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A PRELIMINARY CONCEPT AND LIFE-CYCLE ANALYSIS OF A LUNAR SETTLEMENT

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ABSTRACT

This paper offers a concept for a *lunar development scenario* which could lead to a permanent lunar settlement by the end of the 21st century. A three-phase operational life-cycle is planned: a ten year initial phase, leading to beneficial occupancy of a nucleus lunar base primarily serving as a construction camp, to be followed by a 50 year growth phase, leading to a population of nearly 2000 people, and a 25 year consolidation phase at that level. The space transportation system supporting this lunar settlement logistically during its entire life-cycle is a fully reusable *heavy lift launch vehicle* of the NEPTUNE class, transportating of people and cargo to a *lunar orbit service station* , complemented by a *lunar ferry* for the local transportation between the lunar spaceport and the lunar orbit service station. The duty-cycle anticipated for the lunar crew members is about 6 months in the early years growing to about 2 years in the final years.
This report is comprised of 25 tables, 2 figures and 16 references on a total of 24 pages.

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List Tables and Figures

1.Introduction

The Earth and the Moon are a double planet. The Earth has been explored, it is populated and the resources of this celestial body have been widely developed for the benefit of humankind. The population is growing to the limit *spaceship Earth* can accomodate comfortably. Thus it is only a question of time, that the resources of the Moon will have to be developed and utilized to improve the quality of life on Earth. Also, a situation might arise on Earth where the urgent development of a lunar settlement appears to be opportune, or - in case of a catastrophe - may be a matter of survival of our species. While this is unlikely to occur in the near future, it could happen any time thus a lunar settlement is an interesting case of emergency planning. If such an emergency should arise overnight, the time for careful planning will not be available, consequently it should be done in time.

The idea of a lunar base and/or a settlement is not new. Wernher von Braun et al. published a detailed plan in *COLLIER'S* magazine (1952)[1] which received considerable attention in the general public. The launch of the first satellite by the Soviet Union prompted the US Army in 1959 to study in detail the construction of a lunar base[2]. Other studies followed even before the first man set foot an the Moon[3,4]. The lunar flights of the *APOLLO* program[8] led to several proposals to continue the exploration of the Moon and utilization of its resources[5-7,9,10]. Regardless how this may be done, the key to return to the Moon is in any case the development of a new space transportation system, since none is available at the present time after closing the production line of the *SATURN* launch vehicle in 1969. Proposals in this direction have frequently been made[12-15], also the Russian launch vehicle *ENERGYA* could have been a useful element of a new lunar transportation system, but has not been put into production.

New computer codes are now available allowing an annual simulation of the acquisition and operation of complex lunar installations, including their logistics support by space transportation systems[10,12]. A few years ago, also a Japanese construction company has published plans on how to build a city on the Moon[11]. One of the lastest near term proposals for the next step of lunar development is to build a *Lunar Laboratory* [16]. It proposes the beginning of developing a 100 person *Lunar Laboratory* on the Moon for the year 2016 with a 50 year life-cycle. The year 2006 was assumed to be the year of a decision to go ahead with such a multi-national enterprise. A *Lunar Settlement* would even be a more ambitious project than the Lunar Laboratory. It would have a population of more than 1,000 people and a life-cycle closer to a century.

It is likely that the life-cycle of a lunar settlement will go through several phases: Initial development - beneficial occupancy - rapid growth - maturity towards the end of the 21st century - and eventually disbanding or destruction at an unidentified point in time in the evolution of our civilization. A representative concept for the first four phases, including maturity, leading to a stable lunar population of about 2,000 people will be analysed in this report. Many people will think that studying a lunar settlement is premature, but **a long range perspective is required to take the next step in the right direction!**

2.Ground Rules and Definitions

There are many approaches to enter a new step of lunar development, but those to be investigated should be based on past experience and on mature technology available in the foreseeable future and not in the hope of possible breakthroughs. Also, the present social, political and economic situation on our planet today and expected in the future must be taken into consideration in structuring the next steps in the lunar development program, after the intitial exploratory landings have been accomplished, which took place in the sixties and early seventies. The option recommended as a result of any analysis must be technically and economically feasible at an acceptable risk.

The frame of reference selected for this analysis is as follows:

- The *Initial acqvisition phase* should be based on the first 10 years of the LULAB Model (3.0)[16] to be followed by
- a *50 year growth phase* to bring up the lunar population to about 2,000 people
- followed by a 25 *year saturation phase*,

resulting in a 85 year operational life-cycle which could begin in the year 2016 and continued until the year 2100.

It is too early to speculate about a follow-on program for the 22nd century, but it should be mentioned that a Japanese construction company has made visionary studies[11] already on how a *lunar city* may look like with up to 10,000 inhabitants. This might be a reasonable goal for the year 2200, but the technology for such an undertaking is not yet in sight. Consequently, we will study more modest alternatives for the next century based on our present insights and on employing near term technology.

In this analysis,we will distinguish between the following *members* of the lunar population:
- Permanent Settlers are those who secide to stay on the Moon including their children.
- Temporary Settlers return at the end of their duty cycle, but may return for a new duty cycle after several years on Earth.
- Visitors are those to come to the Moon for a short single stay of a month or less witout to return to the Moon.
- Children born on the Moon return to Earth with the parents at the end of the duty cycle at the age of about 1 year.

The *imports* delivered from the Earth to the lunar settlement include:
facilities, equipment, spareparts, materials for production, gases, supplies, consumables (perticularly water and food).

The *lunar products* for usage on the Moon or export are classified as follows;
Raw material, construction material, fabricated products, assemblies, spareparts oxygen, other gases, food and other consumables.

3. Initial Acquisition Phase

3.1 Lunar base facilities

This initial ten year acquisition phase leading to benefical occupancy of a base camp is identical with the first ten years of the *Lunar Laboratory* (LULAB)[16]. It lays the groundwork for a rapid expansion of the *Lunar Settlement* (LUSET) within a 50 year growth period, to be followed by a 25 year consolidation phase.

A set of representative *state variables* has been selected from a detailed system analysis to illustrate the size and growth trend of the initial lunar facility, they are presented in table 3-1.

