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LUNAR BASE FACILITIES
DEVELOPMENT & OPERATION

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Abstract

The subject of developing and operating of lunar facilities has been covered widely during the last decades. This report attemps to integrate these various contributions discussing specific details from the systems viewpoint. This is mandatory for the simulation of the acquisition process and the lunar base operation of extended periods. Lifetimes of several decades have to be considered. The functions of lunar facilities are defined and assigned to specific installations. Mass flows between the elements of the lunar base are identified as well as their interrelations with eachother and the facility elements. Some initial information is presented on the 14 types of facilities identified. State-variables and performance indicators are defined to compare alternative facility concepts on the same bases.
Some illustrative schedules are dveloped to place the developments expected into a frame of reference with respect to time. A sub-program of Lunar science is described because this is one of the strongest motivations to continue lunar development in the 21st century. The report is closed with some guidelines on how to simulate and compare alternative lunar base concepts over their lifecycle. 45pages, 13 tables,178 references.

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1. INTRODUCTION

When we get to the Moon, we will have to install adequate facilities which have to be operated effectively and probably be expanded in due course of the base lifetime with increasing number of people, expanding services and growth in manufacturing of lunar products. The functions of these facilities determine their characteristics, their equipment, their power- and manpower requirements but also their dimensions. The latter ones are primarily a function of the annual mass flows and resulting outputs demanded.

To design a lunar facility we have to have information on the objectives of the program and the desired attributes such as

- individual products to be manufactured
- individual services to be provided
- mass flows per unit time
- thermal and electrical power during day and night cycles
- requirements of human labor during day and night cycles
- design lifetime of facilities
- design lifetime of equipment
- living volume per lunar crew member required
- surface transportation requirements of cargo and personnel
- sparepart requirements
- life support system performance level desired
- data flow rates between facilities and outside users etc.

It is obvious that a lunar base is characterized by a great number of state variables. Between those exist many relationships which together determine the behaviour of the *lunar base system* . This is certainly a fairly complex system. This can and must be modeled in such a way that its behaviour can be simulated as function of time for the entire life-cycle of the system envisioned. Without extensive simulation we can not obtain the insights required to optimize the design of the lunar base with respect to the defined objectives.

It is interrelated with the system design but an other question on how this lunar facility has to be supported by a logistic system transporting personnel and cargo from the Earth to and from the Moon. This subject is discussed seperately in an other report.

2.FUNCTIONS

Any facility plan for a potential lunar base must be preceded by a definition of the functions to be carried out at the lunar base. The identified functions are :

1. Lunar science and technology activities:
LS01: Operation of research laboratories and observatories
LS02: Operation of mobile research equipment
LS03: Operation of component-, subsystem- and system test facilities

2. Production of raw materials
LP01: Mining of minerals
LP02: Beneficiation of lunar soil and minerals
LP03: Production of gases, raw materials and feedstock
LP04: Production of metallic products
LP05: Production of non-metallic products

3. Manufacturing of end-products and commercial services
LM01: Manufacturing of structural components for lunar use
LM02: Production of foodstuff for lunar use
LM03: Manufacturing of other products for lunar use
LM04: Production of propellants
LM05: Assembly of parts and subsystems for lunar use
LM06: Manufacturing products for export
LM07: Assembly of products for export
LM08: Services produced for external customers
(incl.custodial services, storage of hazardous waste, storage of secure archives, monitoring Earth-Moon space, tele-education, tele-medicine, entertainment)
LM09: Energy for export (electric-, solar and/or He-3)
LM10: Operating facilities for lunar tourism

4. Direct support operations:
DS01: Supervision and control of equipment and processes,
DS02: Internal and external communication services, data management
DS03: Electric and thermal power supply for lunar users
DS04: Housing of lunar personnel
DS05: Life-support for lunar crew
DS06: Health- and recreation services for lunar crew
DS07: Services for the space transportation system at the lunar spaceport
DS08: Personnel transportation on the lunar surface
DS09: Materiel transportation on the lunar surface
DS10: Construction and extension of facilities
DS11: Maintenance and repair of facilities and equipment
DS12: Collecting and recycling of waste and scrap
DS13: Storage
DS14: In-situ training and specific education

