7	2,000	24	67	90	68	439	597
8	2,116	27	69	96	71	456	623
9	2,220	29	71	100	75	470	645
10	2,324	33	73	106	78	482	666
11	2,424	35	75	111	80	494	685
12	2,523	39	77	116	83	504	702
13	2,620	42	79	120	85	513	718
14	2,716	45	80	125	87	522	734
15	2,811	48	82	130	89	530	748
16	2,906	51	83	134	91	537	762
17	3,001	55	84	139	92	544	776
18	3,094	58	86	144	94	551	788
19	3,189	61	87	149	95	557	800
20	3,282	65	88	153	97	563	812
21	3,475	81	91	172	92	568	831
22	3,588	80	93	173	97	573	843
23	3,731	88	95	183	96	577	856
24	3,873	94	96	190	97	582	869
25	4,018	100	98	198	97	586	882
26	4,163	106	100	206	98	590	895
27	4,309	112	102	214	98	594	907
28	4,457	119	104	222	99	598	919
29	4,607	125	105	230	99	602	931
30	4,820	143	108	251	92	605	948
sum	-	1,776	2,460	4,230	2,460	15,210	21,900
average	2,935	59	82	141	82	507	730

As shown in table 3-1, the initial facilities are extended as required by the projected production rates, partly by imported parts and partly by lunar produced parts. The lunar produced components have to be subtracted from the total mass for extention to obtain the imports required. All complex facilities and equipment will have to be imported, also most of the higher quality food. In general it can be stated that the import rate of supplies per crew member will decline during the life cycle due to increased use of lunar products.

The initial facilities have to be transported to the Moon before or shortly after the arrival of the first crew,they are not included in the following table.

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 supple-ment materials	spare parts	new facilities and equip.	life support & consumi-mables	space vehicle parts	total projected imports
1	30	25	0	23	0	73
2	40	27	79	26	0.3	167
3	44	23	10	25	0.7	97
4	45	21	7	26	1	92
5	45	20	6	26	1.4	89
6	46	20	12	29	1.7	97
7	48	20	20	31	2.1	109
8	50	20	21	33	2.4	112
9	51	20	18	36	2.8	112
10	52	20	18	38	3.1	114
11	53	20	18	40	3.4	116
12	54	19	17	42	3.8	117
13	55	19	17	44	4.1	119
14	56	19	17	46	4.5	120
15	57	19	16	48	4.8	122
16	57	19	16	50	5.2	123
17	58	19	16	52	5.5	125
18	59	19	16	55	5.9	126
19	59	19	16	57	6.2	128
20	60	19	15	59	6.6	129
21	60	19	34	64	6.9	152
22	61	19	20	67	7.2	139
23	61	19	24	71	7.6	146
24	62	20	24	75	7.9	148
25	62	20	24	79	8.3	150
26	63	20	23	83	8.6	152
27	63	20	23	87	9.0	154
28	64	20	23	91	9.3	155
29	64	20	22	95	9.7	157
30	64	20	35	100	10	173
sum	1,584	603	608	1,551	150	3,813
average	55	20	20	53	5	127

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. After about ten years of operation more supplies come from lunar sources than from the Earth!

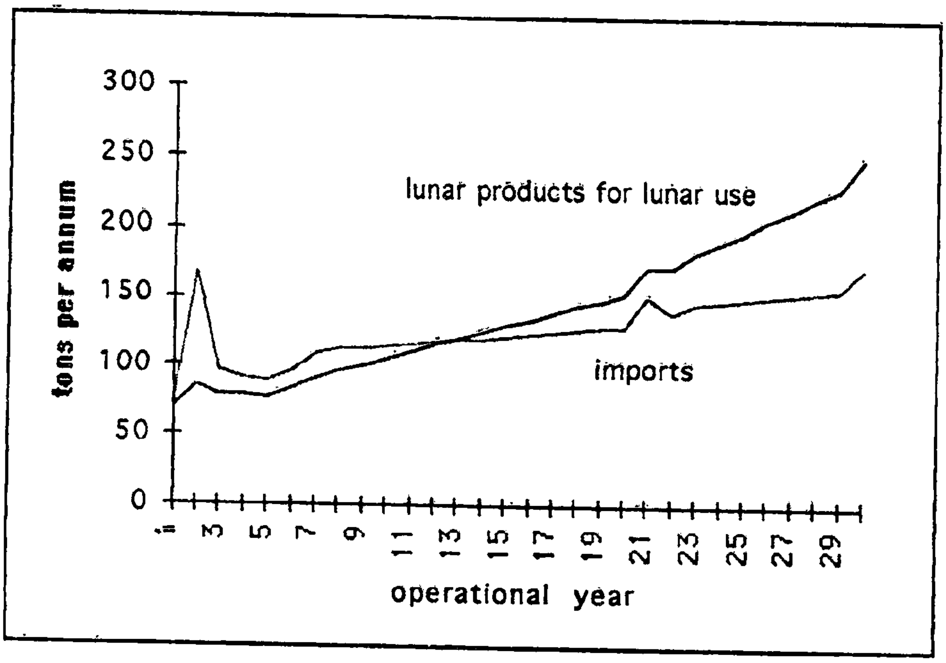


Figure 3-3 : Development trends of lunar products for lunar use and the mass of imports to the lunar surface

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 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 an idea with respect to the space transportation system assumed to be available, otherwise an iteration process between lunar facility and lunar space transportation system will be unavoidable.

3.2 Acquisition and operating costs of lunar facilities

Non-recurring cost:

The program structure is the basis for estimating program cost, it was developed and presented in the previous chapters. To estimate cost and distribute these over the calender 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 system tests.

Table 3-4: Overview of preliminary estimates of the upfront costs of lunar facilities (1 direct labor-year = 0. 2 M 1994 $)

no.	Facility designation	develop-ment cost M $	first unit cost M $	system ckeckout cost M $	total upfront costs M $
1	strip mine	90	10	3	103
2	beneficiation facility	180	10	3	193
3	chem.processing facility	900	20	16	936
4	mech.processing facility	480	14	2	496
5	fabrication & assy.shop	180	6	1	187
7	laboratories	900	14	1	915
9	gas processing facility	600	13	1	614
10	propellant storage	180	2	1	183
11	power plant	900	212	6	1,118
13	space port	360	24	2	386
14	central storage	120	11	2	133
15	central workshop	90	12	1	103
16	carpool	480	15	1	496
17	control center	900	35	4	939
18	housing facility	1,200	144	16	1,360
19	biol.processing facility	840	20	4	864
sum		8,400	562	62	9,022

A distribution of these totals versus time is shown on the next table.

Table 3-5: Summary of non-recurrent cost of lunar base
(million 1994 dollars)

Legend:

(1) Year of development
(2) Initial development cost of lunar facilities prior to initial beneficial occupancy.
(3) Cost of first units of lunar facilities and equipment, if manufactured during the years before the beginning of the operational period including system checkout.
(4) Four 3rd stages of the HLLV which -after landing - will remain on the Moon serving as storage containers at 330 $ each, not included in the model!
(5) Cost of planning activities, systems engineering and training of initial lunar crew members, this is not included in the operational part of the model!
(6) Total lunar base facilities =(6) + (7) + (8)

year (1)	(2)	(3)	(4)	(5)	(6)
-8				10	10
-7	240			50	290
-6	600			75	675
-5	960			100	1060
-4	1200			100	1300
-3	1800			100	1900
-2	1800	75	360	100	2335
-1	1200	200	400	150	1950
0	600	350	500	230	1680
totals	8,400	625	1,260	875	11,200

Recurrent cost of laboratory:

The "recurrent cost" during the operational phase are presented next, first of the lunar facilities and equipment to be followed by the recurrent cost of the space transportation system.

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, training of lunar crews and their salaries. All this adds up to the operating cost of the LULAB facilities, but does not include transportation cost. Alternatively the LULOX cost are deducted because they have been charged to the space transportation system.

Table 3-6: Direct operating cost of lunar laboratory
(million 1994 $ p.a.)
Legend:
(1) Operational year.
(2) Cost of the personnel for sustained engineering, training of lunar crews and administration supporting activities on the lunar surface (the largest share of all cost elements!)
(3) Cost of goods imported
(4) Salaries of the lunar crew members including their duty cycles on Earth.
(5 Cost of facility modules, equipment and other imports.
(6) Cost of Earth ground support of science operations on the Moon.
(7 Cost of reimbursed Lulox from LSTS
(8) Total cost of LULAB activities on the Moon during the operational years without and with consideration of reimbursed lulox cost.

(1) year	(2) sust.eng admin. crew training	(3) total import goods	(4) crew salaries	(5) science support	(6) total recurrent lunar base costs	(7) re-imbursed lulox cost	(8) total direct recurrent costs
1	408	44	30	100	582	341	242
2	408	183	35	100	726	451	275
3	408	63	33	100	603	313	290
4	408	56	32	100	595	297	299
5	408	53	32	100	592	285	307
6	408	62	33	100	603	283	321
7	408	78	36	100	622	285	337
8	408	84	38	100	630	286	344
9	408	81	40	100	629	281	348
10	408	83	42	100	633	277	356
11	408	83	43	100	634	272	362
12	408	83	45	100	637	269	368
13	408	84	47	100	639	265	373
14	408	84	49	100	641	262	379
15	408	85	50	100	643	259	384
16	408	85	52	100	645	256	389
17	408	87	54	100	648	254	395
18	408	87	55	100	650	251	399
19	408	88	57	100	653	249	404
20	408	87	59	100	654	247	408
21	408	125	63	100	697	252	445
22	408	102	66	100	675	242	434
23	408	110	69	100	686	240	447
24	408	111	71	100	690	236	454
25	408	111	74	100	694	232	461
26	408	112	77	100	697	229	468
27	408	113	80	100	700	226	475
28	408	113	83	100	704	223	481
29	408	114	86	100	708	221	487
30	408	136	91	100	735	223	512
sum	12,240	2,784	1,620	3,000	19,644	7,324	11,641
av	408	93	54	100	655	244	388

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 and feedstock. The mass flows and services as projected have been presented in table 3-1 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 we obtain the specific cost of products and services. If we can find a market for some of these, we would be able to reduce the expenditures to be provided by public funds in the beginning of this extraterrestrial human activity 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 costs only, since they do not yet take into consideration 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.