Table 3-1:
Summary of the most important state variables of the ten-year LULAB phase

Definitions:
import rate = mass of imports/mass of total lunar products
self-sufficiency = lunar produced consumables/total lunar base consumption
net production = mass of total products - mass of imports imports
productivity = net mass production / number of lunar population
total mass output = lunar products for lunar usage + products for export or infrastructure + lunar propellants
minimum crew duty cycle = crew size/ number of available roundtrips
*) over and above initial facilities of 434 t

year of operation	lunar popu-lation	facility mass (t)	power plant capacity (kW)	total import mass req. (t) *)	lunar products for lunar use (t)	lunar products for other uses (TBD)	lunar produced propel-lants (t)
1	27	434	991	46	47	12	125
2	33	531	1,433	146	64	13	191
3	35	580	1,730	104	66	22	243
4	40	638	2,036	118	76	26	289
5	42	668	2,187	94	80	31	310
6	43	689	2,309	87	86	35	326
7	44	714	2,433	92	92	36	339
8	47	740	2,553	95	98	37	350
9	49	767	2,670	97	104	39	360
10	52	794	2,786	100	110	40	370

year of operation	import rate	self-sufficency	net pro-duction (t)	produc-tivity (t/person)	total mass output (t)	minimum crew duty cycle(yrs)
1	0.274	0.425	125	4.7	184	0.34
2	0.586	0.243	104	3.2	267	0.41
3	0.340	0.300	205	5.8	335	0.44
4	0.327	0.300	247	6.2	395	0.50
5	0.246	0.344	296	7.1	424	0.53
6	0.218	0.364	323	7.5	447	0.54
7	0.222	0.366	335	7.5	467	0.55
8	0.221	0.372	348	7.4	485	0.39
9	0.220	0.379	360	7.3	503	0.41
10	0.220	0.386	370	7.2	519	0.43

Non-recurrent cost of the initial lunar facilities (1st phase)

The facilities and equipment to be installed and used on the Moon have to be developed on the Earth prior to the deployment. This will probably take about ten years, depending on the level of effort and technology employed. This investment has to be born by the governments of the participating nations. Estimates of the required funds - not including the development of the space transportation system required - have been made[16] resulting in the following typical figures:

Table 3-2: Non-recurring cost of lunar base facilities during the initial acquisition phase prior to beneficial occupancy (million 1994 $)

year	initial development cost	cost of first units of base facilities and equipment	cost of planning activities and system integration	total lunar base facilities development cost
-8			10	10
-7	240		50	290
-6	600		50	650
-5	960		50	1,010
-4	1,200		50	1,250
-3	1,800		50	1,850
-2	1,800	460	50	2,310
-1	1,200	460	120	1,780
0	600	460	220	1,280
totals	8,400	1,380	650	10,430

Recurrent costs of laboratory

The non-recurring cost have to be supplemented by the annually recurring costs. Table 3-3 presents the direct operating costs (recurrent cost p. a.) associated with the lunar facilities proper,excluding space transportation. This includes the the costs of imported facilities, equipment and consumables. It includes also the labor cost connected with the supporting effort required on Earth, such as sustained engineering for facility extensions and improvements, administration, science support, as well as training of lunar crews and their salaries. All this adds up to the annual operating costs of the lunar facilities of 6,480 M$ for years 1 through 10.
It should be noted, however, that the calculated cost of producing lunar propellants and launch/vehicle overhaul services for the lunar logistic system may alternatively be charged to the space transportation system. In this case they are elements of the lunar facility costs.

Table 3.-3: Direct operating cost of lunar laboratory (million 1994 $ p.a.)

Legend:

(1) Operational year.
(2) Cost of sustained engineering,training of lunar crews and administration supporting activities on the lunar surface (the largest share of all cost elements!)
(3) Salaries of the lunar crew members including their duty cycles on Earth.
(4) Cost of facility modules, equipment and other imports.
(5) Cost of Earth ground support of science operations on the Moon.
(6) Total cost of LULAB activities on the Moon during the first ten operational years

(1) (2) (3) (4) (5) (6)

year	sust.eng.,admin. crew training	lunar crew salaries	total import goods	science support	total LULAB recurrent cost
1	408	20	26	100	554
2	408	25	220	100	753
3	408	27	153	100	688
4	408	30	158	100	696
5	408	31	109	100	648
6	408	32	93	100	633
7	408	34	100	100	642
8	408	35	102	100	645
9	408	37	104	100	649
10	408	39	107	100	654
total	4,080	310	1,172	1000	**6,562**

3.2 Logistics during the initial acquisition phase[12-15]

The governing factor for the acquisition process and operation of the lunar settlement specified above is the payload capability and launch rate of the **lunar space transportation system (LSTS)** to be employed. It determines the growth rate of the lunar settlement, but also the amount of manual labor required to put the facilities on the Moon in operation.

The logistic support system for the lunar settlement selected is basically the same for the lunar laboratory first ten year phase and the other phases. It is a *fully reusable space transportation sytem* using chemical propellants only and available subsystems from the *Space Shuttle* and other existing programs. Aside from spaceports on the Earth and the Moon, the lunar space transportation system (LSTS) is comprised of three elements :

(1) a heavy lift launch vehicle(**HLLV**)[12] for passenger and cargo transportation between the Earth spaceport and a space operations center in lunar orbit,

(2) the space operation center (**LUO-SOC**)[14] in a low lunar orbit (100 km), being used 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[16].

The **HLLV** has a nominal payload capability of **100 metric tons (t) to lunar orbit** which do include the return propellants in case they are not refueled in lunar orbit from lunar sources. This payload capability is assumed to be the average performance during the entire life cycle and is a conservative assumption. This heavy lift launch vehicle is based on the NEPTUNE concept of the Aerospace Institute of the Technical University Berlin[12]. It can either transport cargo or passengers, but also a mix of passengers and cargo to the lunar orbit.

The passenger version has a **50 t** return payload, e.g. a 45 t crew cabin with **40 passengers** and 5 t for additional aerobrakes. The passenger module is attached to the 3rd stage and is capable of returning to the Earth from the LUO-SOC, for which 30 t return propellants, initially 25 earth - and from the 11th year on lunar produced oxygen, and 5 t earth produced LH_2) are needed. A nominal net payload of 55 t leaves additional 45 t for return propellants and/or lunar use, such as 20 t of extra hydrogen required for the continuing flight of the LUBUS roundtrip between LUO and lunar base including reserves for losses. In the latter case, beginning in year eleven of the 85 year operational life-cycle, 100 - 55 - 20 = **25 t of cargo** can be delivered to the LUO-SOC in the addition to the passenger module. This scenario assumes the availability of lunar oxygen for the return flight of the HLLV 3rd stage. During the first phase the passenger vehicle does not carry additional cargo but all of its return propellants.