3. IDENTIFICATION OF LUNAR FACILITIES AND EQUIPMENT (LF)

3.1. CLASSIFICATION

The functions listed above can be carried out only with the help of facilities, equipment and people. The activation of all identified functions has to be specified with respect to a particular point in the development timeline, since this will determine development and delivery schedule as well as labor requirements for this specific facility or piece of equipment. The size of the facility or equipment will depend on the performance required. There will be an initial size at the beginning of the operation, a growth rate and a final size, determined by the maximum performance or throughput required during its lifetime. All of these variables will have to be specified for each scenario analysed. This is done by the simulation of the entire life cycle of the respective base model.- In general, one has to expect the following types of facilities and equipment in a major lunar base:

Infrastructure facilities and equipment:

LF01: Research laboratories, observatories and related facilities & equipment
LF02: Control Center (communication, data storage and processing, software)
LF03: Habitats (living quarters, sleeping areas, food preparation, eating areas, laundry facilities, recreation facilities, hospital, space suits, etc.)
LF04: Maintenance and repair facilities (workshops, tools, equipment, etc.)
LF05: Storage facilities (spares, waste, import products, export products, etc.)
LF06: Power plants (power conversion ,- storage and distribution equipment)
LF07: Carpool (garage, surface vehicles, frontend loaders, haulers, roads etc.)
LF08: Lunar Spaceport (launch and landing facilities, propellant storage , servicing equipment, lifting devices for unloading , etc.)

Production facilities and equipment

LF 10,11 and 13 include respective waste processing equipment, in simplified models , this group of facilities can be integrated into one element (LFE 09) if the production activity is very small.

LF09: Mining facilities and equipment (soil movers, drills, etc.)
LF10: Chemical processing facilities (for gases, liquids incl. prop. and solids)
LF11: Mechanical processing facilities(furnaces,mills,presses, machine tools)
LF12: Fabrication facilities (for structures solar cells cable trees, radiators etc.)
LF13: Biological production facilities (for vegetables, meat, water, air)
LF14: Assembly facilities and equipment (tools, jigs, shops).

3.2. FACILITY SPECIFICATIONS

For each facility and each major piece of equipment the following information has to be prepared for detailed planning processes(all masses in metric tons):

1. Calender year or operational year of initial operational capability
2. Type and volume of output = performance (e.g. t p.a.)
3. Dimensions when in operation (footprint m * m *height m)
4. Dimensions during transfer from the Earth to the Moon (m * m * m)
5. Reference mass at installation in the first operational year (t)
6. Mass of packaging material if any (t)
7. Expected performance growth p.a.
8. Expected mass growth (t p.a.)
9. Share of Earth produced components for facility growth (%)
10. Sparepart requirements of current facility mass (t p.a.)
11. Share of lunar produced spareparts (%)
12. Material inputs required by type and mass rate (t p.a.)
13. Share of lunar produced inputs required (%)
14. Control and maintenance labor required (hours p.a.)
15. Initial installation labor hours required (hours)
16. Labor hours required for facility extensions (hours p.a.)
17. Design lifetime (years) and MTBF (mean time between failures)
18. Design complexity factor (standard empty habitat module = 1)
19. Experience factor (number of generation in kind)
20. Number of units and production rate to be manufactured (-)
21. Learning factor to be applied for production (-)
22. Thermal energy required for operation (MWh p.a.)
23. Electrical energy required for operation (MWh p.a.)
24. Specific development cost of reference unit (MY/t)
25. First unit cost of reference unit (MY)
26. Specific cost of input material (MY/t)
27. Value of marketable products (MY/t)
28. Radiation dosis allowed (REM or other)

More detailed definitions for individual facilities will be derived in the planning process to come. Some preliminary definitions are compiled below.