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

year	LULOX ($/kg)	Lulab (M$/MY)	Work-shop (M$/MY)	Habitat (M$/MY)	Farm pro-ducts ($/kg)	Control center (M$/MY)	Power plant ($/MWh)	Export goods average ($/kg)	av.total lunar out-put ($/kg)
1	1,430	36.27	16.32	8.83	5,005	35.15	11,835	2,760	1,565
2	1,324	39.04	32.37	11.55	7,244	36.84	13,991	2,806	1,485
3	820	27.56	15.30	7.12	4,970	32.09	7,062	1,828	943
4	747	24.63	16.42	7.15	5,182	33.06	6,544	1,658	862
5	718	22.59	17.27	7.13	5,255	33.76	6,237	1,570	828
6	672	20.97	17.70	7.07	5,378	32.58	5,747	1,505	782
7	649	19.71	17.79	7.36	5,349	31.56	5,523	1,448	755
8	629	18.34	16.92	7.09	5,284	30.28	5,754	1,381	730
9	598	17.08	16.26	6.72	5,085	29.19	5,365	1,306	695
10	573	16.13	15.75	6.54	4,990	28.23	5,127	1,247	667
11	552	15.28	15.26	6.32	4,867	27.34	4,880	1,195	642
12	533	14.58	14.81	6.15	4,772	26.54	4,681	1,150	620
13	516	13.96	14.40	5.98	4,675	25.79	4,494	1,110	601
14	502	13.41	14.01	5.83	4,589	25.10	4,330	1,073	584
15	489	12.92	13.65	5.69	4,506	24.45	4,178	1,040	570
16	477	12.48	13.31	5.56	4,430	23.86	4,040	1,011	555
17	466	12.10	13.03	5.46	4,370	23.56	3,918	985	542
18	456	11.73	12.73	5.33	4,288	22.99	3,789	960	530
19	447	11.41	12.47	5.24	4,233	22.49	3,688	937	520
20	438	11.09	12.17	5.12	4,157	21.98	3,574	915	510
21	444	11.71	12.38	5.58	4,520	21.88	3,872	915	510
22	422	10.71	11.06	4.88	3,982	20.32	3,386	864	487
23	415	10.40	11.02	4.89	4,000	19.87	3,376	845	477
24	405	9.99	10.69	4.75	3,893	19.20	3,256	822	465
25	396	9.62	10.41	4.61	3,794	18.57	3,148	800	455
26	388	9.28	10.10	4.48	3,698	17.99	3,044	779	445
27	380	8.98	9.83	4.37	3,611	17.45	2,950	759	435
28	373	8.70	9.56	4.25	3,527	16.94	2,859	741	426
29	366	8.44	9.31	4.15	3,450	16.46	2,775	724	418
30	369	8.54	10,.92	4.38	3,646	16.29	2,910	717	418
av	521	11.58	13.96	5.51	4,292	23.63	4.206	2,470	601

In general, it is fairly expensive to produce lunar goods and services within the frame of a small lunar base, because the production volume of this science oriented operation is low.
Of particular interest of the items listed in this table are the specific cost of lunar produced oxygen listed in the first column. The life-cycle average price is 521 $/kg which is an equivalent of 2.6 labor-years. This value would have to be entered into the TRASIM model as the minimum price to be paid for using lunar LOX to obtain the total transportation cost including the Lulox refueled on the Moon. Also of special interest is the next column, indicating that a working space in the laboratory research and development facilities could be leased for an *average* of 11.6 M $ p.a. or 5,8 million $ per 6 month activity period, not including the roundtrip cost of the research scientist.

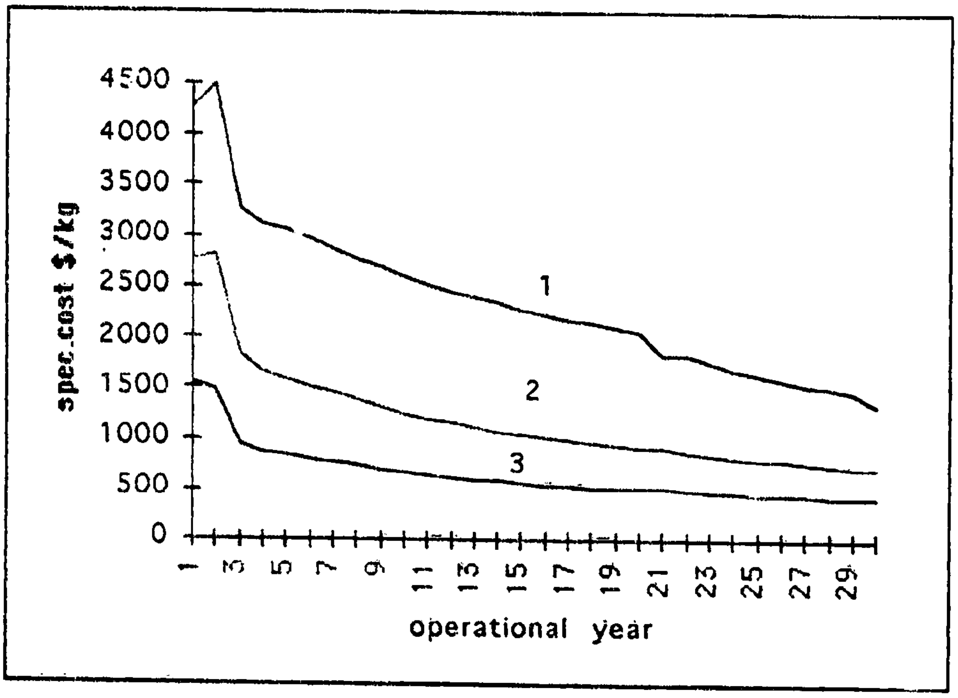


Figure 3-4: Trends of specific cost of selected lunar products
1 = all products for lunar use, 2 = exports, 3 = all lunar products including Lulox

The other limiting case is an operation where the lunar laboratory operation will be charged with the non-recurrent and recurrent cost of the lunar space transportation system. In this case the total space transportation cost are a burden to be distributed over all lunar products and services thus increasing their specific costs. Not yet included are those charges connected with a fully commercial operation such as financing cost and profit,however.

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 (1990) $, if they are to cover the cost of the operation. The lunar laboratory would have - under these assumptions - the following sales potential:

Table 3-8: Projected total annual sales potential (million $ p.a.) with total transportation cost charged to the lunar operator

year	exports or infra-structure	pro-pellants	port services overhaul vehicles	labora-tory spaces	sales of all prod. and services	products used by lunar base
1	74	341	9	72	496	35
2	117	451	20	106	694	61
3	97	313	10	96	515	35
4	95	297	10	104	506	34
5	94	285	11	112	502	34
6	96	283	11	125	515	38
7	98	285	11	137	531	42
8	99	286	11	145	541	43
9	98	281	11	152	542	44
10	97	277	11	160	544	45
11	96	272	10	166	545	47
12	95	269	10	173	547	48
13	94	265	10	180	549	49
14	94	262	10	186	551	50
15	93	259	10	192	554	51
16	92	256	10	198	556	52
17	91	254	10	204	559	53
18	90	251	10	209	560	54
19	89	249	10	215	563	55
20	89	247	10	220	565	56
21	84	252	10	255	600	66
22	84	242	10	255	590	60
23	81	240	10	268	598	63
24	79	236	9	277	602	64
25	78	232	9	286	605	65
26	76	229	9	294	609	65
27	75	226	9	302	612	66
28	73	223	9	310	615	67
29	72	220	9	318	619	67
30	66	223	11	338	638	76
sum	2,593	7,591	322	6,113	17,590	1,638
average	86	253	11	204	586	55

4. The lunar space transportation system

4.1 System definition

The governing factor of the concept, acquisition process and operation of the lunar base 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 base. Logistics cost is the major cost item 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 flight frequency is less than four flights p.a. then the operational flexibility would suffer. Furthermore it must be assured that enough reserve payload capability for unforseen emergencies will be available[10,20].

The **logistic support system for the lunar base** selected in this case study is a near state-of-the-art fully reusable space transportation sytem, using high energy chemical propellants and available subsystems from the Shuttle and other existing programs[9,10,20]. It is expected to offer an initial operational capability by about the year 2016 after a nine to ten year development and flight-test period. It also 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), being used during standard operations for the transfer of passengers and cargo payloads, but also as propellant storage and maintenance facility, and

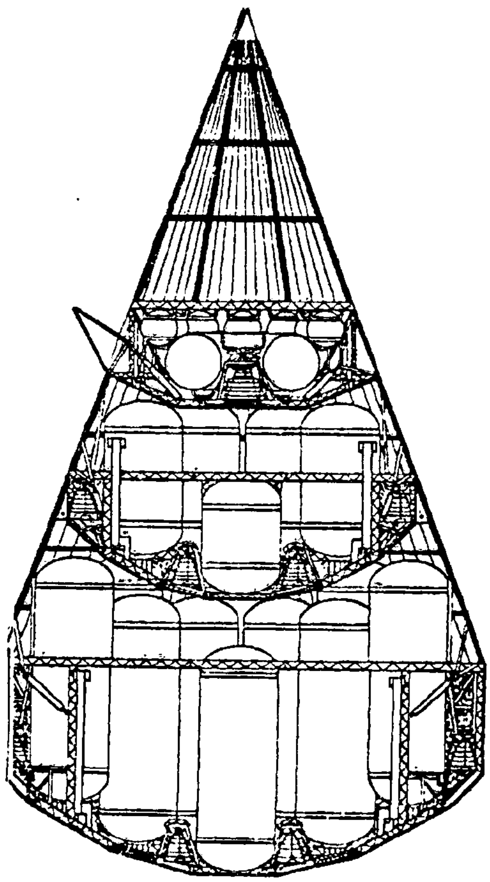
(3) a lunar bus (LUBUS) for local transportation of passengers and cargo between the lunar spaceport and the LUO-SOC.