The HLLV in its early **cargo** version with a nominal payload capability of 100 t would carry a **82 t cargo** module, 3 t of LH_2 return propellants and 15 t liquid hydrogen propellants for LUBUS operation. In this case it would require 12 t of LULOX for the return flight of the LLV 3rd stage to be taken onboard at the LUO-SOC. During the initial ten year phase only **70t** of cargo are delivered to the lunar orbit, because the HLLV has to take its own lox for the return flight along due to limited lunar propellant production. During the initial years the HLLV cargo vehicle can also be used to land directly 45 t of facilities on the lunar surface.

The logistic requirements to be satisfied in years 1 through 10 are very close to those of the laboratory analysed precviously. They determine annual import mass and crew rotation requirements leading to the primary charateristics of the logistic system as shown in the next table.

Table 3-4: Characteristic data of the logistic support of the first 10 years of the LULAB

year	pass/ cargo flights	total HLLV flights	cargo capacity LUS	passengers to LUS	HLLV inventory **)	LUBUS iventory **)	total log. cost p.a. B $ *)
1	1/10	11	170	40	1	2	7.465
2	2/6	8	170	80	2	4	3.657
3	2/6	8	170	80	2	4	1.197
4	2/3	5	170	80	3	4	3.175
5	2/2	4	170	80	3	5	0.985
6	2/2	4	170	80	4	5	2.959
7	2/2	4	170	80	4	5	0.764
8	2/2	4	256	80	5	6	0.956
9	3/2	5	256	120	5	6	2.991
10	3/2	5	256	120	6	6	0.859
total	21/37	58	1,958	2,200	-	-	#)25.008

*) annual operating cost including product improvement,
**) the vehicle inventory at the end of the first 10 years will be transferred to the next phase with a value of about 11.816 B$.
#) This total includes at this point the estimated cost for 2900 t of lunar propellants at the assumed price of 0.6 M $/t to the amount of 1.740 M$. These can be charged either to the lunar facility or the logistic system, but not to both!

The cost estimate of the annual recurrent cost arrived at with the help of the TRASIM code [13] are listed in the last column of the table above for convenience.

These have to be complemented by the non-recurring costs of the program to be carried out during the development and test phase. These costs are primarily the development costs and first unit costs. In case pre-production of vehicles or modules are required due to the anticipated schedules, these are estimated at the level of first unit costs. The following definitions are presented to understand better the calculation procedure used for deriving the non-recurrent costs listed in the specified columns of table 3-5 :

Table 3-5:
Non-recurrent cost of the lunar space transportation system (million 1994 dollars)

Legend:

(1) Development cost the 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 in case of mishaps. - This is not included in the original cost model and has to be accounted for separately!
(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) in million 1994 dollars

year	(1)	(2)	(3)	(4)	(5)
-8	40				40
-7	1,780	23		45	1,848
-6	2,730	910		62	3,702
-5	3,480	1,280		78	4,838
-4	3,980	1,650		88	5,718
-3	4,020	1,810		88	5,918
-2	3,590	1,670	704	78	6,042
-1	2,860	1,350	1,000	62	5,272
0	2,080	950	1,200	45	4,275
totals	24,560	9,643	2,904	546	37,653

The *transportation system cost* estimated with the help of the TRASIM code[13], during the initial acquisition phase - taking about nine years development and ten years of operation - are comprised of:

37.653 B $ for research, development (as shown above)
\+ 2.826 B for sustained engineering and product improvement
\+ 15.883 B $ for production of space transportation system hardware
\+ 4.571 B $ for flight operations , totaling = **60.933 B $** .

Thus the 19 year initial acquisition period leads to average expenditure of 3.2 billion (1994)$ per annum for the *space transportation system* employed which, however, will also be used in the next phase of the lunar settlement life-cycle!

In summary, the total cost of the first 19 year development phase (lunar facilities and logistics)are approximately 61 B $ for the logistic system and 17 for the lunar laboratory adding up to 78 B $ or **approximately 4.1 B (1994)$ per annum.**

4. The Second Development Phase of the Lunar Settlement

4.1 The facilities of the lunar settlement and logistic requirements

The growth rates of the population and number of passenger flights for the operational years 11 through 60 can be selected within a reasonable band. In this scenario the relevant state variables are planned as follows, with the objective to keep the annual expenses nearly constant or declining respectively:

Table 4 -1: Projected Lunar Settlement growth rates

year of operational phase	scientific & other people	construction and service people	total lunar population	no.of annual passenger flights	average duty cycle (years)
11	2	58	60	2	0.75
15	9	77	86	2	1.07
20	22	97	118	3	0.99
25	43	125	167	5	0.84
30	65	152	216	6	0.90
35	142	230	371	7	1.33
40	232	307	537	9	1.50
50	615	685	1,295	19	1.70
60	1,000	970	1,944	24	2.03
total	14,700	17,900	32,600	510	-
average	294	358	652	10.2	1.34

Table 4-2: Growth rates of mass inputs and outputs of the lunar settlement during the 2nd phase

year of operational phase	total cargo imports required	no.of passenger flights	no. cargo flights reqrd.	total no of flights p.a.	export or infrastructure (t) p.a.	lulox produced (t) p.a.	lunar prod. for lunar use (t) p.a.	total lunar outputs (t) p.a.
11	92	2	1	3	100	214	87	401
15	180	2	2	4	334	559	164	1,056
20	233	3	3	6	581	849	230	1,660
25	313	5	3	8	842	1,149	349	2,340
30	377	6	4	10	1,130	1,450	460	3,041
35	633	7	7	14	1,560	2,004	859	4,424
40	809	9	9	18	2,083	2,567	1,220	5,880
50	1,727	19	20	39	3,977	4,846	3,102	11,926
60	2,109	24	20	54	4,744	5,515	4,780	15,040
total	44,850	510	503	1,013	102,750	128,400	77,500	308,650
av.	897			50	2 053	2 568	1550	6 171

These requirements determine the actual performance of the lunar settlement which is best illustrated by selecting the most important state variables as shown in table 4-3.