4. MASS FLOWS WITHIN A TYPICAL LUNAR LABORATORY:

1. DEFINITION OF MASS FLOWS BY TYPE OF MASS

During this initial development phase, only a minimum of production takes place on the Moon, such as simple raw material as fallout from the beneficiation process, e.g. native glass and free iron, and oxygen for life support or propulsion purposes. All this happens in a "pilot-production plant"(LF09), which replaces in this case all production facilities of the standard model LF09 through LF14. The recycling of water and air takes place in the habitat(LF03). This reduces the complete set of individual mass flows(omitted here) considerably as shown in the following list which suffices to illustrate this point:

m-01: lunar soil excavated and collected probes
from lunar environment to LF09 and LF01 respectively

m-02: slag, residues, rocks
from LF 09 to lunar environment

m-03: free iron, native glas extracted by beneficiation for further processing
from LF09 to LF04

m-04: beneficiated soil (ore) for oxygen production
within LF09

m-07: residual anorganic waste material for dumping into lunar environment
from LF04 and LF09 to lunar environment

m-09: research products for export
from LF01 to LF05

m-12: imported construction material
from LF05 to LF04

m-23: non- reusable space vehicles for other uses , disassembly and salvaging
from LF08 to LF04

m-24: defective equipment from lunar facilities for disassembly and salvaging
from all LF toLF04

m-25: salvaged parts from defective equipment for further use
from LF04 to LF05

m-26: imported hydrogen for consumption
from LF05 to LF09

m-27: imported oxygen for consumption
from LF05 to LF03

m-28: lunar gaseous products other than oxygen and hydrogen
from LF09to LF05

m-29: lunar produced oxygen gas for consumption by lunar biological systems
from LF09 and LF13 to LF03(and other inhabited facilities)

m-30: lunar produced liquid oxygen
from LF09to LF05

m-31: lunar produced gasous hydrogen for lunar use
from LF09 to LF05

m-33: imported spare parts required for repairs and replacements
from LF05 to LF04

m-34: imported new equipment required for the extension of lunar facilities
from LF05 to LF04

m-35: CO_2 produced within lunar base facilities for storage and later recycling
from LF03 (and all other inhabited facilities) to LF05

m-36: surplus organic waste and used water
from LF03 (and all other inhabited facilities) to LF05
m-39: imported food and water
from LF05 to LF03
m-41: imported nitrogen required for air leakage replacement
from LF05 to LF13
m-43: imported consumables/supplies for crew and operational support
from LF05 to LF03
m-44: imported operating consumables for lunar power plants
from LF05 to LF06
m-46: air and operating gas leakage into lunar atmosphere
from LF03(and all other inhabited LF) to lunar environment
m-50:lunar personnel and their personal belongings
from LF08 to LF03 and back and between all LF

This list would have to be extended if the lunar laboratory grows to a lunar industrial park with an increased number of products manufactured!

2. DEFINITION OF MASS FLOWS BY FACILITY

All lunar facilities -after initial placement on the lunar surface - have at least the following mass flows to be operable with the potential to be enlarged in case of additional capacities:

INPUTS =

imported construction material (m-12)
\+ imported spares (m-33)
\+ imported new equipment(m-34)

and in case lunar production facilities are in operation also:

\+ lunar produced construction material for repairs & replacements(m-57)
\+ lunar fabricated products for repair and replacements (m-58)
\+ lunar produced assemblies for repair and replacements (m-59)
\+ lunar produced raw material for extensions (m-53)
\+ lunar produced construction material for extensions(m-54)
\+ lunar fabricated products for extensions (m-55)
\+ lunar produced assemblies for extensions (m-56)

OUTPUTS=

defective equipment for dissassembly (m-24)
\+ anorganic waste material for dump (m-07)

and in case lunar production facilities are in operation also:

\+ anorganic scrap for recycling in lunar facilities (m-10)

All lunar facilities with crews working in a shirt-sleeve environment have the following *additional* mass flows:

INPUTS=

lunar personnel and their personal belongings (m-50)
\+ imported food and water (m-39)
\+ food,water and air produced by lunar facilities (m-37)
\+ imported oxygen gas for consumption (m-27)
\+ lunar produced oxygen gas for consumption (m-29)
\+ imported hydrogen gas for consumption(m-26)
\+ lunar produced gaseous hydrogen (for water prod.) - (m-32)
\+ imported nitrogen required for replacement of air leakage (m-41)
\+ imported consumables for crew and operational support (m-44)

OUTPUTS=

lunar personnel and their personal belongings (m-50)
\+ air and operating gas leakage into lunar atmosphere (m-46)
\+ CO2 produced within lunar facilities (m-35)
\+ organic waste and used water (m-36)
\+ residual organic waste material for dump (m-47)

When simulating, these mass flows can be assigned to one facility only ,assuming they are distributed from there. This will considerably simplify the model!