4.2 The heavy lift launch vehicle (HLLV)[10,20]

The HLLV 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** on a direct flight to the lunar surface using in this application its third stage to land the cargo. This payload capability is the average performance during the entire life cycle. It would be somewhat lower in the early years and grow during the life-cycle resulting from regular product improvement efforts, but the payload capability is kept constant throughout the life-cycle of the lunar base to keep the model simple. This assumption does not change greatly the overall life-cycle performance.

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

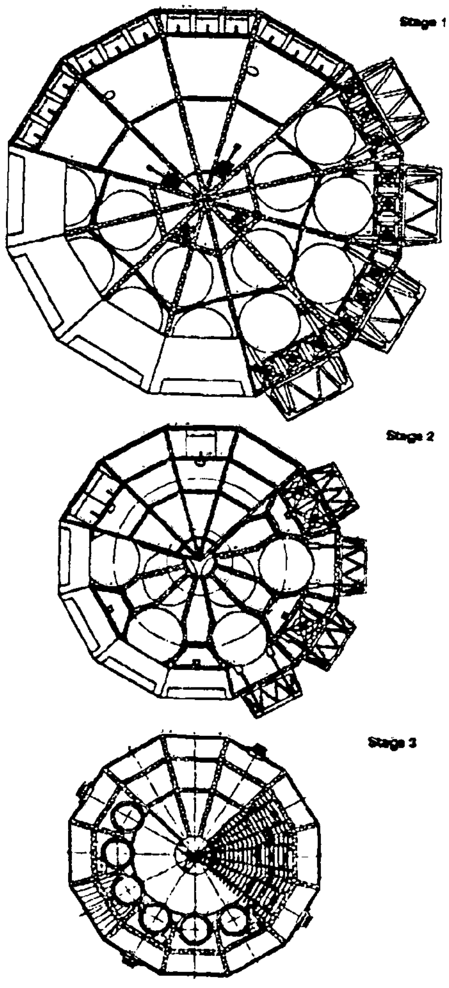
Technical University Berlin



This three stage heavy lift launch vehicle, based on the NEPTUN concept shown in the next 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 t passenger or cargo module (= 102 t) require a mass ratio of 1.30, thus a gross mass of 132 t including 30 t of return propellants which it brings along from the Earth in its early lunar logistics job. Substracting these from the 110 t nominal payload result in an **effective payload delivered to the lunar orbit of 80 tons** for both the passenger and the cargo version of this launch vehicle, aside of the return requirements. - The three stage NEPTUNE dimensions are 40 meters wide and 72 m high.

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 18 t of equipment delivered to support the lunar SOC, or additional hydrogen to compensate for vaporisation losses of the SOC. This excess of payload capability can also be considered as a design and/or performance reserve.

Figure 4-2:
Horizontal cross section of the three stages of the NEPTUNE -2015 heavy lift launch vehicle



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 cargo version would thus have a capability to carry a **60 t cargo** module, a 3 t payload container, 30 t of return propellants and 17 t liquid hydrogen propellants for LUBUS operation, adding up to 110 t nominal HLLV payload capability.

The payload plattform must be compatible with the LUBUS which has a platform with a diameter of about 7 m. Additional payload containers can be placed between the engines of the thirs stage if required

Several **direct flights of the HLLV 3rd stage** to Earth will be needed during the early acquisition phase of the lunar base to transport the initial large facility modules amounting to about 400 tons to the lunar base site before or shortly after the arrival of the first crew. These flights will be in addition to the regular schedule considering only the supply and crew rotation demands. The third stage would have to undergo the following modifications for this purpose :
- enlargement of the propellant capacity by about 25% (from 215 to 270 t),
- change of the heat shields (no aerodynamic braking required),
- addition of a landing gear.

The mass and performance characteristics of this direct lunar landing stage would look approximately as follows:

Velocity requirement = 5,900 m/s, exchaust velocity 4,500 m/s, mass ratio = 3.70.

Initial mass in LEO	365 t
usable propellants	266 t
cut-off mass on the Moon	99 t
stage mass	53 t
residuals and reserves	8 t
net payload on the Moon	45 t

The empty stage would remain on the Moon and be available for storage of liquids and gases. Also the 5 to 8 t of residual propellants and gases after landing and components would be available for other use. The production cost including modifications of these stages which are on the order of 330 million $/unit would have to be included in the cost balance of the lunar facilities to obtain a complete picture. A few flights will be scheduled in the year before the first crew arrives on the Moon with the most critical large facilities, such as habitats, power plants and oxygen plant. These have to be at the lunar base site, checked-out and in operable condition to allow beneficial occupancy when the first crew arrives.

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 HLLV[20]. 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. Two secondary refueling flights to low Earth orbit (LEO) are required by the HLLV (this is a total of 3!) to make this transfer of the LUO-SOC facility into lunar orbit (using its own propulsion system) feasible. These additional flights are calculated automatically by the program as secondary missions in the first operational year. Some propellants remain onboard of the SOC after arrival in lunar orbit if completely fueled in LEO before departure. These propellants are needed for suplying the initial LUBUS flights due to a limited LULOX production capability on the Moon in the early years. This space facility is scheduled to be activated in lunar orbit, before the first lunar crew arrives. Under standard operational conditions, the LUO-SOC has a maintenance crew of 3-6 astronauts depending on the traffic. An average crew duty cycle of six months is assumed resulting in additional secondary missions.

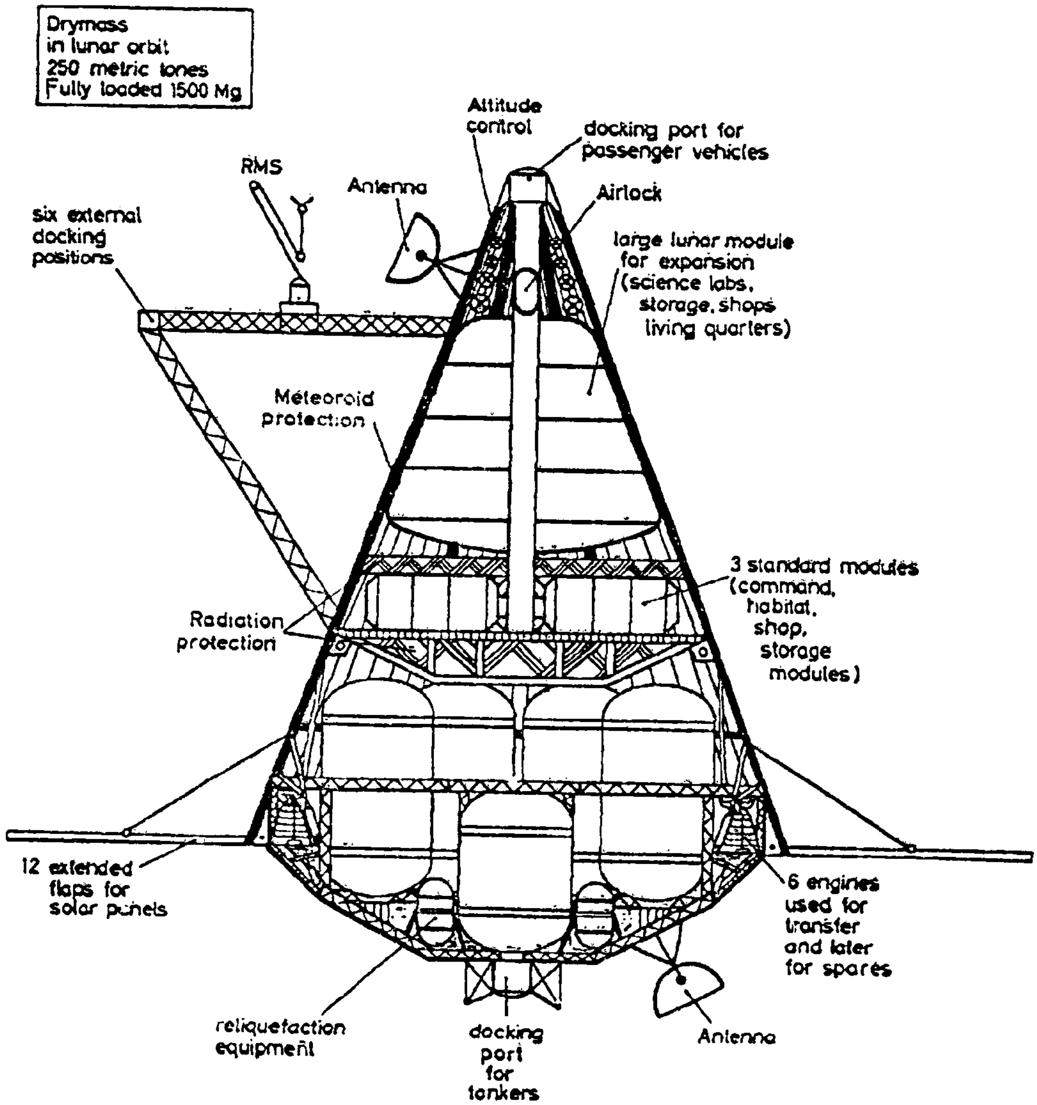


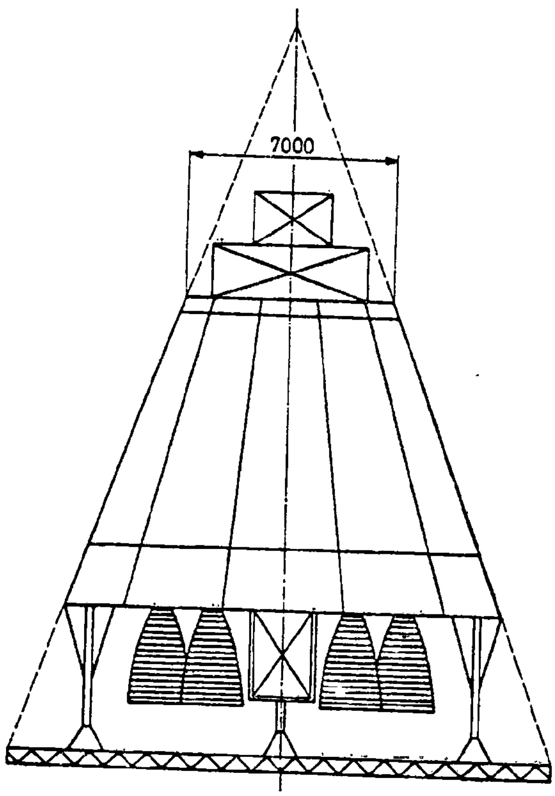
Figure 4-3: Space Operations Center(SOC) derived from the second stage of the NEPTUNE HLLV

Mass model:

The transfer of the LUO-SOC from the low Earth orbit to lunar orbit requires a velocity increment of 4,165 m/s, with an effective exhaust velocity of c = 4,500 m/s this results in a mass ratio of r = 2.523. The LUO-SOC with a dry mass of 250 t arrived in LEO with 300 t residual propellants to be modified for its lunar orbit mission. After refueling 2 x 300 t in LEO its take-off mass is 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.