Table 4-3: Performance of the lunar settlement during the 2nd phase

year of operational phase	lunar soil input(t)	import rate	netproduction (t) p.a.	productivity (t/person)	self-sufficiency	lunar facilities (t)	power required (kW)
11	12,000	0.242	287	4.8	0.415	850	1,287
15	15,714	0.186	828	9.7	0.404	1,174	2,826
20	20,000	0.157	1,347	11.4	0.414	1,583	4,346
25	25,000	0.152	1,904	11.4	0.443	2,191	6,317
30	30,000	0.143	2,494	11.5	0.462	2,824	8,514
35	40,000	0.162	3,521	9.5	0.499	4,474	13,771
40	50,000	0.156	4,583	8.7	0.523	6,292	20,137
50	90,000	0.163	9,292	7.2	0.571	15,642	50,733
60	100,000	0.162	11,455	6.0	0.622	24,533	82,735
average	50,020	0.164	4,812	7.4	0.545	7,956	25,455

4.2 The logistic system supporting the second phase of the lunar settlement

As described in chapter 3, the space transportation system employed in this scenario is a heavy lift launch vehicle (HLLV) which transports cargo and people to a space operations center in lunar orbit (LUO-SOC) and a lunar ferry vehicle (LUBUS), which takes the cargo and passengers down to the lunar spaceport and returns them the same way.

During the first phase, however, the 12 t oxygen propellants required for returning the payload stage from lunar orbit to the Earth was brought along from the Earth, thus reducing the nominal cargo payload to 70 t. Beginning with operational year 11 these return propellants will be brought up to the LUO-SOC from the lunar spaceport originating from lunar resources. This increases the nominal cargo capability of the heavy lift launch vehicle for lunar orbit missions to 82 t.

Lunar oxygen for HLLV return flight and LUBUS roundtrip requirements. -
In this case the HLLV brings along all liquid hydrogen requirements for its own return flight and the LUBUS roundtrip only, but *no LOX propellants for its own return* flight or the LUBUS.

The nominal payload capability of the HLLV is reduced from 100 t to **82** t to be transferred to the lunar ferry in lunar orbit at the LUO-SOC. The LULOX requirements are approximately 110 t per flight as shown in table 4-4.

These assumptions lead to the following mass- and performance characteristics on which the lunar landing- and launch vehicle has to be sized:

Charateristic velocity for a single flight between the iunar orbit and the lunar spaceport = 2000 m/s, exhaust velocity 4500 m/s, mass ratio (minimum) = 1.56 .

Table 4-4: Mass model of LUBUS passenger and cargo flights as employed during the 2nd and 3rd phases of the life-cycle (metrictons)

	passenger flights with some cargo	cargo only flights
Down leg LUO-SOC to LUS:		
empty stage	22	20
cabin with crew	25	0
cargo delivered	25	82
hydrogen for ascent	10	7
stage at cut-off	82	109
propellants required	47(7LH2+40Lulox)	61(9+52)
take-off mass in LUO	129	170
Ascent from LUS to LUO:		
empty stage mass	22	20
cabin with crew	25	0
cargo to earth	0	0
Lulox for down leg	40	52
Lulox for LV 3rd stage	25	15
cut-off mass in LUO	112	87
propellants used	63(10LH2+53Lulox)	49(7+42)
Take-off mass on the Moon	175	136

Mass-balance HLLV passenger flights with max. **40persons** :
50 t crew cabin + 5 t LH_2 return propellants + 20 t hydrogen
for lunar ferry with losses + 25 t lunar cargo = 100 t
Mass balance HLLV cargo flights:
Cargo 82 t + 16 t LH2 for Lubus + 2 t LH2 for HLLV stage return= 100t

LunarLOX -requirements at the lunar spaceport:
Passenger flights : 40 + 53 + 25 + 2 losses = 120 t per flight
Cargo flights: 52 + 42 + 15 + 1 losses = 110t per flight
LunarLOX- requirements in LUO :
Passenger flights : 25 t per return flight to the Earth
Cargo flights with 0 payload return to the Earth: 15 t LOX

It should be pointed out, that some growth potential is available on the long run. In a favourable development of lunar resources, all liquid oxygen and liquid hydrogen propellants required by the HLLV for the return trip as well as those required by the LUBUS for its roundtrip are produced on the Moon. The full nominal payload capability of the HLLV of **100** t is then available for unloading in lunar orbit and transfer to the lunar spaceport by the LUBUS cargo vehicle. The LULOX requirements are then 120 t per flight, the LH_2 requirements are 20 t/flight. This would lead to a further reduction of the logistic cost [15].

After having determined the Lulox propellant requirements for the HLLV and LUBUS vehicles based on the number of flights scheduled, we have to check if these annual amounts of lunar produced LOX are within the capacity of the lunar propellant production facilities. These capacities have been listed on table 4-2 ranging during this phase of the life-cycle from about 100 t to more than 4,000 t p.a. We also have to show that the scheduled passenger and cargo-flights together can deliver all the import masses required. These balances are presented on table 4-5.

The first three years the Lulox production does not quite cover the needs, thus either Lox has to be imported or the Lulox production must be increased. There are some reserves of Lulox available on the Moon at the end of the first phase ! In the 50 year balance of the 2nd phase, however, the Lulox propellants will be sufficient, production is higher by 11.2% than consumption. With respect to the imports it can be seen from the last two columns, that the capacities exceed the requirements. Taking these excess capacities, making use of the Lulox reserves and adding the excess production of the lunar facilities (shown in tables 3-1 and 4-2), it appears possible to adjust the available production and storage facilities in such a way, that a small Lulox production deficit can certainly be managed. -
This analysis indicates a 18.5 % reserve of imports during this phase of the life cycle with an adequate amount of lunar oxygen propellants produced. This can be considered to be a satisfactory logistic supply situation.

Table 4-5: Mass balances of lunar propellants and imports

year of operational phase	lulox req. for flight schedule assumed (t) p.a.	LULOX produced (t) p.a.	total payload capacity available (t) p.a.	total cargo imports required (t) p.a.
11	350	214	132	92
12	460	334	214	201
13	460	422	214	150
14	460	494	214	154
15	460	559	214	180
16	580	620	239	191
17	580	679	239	202
18	690	737	321	212
19	690	793	321	223
20	690	849	321	233
30	1,060	1,450	478	377
40	2,070	2,577	963	809
50	4,480	4,846	2,115	1,727
60	5080	5,515	2,240	2,109
total	115,430	128,412	53,176	44,850
AV.	2,309	2,568	1,063	897

4.3 Cost of operating the lunar settlement during the second operational phase

On the basis of the mass models, launch rates and plausibel assumptions for cost factors it is now possible to estimate the annual cost of the lunar settlement growth phase,excluding logistics. This is done using the simulation program (LUBSIM) for lunar installations[10]. The cost elements have been summarized into three major groups:

- cost of facility elements, equipment and spareparts
- cost of products imported for consumption at the lunar settlement
- crew salaries and cost of all support manpower required on Earth.