3. RELATIONS BETWEEN MASS FLOWS AND FACILITIES

Individual mass flows within this lunar infrastructure and their nature can be illustrated in a simple matrix with elements in top line inputs into elements in the first column elements providing the output mass-flows.

Tab. 4-1: Overview of the relationships between massflows and facilities

	M 1	M 2	M 3	M 4	M 5	M 6	M 7	M 8	M 9	M10
M 1	-	-	-	2	-	-	-	-	-	-
M 2	-	2	5	2,6,7	6,7,8	8	9	9	9,11	-
M 3	-	10	-	2	-	-	-	-	-	-
M 4	1	1	1	1,2	1	1	1	1	1	1
M 5	3	3	3	2,3	3	3	3	3	3	3
M 6	4	4	4	2	4	-	4	4	4	-
M 7	-	-	-	2	-	-	-	-	-	-
M 8	-	-	-	2	-	-	-	-	-	-
M 9	-	12	-	2,12	12	12	-	-	-	-
M10	-	-	-	2	-	-	-	-	-	-

Legend:

Facilities:

M 1 = Research laboratories
M 2 = Production facilities
M 3 = Habitat
M 4 = Maintenance shop
M 5 = Assembly shop
M 6 = Storage facility
M 7 = Carpool
M 8 = Power plant
M 9 = Lunar spaceport
M10= Control center

Type of mass flow:

1 = spare-parts
2 = scrap-metal
3 = construction components
4 = operating consumables
5 = food,water,air
6 = tools
7 = semi finished products
8 = technical gases
9 = propellants
10 = biological waste and trash
11 = exports
12 = imports

The INPUTS and OUTPUTS listed above are the basic mass flows of lunar facilities in general and for inhabited facilities in particular. One can also summarize the facility specific flows in the following manner:

Tab.4-2: Facility specific mass flows

LUNAR FACILITY	SPECIFIC INPUTS	SPECIFIC OUTPUTS
LF01: Research Labs	lunar soil (m-01)	research products (m-09)
LF02: Control Center	-	-
LF03: Habitats	imported food and water (m-39) lunar produced food,water and air(m-37)	organic waste and used water (m-36)
LF04: Workshop	imported construction material (m-12) imported spare parts (m-33) imported new equipment (m-34) lunar prod.raw mat. for extensions(m-53) lunar prod.constr.mat. for extensions (m-54) lunar fabr.products for extensions (m-55) lunar prod.assemblies for extensions (m-56) lunar prod.constr.mat. for repairs & repl.(m-57) lunar fabr.products for repairs & repl.(m-58) lunar prof.assemblies for repairs & repl.(m-59)	same , after rework and adjustment to all lunar facilities as required for repairs, replacements or extensions of facilities and equipment
LF05:Storage	all imports and exports from and to lunar spaceport	to individual lunar facilities as required with or without delay
LF06: Power Plants	imported operating consumables (m-44)	no masses but thermal & el.energy
LF07: Car Pool	-	-
LF08: Lunar spaceport	all imports (m-103)	all exports(m-104)
LF09: Mining facility	lunar soil (m-01)	slag,residuels,rocks(m-02) free iron,nat. glass (m-03) beneficiated soil (m-04)