4.4 The lunar launch- and landing vehicle (LUBUS)

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



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

LUBUS Passenger Flights:

DOWN LEG of the LUBUS from LUO-SOC		
empty stage	20 t	
crew cabin with crew	**25 t**	(40 passengers for 1 hr flight time)
hydrogen for ascent	7 t	
stage at cut-off	52 t	
usable propellants required	30 t	(5 t LH_2 + 25 t Lulox)
take-off mass in LUO	82 t	

ASCENT of the LUS to LUO		
empty stage mass	20 t	
cabin with crew	**25 t**	(max.capacity 40 persons for 1 hr)
Lulox for down leg	25 t	
cut-off mass	70 t	
usable propellants required	40 t	(7 t LH_2 + 33 t Lulox)
Take-off mass on the Moon	110 t	

LUBUS Cargo flights:

DOWN LEG from LUO-SOC		
empty stage mass	20 t	
cargo incl.packaging	**63 t**	
hydrogen for ascent	10 t	
cut-off mass on the Moon	93 t	
usable propellants required	52 t	(7 t LH_2 + 45 t Lulox)
Take-off mass in LUO	145 t	

ASCENT of Cargo-LUBUS		
empty stage mass	20 t	
Lulox for down-leg	45 t	
return cargo	50 t	
cut-off mass	115 t	
usable propellants required	64 t	(9 t LH_2 + 55 t Lulox)
Take-off mass on the Moon	179 t	

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

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

Lunar LOX-requirements at the lunar spaceport:
Passenger flights : 25 + 33 + 2 losses = **60 t per flight**
Cargo flights: 55 + 45 = **90 t per flight**

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 explains the relatively large dry mass of this vehicle.

4.5 Space Transportation System performance

Table 4-1: Typical flight schedule for supporting the lunar base
(passenger flight = 40 persons, cargo flights = 60 t, one-way = 50 t + empty stage)
*) five flights tests, **) 2+2 Lubus delivered partly fueled to LUO,# tanker flights

YEAR	no.and capa-city of pass. flights	no of regular cargo flights	extra cargo flights init. facil.	total cargo capa= city rqrd.	flights to LEO &SOC fac.+ prop.	total no.of HLLV lunar flights p.a.	Lulox reqrd	Lulox pro-duced	Lox brought from Earth
0	0	0	0	0	5*) + 1	0+6	0	0	0
1	1	2	3	120+150	2**)+2	8+2	240	230	280
2	2	2	2	120+120	2**)	8	480	340	100
3	2	2	3	50+120		7	480	380	200
4	2	2	2	120+120		6	480	400	
5	2	2		86		4	300	400	
6	2	2		95		4	300	420	
7	3	2		106		5	300	440	
8	3	2		109		5	360	450	
9	3	2		109		5	360	470	
10	3	2		111		5	360	480	
11	3	2		112		5	360	490	
12	3	2		113		5	360	500	
13	3	2		114		5	360	510	
14	3	2		115		5	360	520	
15	3	2		116		5	360	520	
16	4	2		118		6	420	530	
17	4	2		119		6	420	540	
18	4	2		120		6	420	550	
19	4	2		121		6	420	550	
20	4	2		122		6	420	550	
21	4	2		144		6	420	560	
22	4	2		132		6	420	560	
23	5	2		138		6	480	570	
24	5	2		139		7	480	570	
25	5	2		141		7	480	580	
26	5	2		143		7	480	580	
27	5	2		144		7	480	580	
28	6	2		146		8	540	590	
29	6	2		161		8	540	590	
30	6	2		142		8	540	600	
sum	110	60	10	3,900	4 + 9	186*)	12,060	15,000	580
av	7.33	2		130				500	

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

Matching annual launch rates with a first approximation of the requirements of the lunar base leads to the payload capacities and propellant requirements listed in table 4-1. The table shows that the system performance is greatly determined by the demands for crew rotation. With 2,170 labor-years on the Moon and an

average duty cycle of 6 months the capacity of the passenger flights must offer 4,340 seats, or 4,340: 40 = 108.5 passenger rountrip missions.
The operational performance of the HLLV and the LUBUS in terms of vehicle inventory, number of annual flights scheduled, number of flights per vehicle in the inventory and turn-around time available between flights are presented in the table 4-2.

Table 4-2: Operational performance of space vehicles

YEAR	HLLV inventory	no. flights HLLV	turn-around time	no.fl. p.a.per vehicle	Lubus inventory	no. flights Lubus	turn-around time	no.fl. p.a.per vehicle
1	1	11.3	32	11.3	1	5	73	5
2	2	8.6	84	4.3	2	8	91	4
3	3	7.5	145	2.5	3	4	272	1.3
4	3	6.5	169	2.2	4	6	242	1.5
5	3	5.4	202	1.8	4	5	290	1.3
6	3	5.4	202	1.8	4	5	290	1.3
7	3	5.4	203	1.8	4	5	290	1.3
8	3	5.4	203	1.8	4	5	290	1.3
9	3	5.4	203	1.8	4	5	290	1.3
10	3	5.4	203	1.8	4	5	290	1.3
11	3	5.4	203	1.8	4	5	290	1.3
12	3	5.4	203	1.8	4	5	290	1.3
13	3	5.4	203	1.8	4	5	290	1.3
14	3	5.4	203	1.8	4	5	290	1.3
15	3	5.4	203	1.8	4	5	290	1,3
16	3	6.5	169	2.2	4	6	241	1.5
17	3	6.5	169	2.2	4	6	241	1.5
18	3	6.5	169	2.2	4	6	241	1.5
19	3	6.5	169	2.2	4	6	241	1.5
20	3	6.5	169	2.2	4	6	241	1.5
21	3	6.5	169	2.2	4	6	241	1.5
22	3	6.5	169	2.2	4	6	241	1.5
23	3	7.5	145	2.5	4	7	207	1.8
24	3	7.5	145	2.5	4	7	207	1.8
25	2	7.5	96	3.8	4	7	207	1.8
26	2	7.5	96	3.8	4	7	207	1.8
27	2	7.5	96	3.8	4	7	207	1.8
28	2	8.6	84	4.3	4	8	181	2.0
29	2	8.6	84	4.3	3	8	136	2.7
30	2	8.6	84	4.3	3	8	136	2.7
sum	-	202	-	85	110	180	-	53
av	2.6	6.7	153	2.8	3.7	6	230	1.8

The demands for cargo transportation are smaller than those for passenger transportation with the exception of the first few years.With the heavy delivery schedule of facilities plus the additional Earth propellants needed for the return flights in the early years, a fairly high launch rate results,which might be difficult

difficult to attain. But it it quite clear, that only the actual performance during the development phase and the actual rate of progress will determine how fast the acquisition process can be realized. Thus, the flight numbers indicated for year "0" might in the worst case situation, they might have to be distributed over two years. This requires a detailed analysis of a type shown in chapter 5.

As pointed out already, the actual number of vehicles available in the inventory is larger than shown, because the prototype vehicle and the pre-production vehicle are available in the early years in addition and will reduce the annual number of flights. On the other hand it must be noted, that every few years a vehicle will be taken off the flight line for the purpose of overhaul and upgrading. The demands on a particular vehicle with respect to launch frequency are very modest due to the assumption that four vehicles have to be available during the operation. This is a very great growth potential for higher launch rates and cost reduction going along with this.

4.6 Acquisition and operating cost of space transportation system

Non-recurring cost:

The program structure of the space transportation system is the basis for estimating program cost, it was developed and presented in the previous chapter. To estimate cost and distribute these over the calender 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, before the operational phase can be initiated. These costs are primarily the 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[2,10]. In case pre-production of vehicles or modules are required due to the anticipated schedules prior to the first operational year, these are estimated at the level of first unit costs.

This cost estimate of the up-front costs (= non recurring costs) is followed by an estimate of the recurrent cost of the logistic system during its operational phase. Knowing the vehicle flights required, it is possible to derive at preliminary cost estimates for the various elements of the space transportation system. This estimate was done with the help of the TRASIM code which has been used frequently in the past with great success.

The following comments will help to understand the calculation procedure used for deriving the non-recurrent costs listed in the specified columns of table 4-3 :
Legend:
(1) Development cost the heavy lift launch vehicle (HLLV) and lunar lander (LUBUS), including prototype, ground facilities and flight testing, but excluding crew cabins and payload containers.

(2) Cost of development of crew modules and payload containers for HLLV and LUBUS including prototypes and flight tests.

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

(4) Development cost of the space operation center (LUO-SOC) on the basis of a modification of the second stage of the HLLV. The production of the first complete unit will be listed not under development but under production cost.

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

Table 4-3: Non-recurrent cost of space transportation system (million 1994 dollars)

year	(1)	(2)	(3)	(4)	(5)
-8	125				125
-7	1,100	31		45	1,176
-6	1,766	700		62	2,528
-5	2,230	1,032		78	3,340
-4	2,532	1,331		88	3,951
-3	2,544	1,465		88	4,097
-2	2,263	1,358	900	78	4,599
-1	1,802	1,097	1,500	62	4,461
0	1,315	770	2,180	45	4,310
totals	15,677	7,784	4,580	546	28,587

Recurrent cost of space transportation system :

The LSTS is comprised of the two vehicles HLLV and LUBUS plus the LUO-SOC their costs are somewhat more difficult to determine. A total of about 200 HLLV flights comprise this 30 year program. These vehicle costs are estimated with the TRASIM model of the Aerospace Institute of the TUBerlin (1990)[10]. They are presented in tables 4-4 and 4-5 using the following explanations of the individual columns:

Legend :

(1) Operational year of the life-cycle

(2) Cost of sustained engineering & product improvement during the operation of HLLV and LUBUS.