Table 4-6: Overview of annual recurrent costs excluding the logistic cost of the lunar settlement at selected years (M 1994 $)

year of operational phase	cost of facilities & equipment	cost of imported conumables	crew salaries & Earth support	other cost elements	total reurring cost LUSET
11	55	2	789	0	846
15	128	58	797	0	983
20	133	73	808	0	1,014
25	184	84	827	45	1,140
30	194	87	845	68	1,194
35	358	84	904	95	1,441
40	412	80	967	120	1,579
50	1,010	95	1,251	167	2,523
60	1,177	97	1,490	227	2,991
av.	520.8	81.4	1,008.5	96.3	1,709

The total cost for the lunar facilities for this 2nd phase is comprised of :

cost of imported facilities, equipment and spares	26.040 B $
cost for imported consumables	4.150 B $
cost of personnel on the Earth and on the Moon	50.425 B $
other cost items	4.815 B $
Total	85.430 B $

4.4 Cost of operating the logistic system during the second phase

The vehicle mass models, the flight schedule and cost factors derived from past experience are the basis for this calculation.

These costs have been grouped in the following categories:
- product improvement of the elements of the space transportation system;
- vehicle production cost, including the production cost of a second space operations center required during this growth phase, but also the cost of subsystems to be replaced because they have reached their design lifetime are included in the production cost;
- flight operations including maintenence and repair.

The irregular amounts observed in the last column of table 4-7 reflect the fact that the cost of newly manufactured space vehicles are paid fully in the year of delivery Under real life conditions these costs would be spread over several years and thus reduce these local peaks.

Table 4-7: Overview of annual recurrent costs of the space transportation system (M $) at selected years during the growth phase of the lunar settlement

year of operational phase	vehicle product improvement	vehicle production cost	flight operations	total logistic system
11	282.6	2426	572	3281
12	282.6	124	289	696
13	282.6	98	274	655
14	282.6	87	264	634
15	282.6	50	257	590
20	282.6	92	344	719
25	282.6	66	433	782
30	282.6	92	511	886
35	282.6	310	667	1,260
40	282.6	151	811	1,245
50	282.6	721	1,553	2,557
60	282.6	718	1,616	2,617
total	14 130	33,155	43,467	90,752
average	283	663	869	1,815

4.5 Total cost of second phase of lunar settlement life-cycle

After having derived at cost estimates for the extension of the lunar facilities during the growth phase of the lunar settlement and the space transportation system required for the logistics support of this enterprise, we are now able to present an overview of the annual cost of the entire system for the operational years 11 through 60. The irregularities resulting from new vehicle buys in some years are also recognizable in table 4-8.

Table 4-8: Overview of systems cost during the growth phase of the lunar settlement

year of operational phase	LUSET total recurring cost (M$)	logistic system recurring cost(M$)	annual system cost (M$)
11	846	3,281	5,942
12	1,045	696	1,771
13	967	655	1,622
14	951	634	1,585
15	981	590	1,571
20	1,009	719	1,728
25	1,132	782	1,914
30	1,186	886	2,072
35	1,435	1,260	2,695
40	1 ,575	1,245	2,820
50	2,505	2,557	5,062
60	3 ,172	2,617	5,789
total	85,430	90,752	176,182
average	1,710	1,815	3,525

5. The (3rd) Consolidation Phase of the Lunar Settlement

5.1 Development trends of the lunar operation during the consolidation phase

During the consolidation phase the selected state variables of the lunar settlement will change along the lines presented in the next three tables, where the year 60 is the last year of the growth phase. This change in pace will require adjustments for some of the state variables from the 2nd to the 3rd phase of the life-cycle.

Table 5-1: Projected change rates of lunar population during the consolidation phase of the Lunar Settlement

year of operational phase	scientific & other people	construction and service people	total lunar population	no.of annual passenger flights	average duty cycle (years)
60	1,000	970	1,944	24	2.03
65	1,000	879	1,879	24	1.96
70	1,000	959	1,959	24	2.04
75	1,000	983	1,983	24	2.06
80	1,000	990	1,990	24	2.07
85	1,000	1,000	2,000	24	2.08
total	25,000	23,950	48,950	600	-
average	1,000	958	1,958	24	2.04

Table 5-2: Change rates of mass inputs and outputs of the lunar settlement during the consolidation (3rd) phase (year 60 is the last year of the 2nd phase)

year of operational phase	total cargo imports required	no.of passenger flights	no.of primary cargo flights reqrd.	total no of primary flights p.a.	export or infra-structure products (t) p.a.	lulox propellants produced (t) p.a.	lunar products for lunar use (t) p.a.	total lunar outputs (t) p.a.
60	2,109	24	20	54	4,744	5,515	4,780	15,040
65	1,571	24	16	40	5,016	5,027	3,826	13,869
70	1,749	24	16	40	5,762	5,774	4,148	15,684
75	1,727	24	16	40	6,279	6,105	4,135	16,519
80	1,730	24	16	40	6,412	6,161	4,187	16,760
85	1,731	24	16	40	6,530	6,208	4,239	16,977
total	42,775	600	400	1,000	147,500	145,200	102,500	395,200
av.	1,711	24	16	40	5,900	5,808	4,100	15,808

These requirements determine the actual performance of the lunar settlement which is best illustrated by selecting some relevant state variables as shown in table 5-3.

Table 5-3: Performance of the lunar settlement during the consolidation phase

year of operational phase	lunar soil input(t)	import rate	net production (t) p.a.	productivity (t/person)	self-sufficiency	lunar facilities (t)	power required (kW)
60	100,000	0.162	11,455	6.0	0.622	24,533	82,735
65	86,000	0.130	11,172	5.9	0.620	24,192	69,980
70	96,000	0.127	12,722	6.5	0.618	24,598	76,857
75	100,000	0.119	13,539	6.8	0.619	25,391	80,036
80	100,000	0.118	13,737	6.9	0.622	25,478	81,438
85	100,000	0.116	13,908	7.0	0.626	25,508	82,650
25 y total	2 412,000	-	321,750	-	-	-	-
av.	96,480	0.123	12,870	6.6	0.613	24,937	77,162

The total cost for the lunar facilities for the 25 year consolidation phase is comprised of

cost of imported facilities, equipment and spares	15.238 B $
cost for imported consumables	2.175 B $
cost of personnel on the Earth and on the Moon	38.235 B $
other cost items	5.590 B $
Total	61.238 B $

The required performance of the lunar logistic system during the 3rd phase is documented in the next tables.