LF-10: Chemical Processing Facility	beneficiated soil (m-04) imported solid chemicals (m-05) imported nitrogen (m-41)	raw material for mech. processing (m-06) residual anorganic waste (07) lunar oxygen (m-29/30) lunar hydrogen(m-30/31) mixed lunar gases (m-100) raw material for consumption (m-51) raw material for extensions (m-53) solid raw material for export (m-08)
LF11: Mechanical Processing Facility	imported material required for mechanical processing (m-11)	constr.mat.& feedstock for fabrication (m-14) constr.mat.& feedstock for export (m-13) constr.material fo lun. fac.extensions(m-54) constr.mat. for lun. fac. repairs & repl. (m-57)
LF12: Fabrication Facility	imported products for fabrication processes (m-15)	fabricated products for assembly (m-17) fabricated products for export (m-18) fabricated products for lun.consumption(m-52) fabricated products for lun.fac.extens. (m-55) fabricated prod. for lun. fac.repair & repl.(m-58)
LF13: Biological Processing Facility	imported oxygen gas for consumption (m-27) imported hydrogen for consumption (m-26) lunar produced oxygen gas for consump.(m-29) lunar produced hydrogen gas for consump.(m-31) lunar prod.CO2 (m-35) organic waste and used water (m-36) imported nitrogen (m-41) imported supplies for lunar food prod. (m-42)	food,water and air(m-37) residual organic waste for dump (m-47)

LF14: Assembly Facility	imported subassemblies and components req.for assembly processes(m-20) lunar fabricated products for assembly (m-17)	assemblies for export (m-21) lun.prod.assemblies for extension of lunar fac.&equipment (m-56) lun.prod.assemblies for repair & replacement of lun.fac.& equipment (m-59)

When modeling mass flows in terms of interrelated mathematical equations , the following rules may be observed:

(a) The mass of "defective equipment"(m-24) leaving a facility and the mass of "spare parts"(m-33 + m-58) replacing this equipment have identical mass by definition.

(b) All air losses originating from pressurized facilities allowing normal working conditions, may be assigned to the habitat (LF03) to simplify the model.

(c) All water losses originating from inhabited or producing facilities are assigned to the biological production facilities(LF13) to simplify the model.

(d) Some of the raw materials representing the output of the chemical facility can not be processed further immediately due to lack of suitable equipment. This valuable raw material goes to an interim storage. It will be drawn from this storage instead from lunar soil with some delay in due time of the life cycle.

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(e) All crew members are moving daily from the habitat to their workstations. The mass of these crew members have to be multiplied with the average length of the trip and the number of trips per annum to obtain the total mass of the personnel to be moved from the habitat to their duty stations and back.

5. PRELIMINARY DESCRIPTIONS AND SPECIFICATIONS OF LUNAR FACILITIES

LF 01: Research Facilities and Equipment

Initially, complete laboratory modules will be transported to the Moon to provide work space and equipment for priority research tasks. The size of these initial laboratories with respect to mass and volume will depend on the capability of the lunar space transportation system. It is likely that these modules will be modifications of those used as elements of the space station in Earth orbit. They should have their own life support system and power supply for emergency operations. As soon as possible these module will be integrated in the lunar facilities network. - Later research modules will be larger and equiped for selected disciplines, e.g.space biology, physics and geology. These laboratory modules will be ocupied by their users only during their tours of duty.

LF02: Control Facility & Equipment requirements for a lunar base.

The nodes applicable to these functions shall include the Earth-based mission control and the the lunar base control center. All communications related functions shall rely on appropriate international standards of interoperability. Telecommunications systems should be capabale of rates up to 10 Mb per sec.
The capability for integrated voice, video and data must be provided for communications in both Earth to Moon and Moon to Earth direction, as well as all equipment required for supervising the dispersed elements on the lunar surface.
The facilities providing room and equipment for the functions of telecommunications, navigation and information management will be located in the lunar base control center. This might be a separate module or be part of the habitat. Provision must be made for real-time communications as well as store and forward modes of operations.

LF03 : Habitat

The habitat houses the lunar crew and provides all support functions required to sustain life and insure the health of the people living on the Moon. This requires a certain amount of floor space and volume for the facilities comprising the habitat. There will probably several sizes of modules depending on the transportation capacility (mass and volume) of the space transportation systems available. In general it can be concluded, that these modules should be fully equiped, functional and be large enough to minimize the assembly labor and checkout activities on the Moon due to the high lunar labor cost. There will be a strong interaction with the socalled "lunar farm" because it is there where all the recycling of air,water and biological wastes will take place under standard operational procedures.