(3) Production cost for both vehicles and LUO-SOC with full cost of a unit listed in the year of delivery, excluding one HLLV which was already considered as a preproduction unit under development costs, but including the production cost of the LUO-SOC.

(4) Operational cost for the individual vehicle flights, including LUO-SOC operations, but excluding Lulox cost

(5) Sum of columns (2)+(3)+(4).

(6) annual cost of Lulox originating on the Moon but to be charged to the transportation system

(7) total recurring cost of space transportation system

(8) Direct cost per HLLV flight with passengers from Earth to LUO and back, but excluding front-end and lulox costs.

(9) Direct cost per HLLV flight with cargo from Earth to LUO and back, but excluding front-end and lulox costs.

(10) Direct cost per LUBUS flight with passengers from LUO to LUS and back LUO excluding front-end and lulox costs.
(11) Direct cost per LUBUS flight with cargo from LUO to LUS and back LUO excluding front-end and lulox costs.
(12) Direct cost per passenger roundtrip mission Earth spaceport to lunar spaceport.
(13) Direct cost per cargo trip one way Earth spaceport to lunar spaceport and empty return.
(14) Specific cost 1000 $ per passenger rountrip (Earth-Moon) including Lulox cost at 525 $/kg
(15) Specific cost of cargo $/kg (Earth-Moon) including Lulox cost at 525 $/kg

Table 4-4: Overview of sustained engineering, production, operations and total cost during the operational phase (million 1994 $)

(1) year	(2) sustained engng. cost	(3) production cost	(4) opera-tions cost	(5) total cost w.o.lulox	(6) re-imbursed lulox cost	(7) total recurring cost
1	166	6031	936	7,133	341	7,474
2	166	3522	599	4,287	451	4,738
3	166	3406	483	4,055	313	4,369
4	166	276	414	857	297	1,153
5	166	68	348	582	285	868
6	166	59	343	568	283	851
7	166	93	339	598	285	883
8	166	55	335	556	286	843
9	166	81	331	579	281	860
10	166	58	328	552	277	829
11	166	496	325	988	272	1,260
12	166	55	322	544	269	812
13	166	75	320	561	265	826
14	166	48	318	533	262	795
15	166	52	316	535	259	794
16	166	51	377	595	256	851
17	166	106	375	647	254	901
18	166	50	372	589	251	840
19	166	54	370	590	249	839
20	166	245	368	780	247	1,027
21	166	481	365	1,013	252	1,264
22	166	48	364	578	242	820
23	166	102	422	690	240	930
24	166	211	420	798	236	1,034
25	166	711	418	1,296	232	1,528
26	166	76	416	658	229	888
27	166	220	414	800	226	1,026
28	166	220	471	857	223	1,080
29	166	190	468	734	220	955
30	166	81	466	714	223	937
sum	4,998	17,130	10,271	34,269	7,324	42,275
average	167	571	342	1,142	244	1,409

Table 4-5: Overview of space vehicle direct operations cost of primary flights without Lulox cost (8) thru (13) and specific transportation costs of cargo and passenger transportation during the operational phase with Lulox cost (14 and 15) - (million 1994 $, M $ p.seat and $/kg respectively)

(1) year	(8) dir.cost p.pass. flight HLLV	(9) dir.cost p.cargo flight HLLV	(10) dir.cost p.pass. flight Lubus	(11) dir.cost p.cargo flight Lubus	(12) tot.dir. cost pass.fl. ES-LUS	(13) tot. dir. cost cargo fl. ES-LUS	(14) cost per passen-ger seat ES-LUS	(15) $/kg cargo direct ES-LUS
1	164.6	159.3	12.6	9.5	177	169	6.367	2,544
2	149.2	144.2	11.4	8.4	161	153	4.299	1,760
3	144.8	139.9	11.6	8.7	156	149	4.180	1,713
4	144.7	139.9	11.3	8.4	156	148	4.164	1,708
5	144.4	139.7	11.2	8.4	156	148	4.154	1,706
6	142.9	138.3	11.1	8.4	154	147	4.110	1,688
7	141.7	137.1	11.0	8.3	153	145	4.074	1,674
8	140.8	136.3	11.0	8.3	152	145	4.046	1,663
9	139.3	134.8	10.9	8.2	150	143	4.004	1,646
10	138.5	134.1	10.9	8.2	149	142	3.981	1,637
11	137.6	133.4	10.7	8.2	148	142	3.953	1,628
12	136.9	132.7	10.7	8.2	148	141	3.932	1,620
13	136.2	132.0	10.7	8.2	147	140	3.912	1,611
14	135.7	131.5	10.6	8.1	146	140	3.895	1,605
15	135.1	131.0	10.6	8.1	146	139	3.880	1,599
16	133.5	129.4	10.5	8.0	144	137	3.832	1,579
17	133.9	129.7	10.4	8.0	144	138	3.841	1,583
18	131.8	127.7	10.4	8.0	142	136	3.784	1,559
19	126.2	122.1	10.4	8.0	137	130	3.634	1,495
20	129.7	125.7	10.4	8.0	140	134	3.727	1,535
21	129.3	125.3	10.3	7.9	140	133	3.711	1,531
22	127.3	123.3	10.3	7.9	138	131	3.657	1,509
23	123.5	119.6	10.2	7.9	134	128	3.554	1,464
24	125.7	121.8	10.1	7.8	136	130	3.612	1,489
25	114.2	110.3	10.1	7.8	124	118	3.305	1,358
26	112.8	109.0	10.1	7.8	123	117	3.266	1,342
27	112.5	108.7	10.1	7.8	123	117	3.258	1,338
28	109.5	105.6	10.0	7.7	120	113	3.173	1,303
29	109.2	105.3	10.0	7.7	119	113	3.165	1,299
30	108.9	105.1	9.6	7.3	119	112	3.146	1,291
average	128.1	132.4	10.5	8.2	139	141	3.706	1,688

The production cost of the individual vehicle (column 3, table 4-4) is paid fully in the year of delivery in this model. Any financing costs will have to be part of this cost. Consequently the distribution of annual expenditures is irregular as can be seen in column 5 of table 4-6. This is listing for selected years the annual expenditures required for the lunar logistic system employed in this model. In reality the peaks will be lower since 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.

Useful for general comparisons are the cost per mission (figure 4-1)because they do not specify exactly the payload. But more precise are the specific transportation cost trends of the columns (14) and (15) are presented in figure 4-2 because they do include the payload delivered. This calculation is based on the assumption that the vehicles will fly as often as their design life will allow. In this conservative scenario, however, this is not the case, they are not used fully. The number of vehicles is determined by the minimum number of vehicles required on the flight-line. When they are taken-off, they will have a residual value because the production costs are prorated over the number of flights designed into the vehicles. Thus, the specific costs given below are considered to be the lower limit, they could be about 10 % higher. In case the nominal payload capacity of the vehicles is not fully used, the cost go up proportionally.

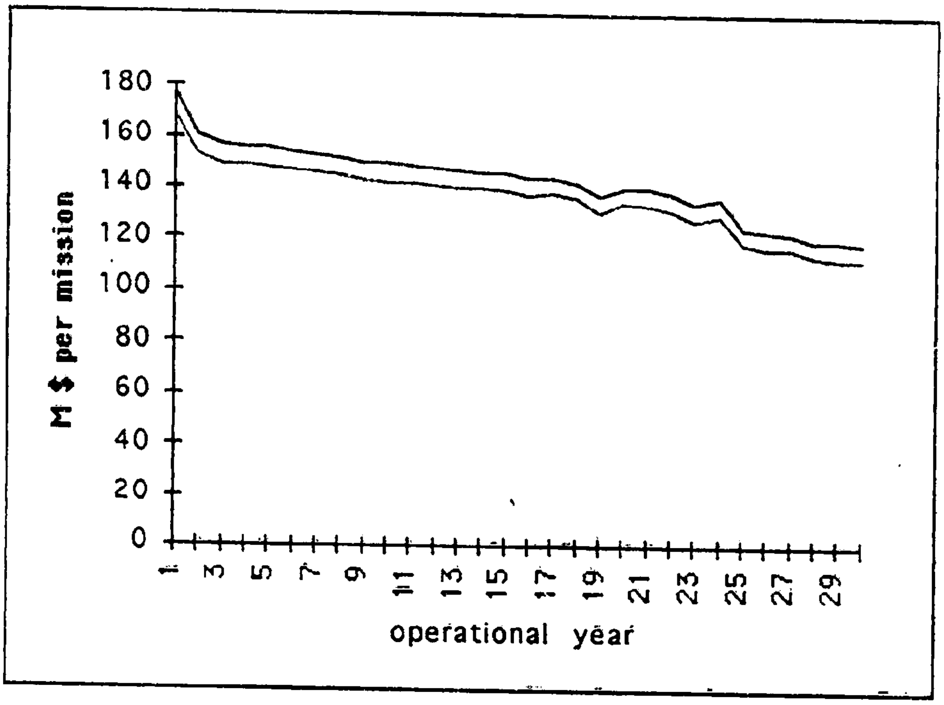


Figure 4-5: Mission cost for passengers without lulox cost -upper curve , and for cargo without lulox cost -lower curve , (million 1994 $)

In calculating the cost per roundtrip, the production cost are prorated over the number of maximum flights the vehicle is designed for if fully used during its lifetime. This scenario will not fully use the number of allowed flights, thus they will have a residual value when taken off the flight line.