5.2 The logistic system supporting the third operational phase of the lunar settlement

As described in chapter 3, the space transportation system employed in this scenario is not changed during the entire life-cycle of the lunar settlement. However, this is a conservative assumption because the state-of-the-art will be improving as function of time leading to an increase of payload capability of the space vehicles as well as an improvement of their reliability and maintainability. This is not reflected in the assumptions made for the second and third opüerational phases of the lunar settlement life-cycle. During the entire operation an amount of almost 300 M $ p.a. will be spent in this scenario to sustain a small development group to take care of technical difficulties developing during the operation, but also to improve the system due to learning and upgrading. This will show up some time in the life-cycle, but has been neglected to stay on the safe side with the performance estimates.

The launch rates during the 3rd phase will be kept constant: 16 p.a. for cargo flights and 24 p.a. for passenger flights e.g. a total of 40 p.a., less than one per week. Excess lunar propellants available could be used for increasing the return payload capability of the space vehicles resulting in imports of lunar products to the Earth if economically justified, such as Helium-3, rare metalls or even souveniers.

The simulation of the lunar space transportation system for a 25 year consolidation phase(year 11 - 85 of the life cycle) with constant launch rates and some 2,030 flights total - using lunar oxygen for the LI[illegible]JS and HLLV return flights - produced the following data:

Product improvement efforts	7.065 B $
production of vehicles and subsystem replacements	28.132 B $
flight operations	35.906 B $
total logistic cost during 3rd phase	71.102 B $
average annual logistic cost 3rd phase	2.844 B $

6. Comparison of Life-cycle Phases

After completion of the analysis of the three development phases it is now possible to compare the performance of the individual phases of the system life-cycle and relate them to the overall system performance. This is done in this chapter illustrating some of the trends to be expected.

Table 6-1: Overview of the development of lunar population

operational years	cumulative lunar labor years	years of science capacity	infrastructure labor years	passenger capacity	average lunar crew duty cyle
1-10	412	119	293	840	0.50
11-60	32,600	14,700	17,900	20,400	1.34
61-85	48,950	25,000	23,950	24,000	2.04
total LC	81,962	39,819	42,143	45,240	1.81

The cumulative number of available labor years on the Moon is perhaps the best overall parameter to compare various lunar facilities. This lunar settlement with 81,962 lunar labor years in 85 operational years are close to an average population of 1,000 (exactly 964). - the development of the lunar crew as function of time is shown in figure 6-1. It begins slow with about 27 people in the first year, grows rapidly during the second phase and levels off during the consc' ion phase.

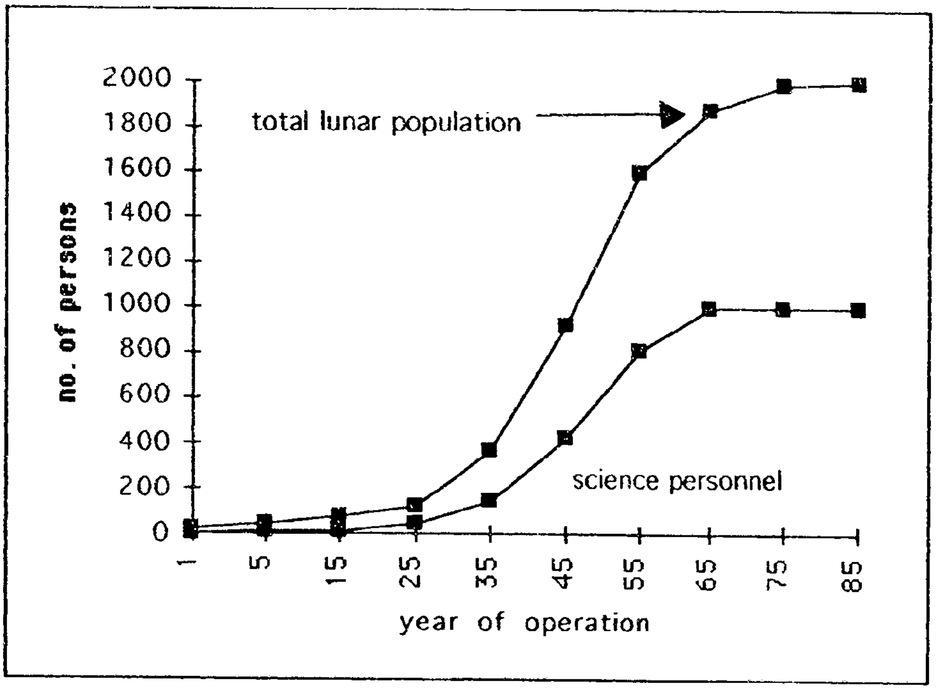

Figure 6-1: Development of scientific personnel and total population during the operational period of the lunar settlement life-cycle

Table 6-2: Overview of masses processed (t)

	imports required	import capacity	import reserve	lunar products for lunar usage	lunar products for export or TBD	lunar propel-lants produced	total output of lunar products
1-10	1,773	1958	185	820	250	2,900	3,970
11-60	44,850	53,176	8,326	77,500	102,750	128,400	308,650
61-85	42,775	47,800	5,025	102,500	147,500	145,200	395,200
total LC	89,398	102,934	13,536	180,820	250,500	276,500	707,820
av.LC	1,052	1,210	15.1%	2,127	2,947	3,253	8,327

A 15% import reserve illustrates that this is not a marginal supply proposition!