LF04 Maintenance and Repair-Facilities

A lunar base is a highly complex technical system. The home base is 385 000 km away. Initially only quarterly supply flights may be available. Repairs will offen have to be done quickly, requiring a versatile repair capability at the lunar base to take care of all maintenance tasks. This maintenace and repair workshop has to be in place and functional at the time the first lunar crew arrives. The largest possible module, fully equiped including an emergency power supply, is the most desirable solution to this problem. The assembly of the individual elements arriving in individual packages - some probably damaged or with technical faults - requires manual labor and repair operations. This initial facility should have a mechanical, an electrical and an electronic workshop with all neccessary tools and machines. There should also be a sizable storage of spare parts and materials. -
This maintenace and repair facility might be combined with the assembly facility in one complex, if the payload capability of the space transportation system permits. This is desirable from the viewpoint of effectiveness in terms of mass, energy and human labor.

LF05 Storage Facilities

The lunar base requires storage facilities for food, spares and propellants. These commodities can be stored in a central facility or in available elements of other facilities. Propellant storage facilities are required early during the acquisition period, since refueling the return vehicles on the Moon will be an essential feature of the space transportation system. Lunar landers stranded on the Moon, or one way space vehicles transporting cargo to the Moon in the early phase, should be designed in such a way, that their tanks can serve as storages for gases and liquids. Later in the lunar development lifecycle additional storage capacity is required for export goods awaiting shipment to their destinations.

LF06 Lunar Power Plants

Without operable power supplies on the lunar surface there can be no operations of robots and/or people on the Moon. During the early exploration of the Moon the lunar probes required tens to hundreds of watts, the first lunar astronauts had a few kilowatts available. In the future there may be the following users of lunar power :

1. Automatic installations on the lunar surface,
2. Lunar facilities operated by and for humans,
3. Operators of lunar production facilities,
   manufacturing construction material, gases or propellants etc.,
4. Electrically driven surface transportation systems,
5. Electrically driven space transportation systems,
6. Space based consumers of electrical power communication, propulsion etc.,
7. Earth based consumers of laser or microwave power.

The key to operate a lunar installation is a lunar power plant, that must provide all the thermal and electric power required by the other lunar facilities during lunar day and night. It is quite obvious that several energy systems and technologies must be employed for reasons of redundancy and economy. Energy systems have

thus to be defined as well as criteria to select a combination of these systems for each phase of lunar development.
In principle there is a *choice of combinations* among the following alternatives:
1. Solar power plants producing thermal energy
2. Solar power plants producing electric energy
3. Nuclear power plants to provide process-energy and electric energy
4. Fuel cell power plants providing electric energy and water
5. Mechanical energy storage systems and converters.

Each concept of a lunar installation requires a specific optimized acquisition and development plan for the entire life-cycle.*Typical criteria* for selecting the "optimum" combination of systems in due course of developing the lunar infrastructure are:
1. Availability of specified power levels during lunar day and night
2. Reliable service
3. Safety to lunar personnel
4. Transportation mass and volume requirements to the Moon
5. Assembly and maintenance requirements on the Moon
6. Feasible and practical growth rates
7. Life cycle specific cost.

LF07 : Carpool and Road Infrastructure

Mobility of the lunar crew is an essential prerequisite for lunar base development and operation.The modules of the lunar base camp cannot be assembled without some equipment to move them from their landing spots to the selected base site. In addition the following functions require transportation equipment:
- preparation of construction sites
- preparation of road beds
- transportation of cargo, construction material and personnel
- transportation of equipment within and near the base camp
- transportation of crews on field trips
- transportation of minerals and raw materials to the production facilities.

The minimum equipment requirements in this facility for the initial phase of the lunar base buildup are:
- two lunar rovers for the transport of several suited astronauts and their equipment of several hundred kilograms,
- two multi-purpose trucks housing a small crew (2-6) in a shirtsleeve environment for trips up to 8 hours and a capacity for several tons of cargo,
- a mobile crane with a capacity of 50 tons,
- a trailer with a 30 kW fuel cell battery for power supply,
- a trailer for transporting the largest facility module and other loads with up to 100 tons,
- a front-end loader for grading the landscape and moving rocks.