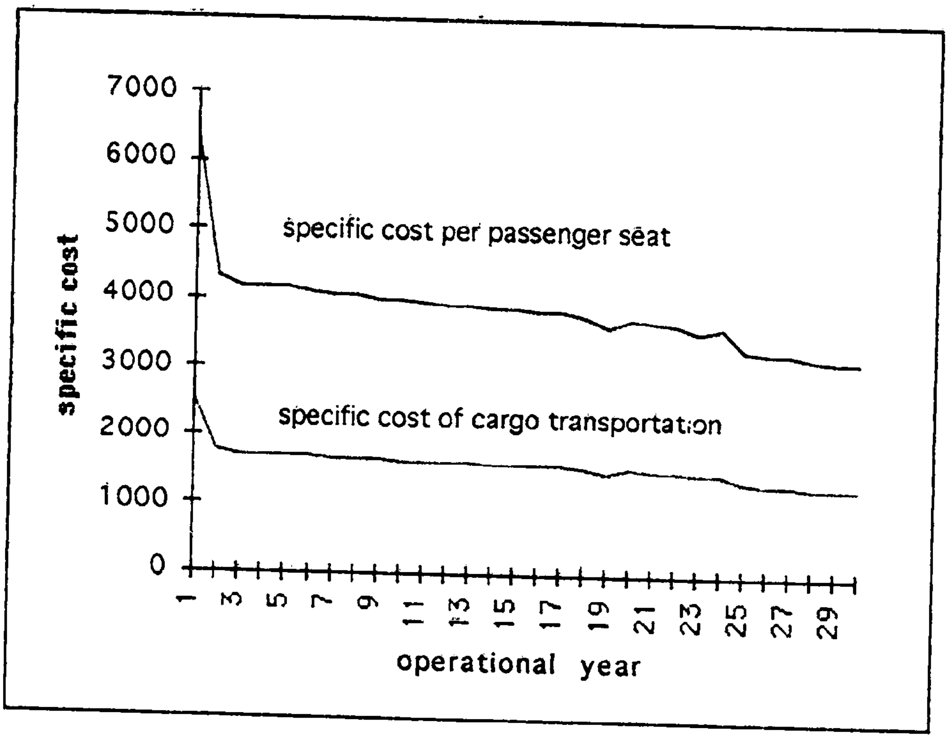


Figure 4-6: Specific recurrent transportation cost for passengers 1,000 (1994) $/seat and for cargo transportation $/kg to the Moon taking into account the cost of government furnished lunar propellants at 521 $/kg.

5. The acquisition of the lunar laboratory

The development phase is part of the acquisition phase of the lunar laboratory. After reaching a decision to proceed with the program, which can be very time consuming as experienced with the International Space Station(ISS), we know from previous programs 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 at this point 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.

Table 5-1: Initial Lunar Base Program Development Schedule
year x = year of first development flights

year & Qarter	**activity or flight mission**
x-10	Program planning activities are initiated
x-9	program definition & 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 modification
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

A precise list of hardware requirements and a flight schedule must be available before high quality cost estimates of the vehicles can be derived. This leads to a manifest for the flights planned with emphasis on the first five years.

Table 5-2: Detailed quarterly flightplan for the acquisition period
* = HLLV + LUBUS flights, all other HLLV flights without LUBUS
Legend:
Year 0 used for initial flight tests, year 1 is the year of beneficial occupancy
(1) Period of time (quarter)
(2) Flight tests of the HLLV prototype vehicle
(3) Flight tests of the HLLV + LUBUS prototype vehicles
(4) Direct flights of the 3-stage HLLV to LUS, 3rd stage one-way (50t module)
(5) 2 stage HLLV flights to LEO in support of LUO-SOC acquisition (300 t LEO)
(6) HLLV Earth-Lox Tanker flights to LUO-SOC for replennishing (100t)
(7) Delivery of partly fueled LUBUS units to LUO (20 + 50 t Lox)
(8) Special facility delivery flights with LUBUS roundtrip (60 t facility modules)
(9) Standard operational cargo flights (60 t equipment and supplies)
(10) Standard operational passenger flights (40 passengers + luggage)
(11) Total number of HLLV flights in this quarter
(12) Total number of LUBUS flights in this quarter

(1)	(2)	(3)*	(4)	(5)	(6)	(7)*	(8)*	(9)*	(10)*	(11)	(12)*
0/I	1									1	0
0/II	1	1								2	1
0/III		1		1						2	1
0/IV		1								1	1
1/I			2	1						3	0
1/II			1	1		1				3	1
1/III						1		1		2	2
1/IV								1	1	2	2
2/I						1	1	1		3	3
2/II						1			1	2	2
2/III							1	1		2	2
2/IV									1	1	1
3/-I-			1					1		2	1
3/II-					1				1	2	1
3/III								1		1	1
3/IV					1				1	2	1
4								4	2	6	6
5								2	3	5	5
SUM	(2)	(3)	4	3	2	4	2	12	9	42	31

Including the test flights during the last year of the development period ("0"), **42 HLLV and 31 LUBUS** vehicle flights are on the regular schedule for the first five operational years!

After defining the number and type of flights, the balance between masses required at the individual destinations must be compared with the payload capabilities of the scheduled vehicle flights.

Table 5-3: Mass balances

Total mass delivered from the Earth during first five years:	
4 direct flights with complete modules 50t each	200 t
12 regular cargo flights with facilities, equip. &supplies 60 t each	720 t
total delivered from the earth including reserves	920 t
Mass required during the first five years	
At the end of the third year the following masses must be on the Moon:	
Lunar facilities and equipment as estimated by the model	465 t
imported spares	115 t
supplies	300 t
total mass imported from the Earth	870 t
Lox propellant balance first 5 years	
Lox left in SOC at arrival in LUO	180 t
Lox left in 4 LUBUS flights brought to the LUO-SOC	200 t
2 tanker flights to LUO with 100t each	200 t
LULOX produced by lunar facilities during first 5 years	1,753 t
Total Lox available in LUO or on LUS	2,333 t
LULOX requirements :	
12 cargo flights with facilities from LUO to LUS,90 t each*)	1,800 t
9 regular passenger flights LUO to LUS, 60 t each	450 t
sub total	2,250 t

*) only in case all of the return payload capability of 50 t is used

Balance: Available 2,333- required 2,250 = 83 t reserve
plus cargo return propellants not used

Most of this reserve will probably have to cover vaporization losses ! This balance shows that the planned typical flight schedule for the logistic support of a lunar base with the desired attributes and performance is about what must be expected. Now it is possible to specify the missions and payloads for each of the flights scheduled during the flight operations in the early years of the acquisition as shown in the next table. At this point in time it is sufficient to use a quarterly schedule which has to be replaced later with a monthly schedule to make sure that the needs of the initial lunar crew are satisfied.

Table 5-4: Typical manifest for HLLV and LUBUS flights

quarter	vehicles	missions
0/I	HLLV	1st test flight with 2 stages to LEO for recovery
0/II	HLLV HLLV+Lubus	test flight with 3 stages to LUO and return test flight to LEO for Lubus flight test + rendevouz
0/III	HLLV+Lubus HLLV	back-up vehicle for systems test 2 stage flight with SOC module to LEO
0/IV	HLLV+Lubus	systems verification flight test to LUO + return
1/I	HLLV HLLV HLLV	2 stage flight to LEO with propellants for SOC 3 stage dir. flight to LUS with 50t fac. module 3 stage dir. flight to LUS with 50t fac. module
1/II	HLLV HLLV HLLV+Lubus	2 stage flight to LEO with propellants for SOC 3stage dir.flight to LUS with 50 t fac.module 3stage transfer flight of Lubus to LUO +50 tlox
1/III	HLLV+Lubus HLLV+Lubus	3stage transfer flight of Lubus to LUO +50 t lox 3stage flight to LUO/LUS with 60 t supplies
1/IV	HLLV+Lubus HLLV+Lubus	3stage cargo flight to LUS with 60 t equipment 3stage passenger flight to LUO/LUS & return
2/I	HLLV+Lubus HLLV+Lubus HLLV+Lubus	3stage flight to LUO/LUS with 60 t facility module 3stage flight to LUO/LUS with 60 t supplies 3stage transfer flight of Lubus to LUO +50 tlox
2/II	HLLV+Lubus HLLV+Lubus	3stage passenger flight to LUO/LUS & return 3stage transfer flight of Lubus to LUO +50 tlox
2/III	HLLV+Lubus HLLV+Lubus	3stage flight to LUO/LUS with 60 t facility module 3stage flight to LUO/LUS with 60 t supplies
2/IV	HLLV+Lubus	3stage passenger flight to LUO/LUS & return
3/I	HLLV+Lubus HLLV	3stage flight to LUO/LUS with 60 tsupplies 3stage dir.flight to LUS with 50 t fac.module
3/II	HLLV HLLV+Lubus	3stage tanker flight to LUO with 100 t lox 3stage passenger flight to LUO/LUS & return
3/III	HLLV+Lubus	3stage flight to LUO/LUS with 60 t facility module
3/IV	HLLV HLLV+Lubus	3stage tanker flight to LUO with 85 tlox 3stage passenger flight to LUO/LUS & return
4/I	HLLV+Lubus HLLV+Lubus	3stage flight to LUO/LUS with 60 t facility module 3stage flight to LUO/LUS with 60 t supplies
4/II	HLLV+Lubus HLLV+Lubus	3stage flight to LUO/LUS with 60t supplies 3stage passenger flight to LUO/LUS & return
4/III	HLLV+Lubus	3stage flight to LUO/LUS with 60t supplies
4/IV	HLLV+Lubus	3stage passenger flight to LUO/LUS & return
5/I	HLLV+Lubus	3stage flight to LUO/LUS with 70t supplies
5/II	HLLV+Lubus	3stage passenger flight to LUO/LUS & return
5/III	HLLV+Lubus	3stage flight to LUO/LUS with 70t supplies
5/IV	HLLV+Lubus HLLV+Lubus	3stage passenger flight to LUO/LUS & return 3stage passenger flight to LUO/LUS & return

The chapters above supply the basic information to estimate the acquisition and operating cost of the lunar facilities and the space transportation system supporting the lunar base logistically.

6. Cost Summary and System Effectiveness

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 derive at 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 the logistics of it during the entire life cycle, which was assumed to be 10 years for development and 30 years of operation.

6.1 Program Cost summary

To obtain the total cost of the program one has to estimate the two major elements of the system seperately, the *space transportation system* and the *lunar base.* This has been done in the respective chapters above. In case the space transportation operator reimburses the lunar base operator for the Lulox used at an agreed price level, then the total amount paid to the lunar base operator for the Lulox used during the life-cycle must be deducted from the total base cost! In addition 1,500 M$ of 1,644 M $ for the LUO-SOC production have been shifted as follows to avoid undesirable peaks: from year 1: 900 M$ to year 0; 550 M$ to year -1 and 50 M $ to year -2 .This is more realistic, these costs are now where they occur. With these changes the cost summary looks as follows:.