Table 6-3: Overview of flight numbers and system efficiencies

	cargo flights	passenger flights	total flights	import ratio	self-suf-ficiency	produc-tivity
1-10	37	21	58	0.29	0.35	9.6
11-60	503	510	1,013	0.16	0.55	7.4
61-85	400	600	1,000	0.12	0.61	6.6
total LC	940	1,131	2,071	0.13	0.58	8.6

Table 6-4: Overview of lunar facility and operation costs during operational phase

dev.Phase	imports	earth support	crew salaries	other	total
1 - 10	1,172	5,980	310	0	6,562
11 - 60	30,190	30,000	20,425	4,815	85,830
61 - 85	17,413	23,235	23,235	5,590	61,238
LC total	48,775	50,080	43,970	10,405	153,230
av.p.a.	574	589	517	122	1,803

Table 6-5. Overview of space transportation costs during operational phase

	sustained engineering	production	flight operation	total
1 - 10	2,826	15,883	4,571	23,280
11 - 60	14,130	33,155	43,467	90,752
60 - 85	7,065	28,132	35,906	71,103
LC total	24,021	77,170	83,944	185,135
av.p.a.	282	908	988	2,178

Table 6-6: Overview of life-cycle system cost (billion 1994 $)

phase of LC	lunar facilities	lunar logistics	total phase
init. development (- 9 to 0)	10.430	37.653	48.083
init.laboratory (op.year 1 to 10)	6.562	23.280	36.128
growth phase (11 to 60)	85.430	90.752	176.182
consolidation (61 to 85)	61 238	71.103	132.340
LC system cost (- 9 to 85)	163.660	222.788	386.448
annual average during 94 yr LC	1.744	2.370	4.111

In this analysis it has been assumed that this is a non-commercial program run by a single agency. These system cost can be split either on the basis of lunar operation and logistics, or between the lunar settlement operation (minus the services to the space transportation system) and the total cost of the space transportation system. To illustrate the difference, the next table shows the cost of lunar produced propellants and services utilized by the space transportation system, which would have to be added to the transportation cost to obtain a complete picture.

Table 6-7 : Overview of space transportation cost including lunar propellants and services(B $)

	cost of dev. production and operation on Earth	cost of lunar propellants	cost of lunar overhaul and launch servives	total cost of space transportation	share of cost originating on the Moon of total cost
-9 - 0	37.653	-	-	37.653	0
1-10	28.203	7.930	1.133	37.266	24.3%
11-60	102.207	15.965	1.660	119.832	14.7%
61-85	72.393	5.058	1.000	78.451	7.7%
total LC	240.456	28.953	3.793	273.202	12.0%

Also of interest in this connection is the balance of lunar propellants produced and propellants required. The excess of production over requirements can be used for exports:
Lunar propellants required 1 -10 : 3,555 t, produced : 2,900t, imported 655 t
Lunar propellants required 11-60 : 116,530 t, produced : 128,400t, excess: 11,870 t
Lunar propellants required 61-85 : 116,000 t, produced : 145,200t, excess : 29,200t
LC totals: Required 236,085 t, produced 276,500, excess 40,415 t = 175 reserve !

If the cost on the lunar side related to space transportation transportation are not included, because this is somewhat simpler and desirable for certain comparisons, the specific transportation cost as function of time are summarized in table 6-6 and graphically presented in figure 6-1.

Table 6-8 : Overview of space transportation costs per flights and per unit payload respectively during the life-cycle of the lunar settlement
(lunar propellants and services not charged to the space transportation system!)

year of life-cycle	HLLV cargo M$/fl.	HLLV pass. M $/fl.	LUBUS cargo M $/fl.	LUBUS pass M $/fl.	cargo ES-LUS $/kg	pass. ES-LUS-ES *)T$/seat
5	156	159	25	18	2,207	4,425
15	106	111	8.2	11.3	1,361	3,123
25	92	97	7.5	10.2	1,190	2,726
35	86	90	7.0	9.5	1,102	2,524
45	78	82	6.4	8.8	1,006	2,308
55	68	72	5.5	7.7	872	2,010
65	69	73	5.3	7.4	851	1,961
75	61	65	5.1	7,.1	745	1,727
85	57	60	4.4	6.3	728	1,686

*)These figures do not take into consideration the fact that the specific passenger costs are actually reduced by carrying 25t of cargo along. This can be accounted for by reducing the passenger cost by about 32 percent. But they increase by about 12%(as shown above) if the cost lunar resources are included.

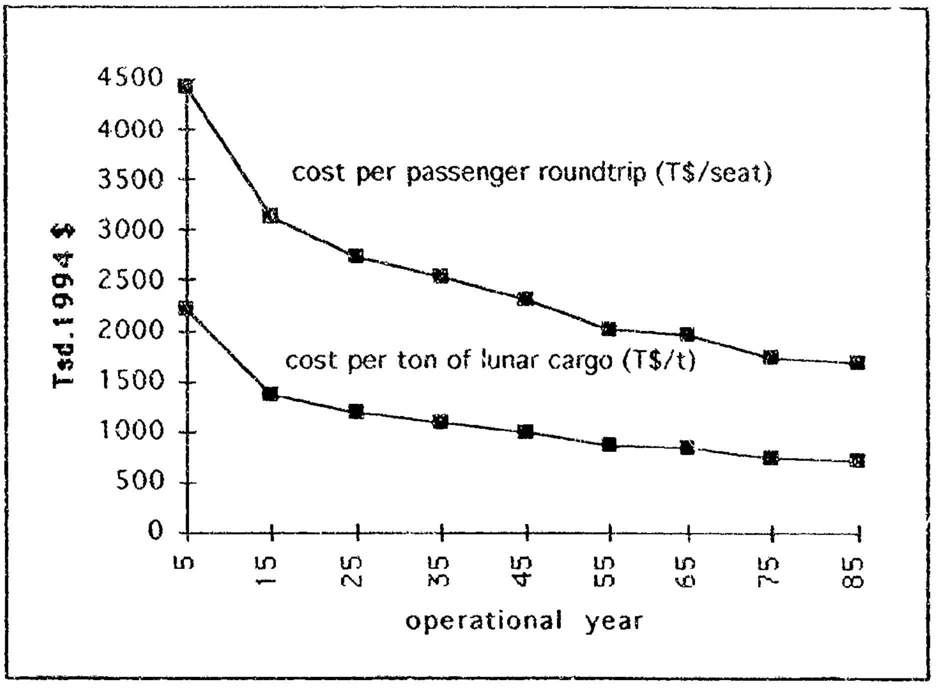

Figure 6-2: Specific cost of lunar transportation excluding the cost of lunar propellantsandlunarservices

7. The System-Effectiveness of the Lunar Settlement

The most important system performance parameters are summarized in the next table to enable a comparison with other lunar bAse concepts:

Table 7-1: Life-cycle performance and cost summary of lunar settlement program-model 2.0 of 1996 -(cost in million 1994 dollars)

lunar facilities available at the end of the life-cycle	24,550 t
total lunar products available	707,820 t
— lunar propellants used for space vehicles	276,500 t
— lunar products available for export	250,500 t
— lunar products used on the Moon	180,820t
total lunar labor-years available	81,962
— max. laboratory-years available for lease	39,819
Initial development of lunar facilities and first units	10,430 M $
Engineering and science support during operation, admistration, training,	50,080 M $
salaries of lunar crew	43,970 M $
imported spares, equipment, facilities, consumables	48,775 M$
subtotal lunar base acquisition and operation	163,660 M $
vehicle development and engineering	37,653 M$
sustained engineering and support during operation	24,021 M $
total production cost	77,170 M $
total operations cost	83,944 M $
subtotal logistic system	222,788 M $
total cost for 94 yr life-cycle	386 ,448 M$
annual average during the 94 year life-cycle	4,111 M $
specific cost per lunar labor -year (no commercial sales)	4.71 M$/MY
Potential sales:	
lease of laboratory spaces (ca. 20 000 * 5 M$)	100,000 M$
sale of lunar export products (250 000 t * 0,1 M $/t)	25,000 M $
total sales	125,000 M $
net cost = subsidy	261,448 M $
net cost per lunar labor-year (261 448/81 962)	3.19 M $/y
average net cost per annum	3.076 M $/y
cost reduction factor compared with OPTION 1 (Outpost) a.no commercial sales: 536 M $: 4,71 b.with estimated commercial sales 536 M$: 3.19 M $	 114 168

8. Summary and Conclusions

This report presents a concept and a preliminary analysis of a lunar settlement which is conceivable to be established on the Moon during the 21st century under favourable development conditions on Earth.

This scenario assumes that a multi-year planning period, soon after the turn of the century, is expected to clear the way for the acquisition of a lunar laboratory. This lunar project gets underway during the second decade of the next century beginning about the year 2016, assuming that financing begins about the year 2006. The development period will last nearly one decade, before the first construction crew returns to the lunar surface. After an initial ten year period of establishing a laboratory at the selected base site, a growth phase of the lunar settlement will follow to last about fifty years. This step of lunar development is concluded by a 25-year consolidation phase and leads to a lunar population of about 2 000 persons. This scenario ends abruptly in the year 2100, however, it is anticipated that the lunar settlement will somehow continue after that in an undefined way.

The logistic support of this enterprise is provided by a near state-of-the-art, fully reusable space transportation system, using lunar propellants as much as possible. A heavy lift launch vehicle(HLLV) transports people and cargo to a transportation node in lunar orbit(SOC), where the payloads are transferred to a lunar ferry vehicle(LUBUS), which takes care of the local transportation between the lunar settlement and the space operations center in lunar orbit. The nominal payload capability of the HLLV to lunar orbit is 100 metric tons or 40 passengers.

In this scenario, the mass of the lunar facilities grows from less than 1,000 tons to about 25,000 tons at the end of the 85 year operational period, a considerable share of these originate from lunar resources. An average of about 1,000 tons of imports are required annually to sustain the settlement which has a self-sufficiency rate of about 60 percent. More than 2,000 tons p.a. of lunar products - other than propellants - find use on the Moon. Nearly 3,000 t p.a. of additional construction material and other products are available at the average for either export or developing the lunar infrastructure (e.g.roads, pipe lines, power lines, solar farms and scientific outposts).

In addition, some 3,000 tons of lunar oxygen are available per annum as propellants for the space vehicles serving the lunar settlement. The logistics support requires a total of 940 cargo flights (11 p.a.) and 1131 passenger flights(13 p.a.), these are average values over the operational period. The activities would lead to a peak of 44 missions p.a., or less than one per week. The specific transportation cost of cargo from the Earth to the Moon is over 2,000 $/kg in the early years, but drops down to less than 1,000 $/kg towards the end of the life-cycle. The passenger roundtrip cost is expected to begin with about 5 M$ per seat and be less then 2 M$/seat at the end of the period investigated.

The average duty cycle for the lunar personnel is 1.8 years. In case each person stays only once on the Moon a total of 45,240 people will have been on the Moon by the year 2100! - The average annual cost to build and operate the facilities and equipment of the lunar settlement have been estimated with the help of detailed simulation codes to be approximately 1.744 B (1994)$ and the space transportation system requires approximately 2.37 B $ p.a., totalling 4.111 B $ p.a. or approximately 386 billion $ for the entire 94 year life-cycle. On one hand these estimates are preliminary, but on the other hand this is not yet an optimized program, there is considerable room for improvements.

These cost are the cost to the participating governments. They can be reduced by leasing some of the available laboratory space to interested commercial entities on Earth for purposes of research and development. If 20,000 of the 40,000 scientific labor-years are leased at five million dollars each, approximately 100 B $ can be obtained from these commercial sources. Also some of the 250,000 t of construction materials and other products for export might be sold (e.g. for the construction of solar power plants of international utilities) which could bring another 25 B $ and reduce the cost to the taxpayer accordingly. The overall total could thus be reduced to somewhere near 250 B$ or 3 B$ p.a. !

CONCLUSIONS

1. The exploration of the Moon and the utilization of its resources to improve the quality of life on Earth may one day prove to be an essential step of the survival of the human species.

2. At this stage of the available insights into a fairly complex geopolitical situation as well into the present state-of-the-art of space technology, it appears technically feasible to establish a lunar settlement during the 21st century providing room for about 2,000 people by the year 2100.

3. Such an enterprise has to be financed primarily by public funds. An average of less than 5 billion 1994 dollars per year are required to pay for the cost of such a program, with a peak slightly below the 10 billion $ mark at the end of the development period.

4. Consequently, the exploration of the Moon by robotic spacecraft should continue during the next decade to improve our knowledge of the Moon and its environment. Also a serious multi-year,multi-nation planning activity should commence shortly after the turn of the century to develop attractive options for the next stage of lunar development leading to a lunar colony of modest proportions be the end of the 21st century.

5. Although controversial, it appears entirely justifyable to debate the pros and cons of a lunar settlement already now, if the total finances required to accomplish this are about fifty percent of the amount spent on this planet every year for military purposes. With other words, the level of resources required is on the order of one percent of the global military expenses per year at the present time. Thus such a program developing a lunar settlement is certainly financially feasible, particularly if several countries are participants in this pioneering enterprise. Whether this is politically opportune at a certain point in time is an other question.

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