These vehicles and associated equipment will have a mass of at least 50 tons, but no more than 100 tons, it should be transported to the lunar base site prior to the landing of the first lunar construction crew.
A central car-pool maintenance shop will have to be provided for the maintenance and repair of all surface vehicles. Initially there will be only soft roads cleaned of rocks and compressed by the mass of the vehicles only. Some roads, which are

frequently used , will be hardenend possibly with crushed rocks, iron or aluminum plates prefereably produced on the Moon .

LF08: Lunar Spaceport

During the acquisition phase the following functions will have to be performed:
- selection of construction site for spaceport
- preparation of ground surface
- road construction between spaceport and other lunar base facilities
- installment of fixed equipment
- placement of permanent facilities.

During the operational phase the following functions will have to be performed:
- landing and launch flight control including communication
- loading and unloading of cargo and personnel
- propellant transfer
- vehicle checkout and countdown
- maintenance and repairs of space vehicles
- disassembly of decommissioned space vehicles
- maintenace and repair of ground equipment and facilities
- expansion of spaceport facilities.

The first facility modules and pieces of equipment will be landed automaticly in an unprepared landing area close to the selected base site. The distance between the "payloads" landed by the lunar bus will be about 200 meters, but has to be far enough from eachother, so that they are not damaged by dust and rocks thrown up by the rocket engine plumes during hovering maneuvers or the tuchdown.
One of the first jobs of the initial crew will be to prepare a regular landing site at a distance from the base camp of about 2 km. Two launch- and landing pads will be needed to ensure steady readiness. The surface around the pads will be hardened with crushed rocks and/or covered with metal plates to avoid damaging the equipment by flying objects.
The following handling equipment will be required early in the lunar base buildup :
- pad markers
- fuell cell power cart
- electric cord system
- propellant tanker vehicle
- supplemental cooling cart
- cargo transporters
- crew transporters
- passenger transfer tunnel
- propellant storage tanks
- service crew habitat with airlock
- various lifting devices for unloading space vehicles.

A preliminary analysis indicates that the total mass of the initial equipment is on the order of 65 tons, but less than 100 tons. Some hundred labor days will be required to prepare this initial lunar spaceport during the first few months of the lunar base acquisition period. The total mass of the lunar spaceport facilities, the annual mass of spareparts and consumables, and the lunar labor required is a function of the number of landings and launches. The operating cost will be prorated over the number of launches and landings. This will result in a certain charge of x $/kg of cargo arriving or departing the lunar spaceport or y $/ per passenger de- or embarking there.

LF09 : Mining Facilities

The initial mining operations will be modest in size. A strip mine might be located a few kilometers from the beneficiation module which is close to the base camp. An electrical driven front-end loader excavates the lunar soil and carries it to a hauler truck. This hauler transports the lunar soil to a beneficiation module. In a typical example, this activity including loading,transporting, unloading and return to the strip mine takes about 172 minutes. On this basis an average of 27 400 tons of raw material would be excavated per year. In the beneficiation module the large rocks will be sorted out, the small rocks will be crashed to pieces of less than a few millimeters diameter. At this point natural glass and iron will be separated and enters special production processes for glass wool and sintered products. The finer soil will be transfered to the oxygen plant.

LF10 : Chemical Processing Facilities

On the bases of all available studies made till now, it can be concluded that the production of lunar propellants, particularly *Lunar Oxygen* (LULOX) will be the key to any future lunar development. If this is not assured, there will be probably no return to the Moon to stay there permanantly .
Potential users and buyers of lunar propellants are:

1. The operator of lunar surface vehicles and rocket driven lunar hoppers for refueling the vehicles on the lunar surface,
2. The operator of lunar launch- and landing vehicles required for the logistic support of the lunar base and lunar installtions on the lunar surface
3. The operator of the transportation system serving the Earth Spaceport - lunar orbit space operation center leg for refueling return-propellants in lunar orbit ,
4. The operator of space operation centers for attidude and orbit control,
5. The exporter of lunar products to other destinations in space .