Table 6-1 : Lunar Base life-cycle cost summary (million 1994 $) with 10 + 30 year life-cycle

COST ELEMENT	Life cycle M $	M $ p.a.	% of LC total
Development & test lunar facilities-10y	11,200	1,120	12.3
Dev.& test of space transp.system-10y	28,587	2,859	31.4
Subtotal Development & Test - 10 y	**39,787**	**3,979**	**43.7**
sustained engineering LSTS- 30 y	4,998	167	5.5
Production space transportation system	17,130	571	18.8
Operation space transportation system	17,595	587	19.3
Operation lunar facilities	11,640	388	12.8
Subtotal operations - 30 years LC	**51,363**	**1,712**	**56.3**
Total Lunar Laboratory System - 40 y	**91,150**	**2,280**	**100**

The next graph illustrates the rate of change in the required development funds and the peak during the end of the development phase.

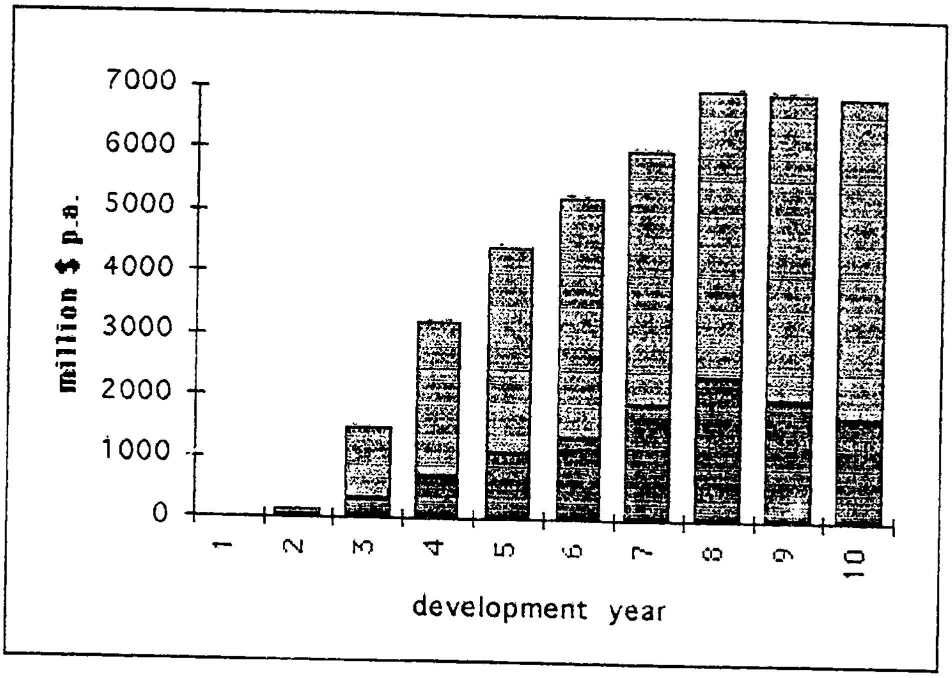


Figure 6-1 : Annual distribution of expenditures for development and testing of the elements comprising the lunar base project
(space transportation system on top and lunar facilities at the bottom)

Table 6-3: Annual total system/program cost (M 1994 $, 1 labor year = 0.2 M $)

year	Lunar facility cost p.a.	LSTS cost p.a.	total system cost p.a.	year	Lunar facility cost p.a.	LSTS cost p.a.	total system cost p.a.
1	0	0	0	22	368	812	1,180
2	10	125	135	23	373	826	1,199
3	290	1,176	1,466	24	379	795	1,174
4	675	2,528	3,203	25	384	794	1,178
5	1,060	3,340	4,400	26	389	851	1,240
6	1,300	3,951	5,251	27	395	901	1,296
7	1,900	4,097	5,997	28	399	840	1,239
8	2,335	4,649	6,984	29	404	839	1,243
9	1,950	5,011	6,961	30	408	1,027	1,435
10	1,680	5,210	6,890	31	445	1,264	1,709
11	242	5,974	6,216	32	433	820	1,253
12	275	4,738	5,013	33	447	930	1,377
13	290	4,369	4,659	34	454	1,034	1,488
14	299	1,153	1,452	35	461	1,528	1,989
15	307	868	1,175	36	468	888	1,356
16	321	851	1,172	37	475	1,026	1,501
17	337	883	1,220	38	481	1,080	1,561
18	344	843	1,187	39	487	955	1,442
19	348	860	1,208	40	512	937	1,449
20	356	829	1,185	sum	22,843	70,862	93,705
21	362	1,260	1,622	40 y.av.	571	1,772	2,343

A graphical illustration of these trends brings out clearly that there is a peak demand of resources during the development phase and a sharp drop after the initial beneficial occupancy of the lunar base. Irregularities indicate new hardware buys.

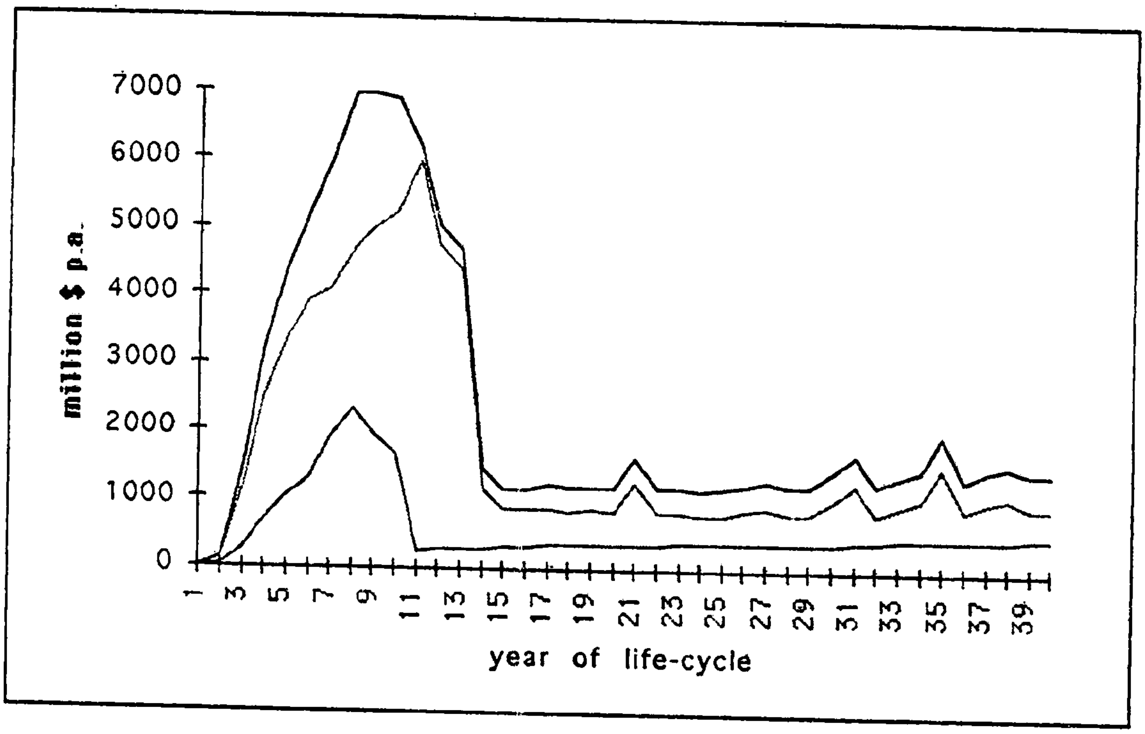


Figure 6-2: Lunar Laboratory Sytem total cost trend (upper curve) with lunar faciliy costs (lower curve) and space transportation costs (middel curve)

The simulation of the system life-cycle has resulted in additional insights into the behavior of this system. The growth of the facility mass with time and the specific output per mass facility as a function of time are depicted in figure 6-3. It appears that the system as a production entity gets less efficient with time. The reasons for this is that the production rates are deliberatly kept down and the strong increase of the laboratory and scientific equipment mass in the second half of the life-cycle does not contribute to the mass output. It was also found that in this specific scenario lunar oxygen is cheaper than imported oxygen from Earth as shown in figure 6-4.

If hardware products (spares and construction material) and lunar produced food are considered, then we have to wait several years to arrive at the break-even point. On the other hand the average cost - including raw materials and lunar oxygen - is in a range clearly below the specific transportation cost. Also the pleasures from growing part of their own vegetables will enhance the weil being of the lunar crew. A more detailed analysis is thus recommended for a specific scenario and life-cycle.

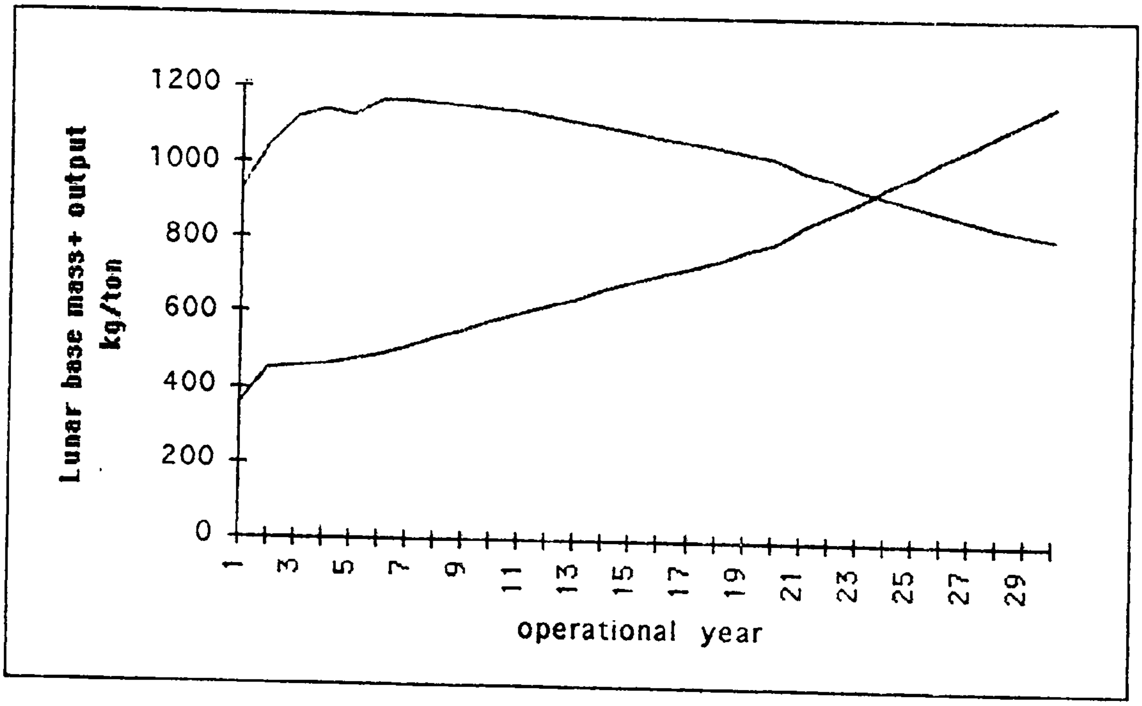


Figure 6-3: Growth of lunar facility mass (tons) and mass of lunar products per ton facility mass (upper curve)

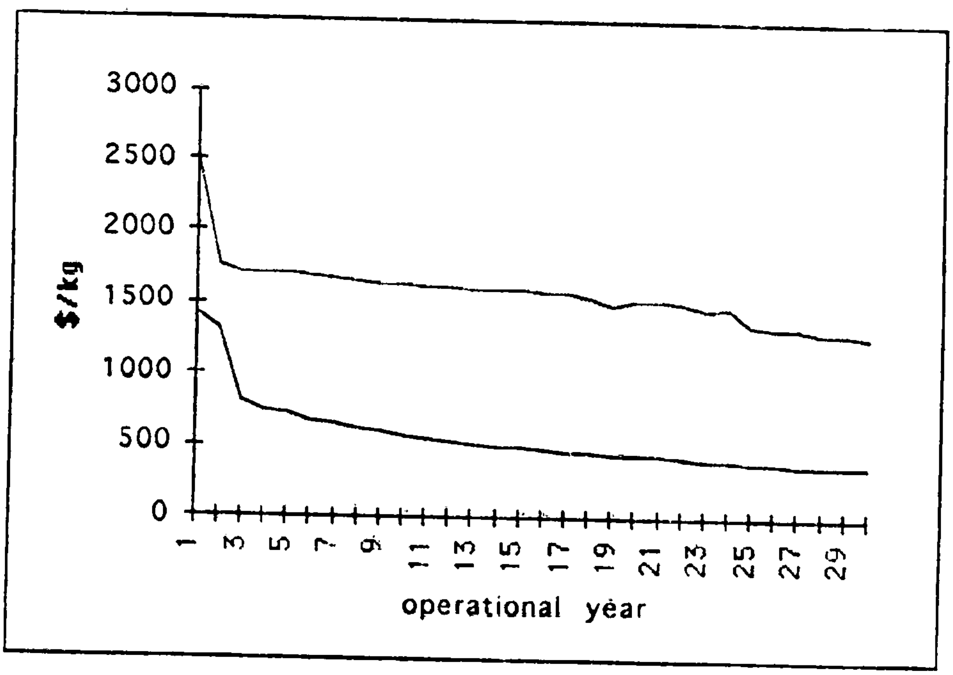


Figure 6-4: Trend of specific cost of transportation of imports (upper curve) and production cost of lunar oxygen(lower curve)

6.2 Program cost- effectiveness

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. The factors depicting the annual trend give a more complete insight into the behaviour of the system analysed than cumulative values. The primary parameters selected for this overview presented in Tab. 6 -4 are the following:

(1) Systems life-cycle cost per lunar labor-year (M 1994 $/labor-year)
(2) Systems life-cycle cost per lunar science year (M 1994 $/ laboratory workplace)
(3) Systems life-cycle cost per unit mass produced on the Moon (M 1994 $ t)
(4) Lunar facility 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) Share of 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.)

Table 6-4: Development trends of primary system-effectivness ratios

year	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	155	3,108	18.577	9.0	1.83	8.36	0.22	0.93	3,51
2	114	1,671	10.711	10.2	3.80	10.64	0.36	1.04	3.40
3	108	1,165	9.096	10.7	2.26	11.95	0.19	1.12	3.26
4	35	363	2.727	11.1	2.29	12.68	0.17	1.14	3.25
5	28	235	2.197	11.3	2.12	12.73	0.17	1.13	3.26
6	27	195	2.063	11.1	2.20	12.91	0.17	1.16	3.29
7	25	174	2.042	10.7	2.27	12.44	0.18	1.17	3.35
8	24	148	1.906	10.7	2.24	12.46	0.18	1.16	3.40
9	23	134	1.872	10.5	2.11	12.17	0.17	1.16	3.44
10	21	119	1.780	10.4	2.04	11.89	0.17	1.15	3.49
11	28	147	2.369	10.4	2.00	11.80	0.17	1.14	3.54
12	20	98	1.680	10.4	1.95	11,70	0.17	1.13	3,59
13	19	92	1.669	10.2	1.89	11.40	0.17	1.12	3.65
14	18	84	1.600	10,2	1.85	11.29	0.16	1.10	3.70
15	17	79	1.574	10.1	1.79	11.00	0.16	1.09	3.76
16	18	78	1.626	10.1	1.76	10.89	0.16	1.07	3.82
17	18	76	1.671	10.1	1.74	10.77	0,16	1.06	3.87
18	17	69	1.572	10.1	1.70	10.65	0.16	1.05	3.93
19	16	65	1.553	10.0	1.66	10.39	0.16	1.03	3.98
20	18	72	1.767	10.0	1.63	10.28	0.16	1.02	4.04
21	20	78	2.055	9.9	1.79	9.78	0.18	0.99	4.18
22	14	52	1.487	9.9	1.58	9.57	0.16	0.97	4.26
23	15	53	1.608	9.9	1.59	9.30	0.17	0.94	4.36
24	16	53	1.712	9.8	1.54	9,05	0.17	0.92	4.46
25	20	66	2.255	9.8	1.50	8.82	0.17	0.90	4.56
26	13	42	1.516	9.7	1.46	8.60	0.17	0.88	4.65
27	14	44	1.653	9.7	1.43	8.40	0.17	0.86	4.75
28	14	43	1.699	9.7	1,38	8.20	0.17	0.84	4.85
29	13	38	1.549	9.7	1,37	8.09	0,.17	0.82	4.95
30	12	36	1.528	9.7	1.44	7.9	0.18	0.81	5.08

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 is neither a complete picture nor a very accurate data base, it is the best presently available and awaits further improvements.

Table 6-5: Life-cycle performance and cost summary of a Lunar Base program - (cost in million 1994 dollars ; 1 labor year = 0.2 million $)

lunar facilities available at the end of the life-cycle	1,167 t
total lunar products available	21,900 t
---- LC lunar propellants used for space vehicles	15,210 t
---- LC lunar products for infrastructure extension or export	2,460 t
---- LC lunar products used directly by the lunar laboratory	4,230 t
total lunar labor-years available	2,170 y
---- laboratory years available for lease	523 y
cost of planning and program integration activities	875 M$
initial development cost of lunar facilities	8,400 M$
production cost of initial facilities	1,885 M$
<u>lunar facilities acquisition</u>	<u>11,200 M $</u>
cost of engineering support during expansion of lunar facilities, administration and training	12,240 M $
salaries of lunar crew	1,620 M $
cost of imported spares, equipment & consumables	2,784 M $
cost of lunar science support (100 million $ p.a.)	3,000 M $
reimbursed lunar produced oxygen	- 7,324 M $
<u>operations cost of lunar facilities</u>	<u>11,640 M $</u>
subtotal lunar laboratory acquisition and operation	**22,840 M $**
cost of space vehicle development and engineering	24,007 M $
pre-production of backup vehicles	4,580 M $
total space transportation system development cost	<u>28,587M $</u>
product improvement during operation	4,998 M $
total production cost	17,130 M $
total operations cost	17,595 M $
total recurring cost lunar space transportation system	<u>39,723 M$</u>
subtotal logistic system acquisition and operation	**68,310 M$**
<u>total LULAB system cost for 60 yr life-cycle</u>	**<u>91,150 M $</u>**
<u>annual average during the 9 dev. + 50 oper. = 60 year life-cycle</u>	<u>2,279 M $</u>
<u>cost per lunar labor-year</u>	**<u>42,0 M $/y</u>**

7. Study Results and Conclusions

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 allowed an annual estimate of the most important system parameters and the system behavior 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-cyle. A science- and technical development oriented lunar base would start out with a crew of about 40 people. The lunar population would reach a level of about 50 after ten years, 80 after 20 years and 120 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 achieved in 40 years for less than 100 billion (1994) US dollars, if planned carefully and realized by a competent international organization. The peak demands of public funds would reach about 7 billion dollars annually at the end of the development phase which is the equivalent of one percent of global military expenditures at the end of the 20th century. The average annual cost over the 40 year life-cycle would be less than 2.5 billion dollar, which is merely one percent of the present annual military expenditures of the United States. Form this viewpoint it appears economically feasible.

Based on the present insights the following conclusions seem to be justified:

1. There is no quick, dirty and cheap solution to return to the Moon soon and proceed with a meaningful activity of lunar exploration within the defined objectives of the long range lunar development program.

2. Based on present or near-term state-of-the-art, it is possible to develop concepts of returning to the Moon establishing semi-permanent or permanent lunar facilities and thus to continue the lunar exploration early in the next century at affordable expenditures and an acceptable risk.

3. The big hurdle of a decision to enter a new phase of lunar development appears to be the up-front investment requiring an average of up to 5 billion (1993/94) $ for a 10 year period. This investment can not come from privat sources, it would have to be made by a group of 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 burden to the public for maintaining the operation of this type of a lunar laboratory can come down to less than a billion dollar per year which makes this option a very attractive propositon.

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