There are several processes available for the production of oxygen. Initialy the hydrogen reduction process is favoured because of its simplicity and low power requirement. But there are several others which would produce also other gases and materials needed on the Moon or for export. These are discussed extensively in the literature e.g. such processes as:

1. Hydrogen reduction of ilmenite
2. Direct electrolytic reduction of oxide melts
3. Hydrogen sulfat reduction of metal oxides
4. Electrolytic reduction of oxides
5. Fluorination of oxides
6. Reduction of metal oxides by Li or Na
7. Carbo-thermal reduction of Ilmenite and other oxides by methane, CO and other C-H compounds
8. Carboclorination of Anorthit and Ilmenite

9. Reduction of plagioclase w/Al, w/electrolysis
10. HF-Acid Leach with electrolytic reduction
11. Vapor Phase reduction
12. Ion-Separation

Each of these processes require special equipment packaging in such a way that it can easily be transported to the Moon and installed in a major production plant. It production requirements are high, these installation will arrive in complete modules ready to go into operation.

Present models of larger production activities in lunar chemical facilities assume production rates of 6 200 metric tons p.a. up to 83 000 metric tons. Assuming a 16 hour working day and 300 days p.a. operation (= 4800 h), this requires an hourly production rate of 1 300 kg to 17 300 kg . If this is connected with human labor for supervison and repairs with 3 and up to 80 people working 8 hours a day, this would result in specific performance between 430 kg/person-hour improving to 220 kg/person-hour at high production rates.

LF11: Mechanical processing facilities (furnaces, mills, presses, machine tools)

Most the raw materials produced by chemical processes, require additional work. This takes place in the mechanical workshop. This shop has all the machinery and equpment required to convert the raw material into the desired products at the specified production rate. This can not be done without manual labor, although mostly automatic processing will be employed. A detailed manufacturing plan is required to determine the number and size of production equipment, tools and machinery required.

LF12: Fabrication facilities (for structures, solar cells. cable trees, radiators etc.)

More complex products will be manufactured in the fabrication shop, requiring individual processes most employing manual labor in a shirtsleve environment. Radiators are are a typical example of the products manufactured in this facility because it will be important element of any lunar habitat and power plant. At 650°K a radiator on the Moon will require about 0.1 m^2/kW surface. The specific mass for heatpipe radiators is about 5 kg/m^2. Advanced liquid droplet radiators require 0.7 m^2/kW and a specific mass of 0.11-0.15 is projected for the future.

LF 13 : Biological Production Facilities (Lunar Farm)

The production of biological products, primarily food, will probably go through three evolutionary phases:

(1) A laboratory sized facility will be used during the first years of a lunar base for experiments under lunar environmental conditions. Various preselected products (at a rate of no more than 1 kg/day bio-mass) will be tested with respect to their growth rates and nutrional values, mass, energy and human labor requirements.

Processes will be highly automated and observed partly by tele-operation from Earth. The purpose is to collect better design information for a larger pilot plant.
(2) A large standard module will be equiped with a complete set of equipment to grow a balanced mix of biological systems with a minimum of energy and human labor at a rate of about 10 kg mass/day. It will reduce the amount of imports somewhat, but would not yet be compatible with the needs of the full lunar crew. The goal is to make a multi-year large scale experiment to determine the working conditions and requirements for a sizable farm which can eventually satisfy the nutritional and psychological needs of the lunar population to a large extent. This module, derived from the standard 100 ton cargo module, has a volume of 1850 m^3 and a floor space of up to 900 m^2, if eight floors are selected. Temperature control is provided by a semi-passive system, e.g.movable shades with different coatings. Daylight will be provided by a special optical system to maximize growth conditions.
(3) The last step of this development is a lunar farm sized for the lunar crew, requiring about 50m^2 per person, growing with time in a cost-effective evolutionary scenario of lunar settlement. In such a lunar farm about 35 kW/person would be needed for food production during the lunar night, resulting in an effective light power of 200 W/m^2 with a power input of 600 W/m^2, if the efficiency of natrium lamps is taken into consideration. In addition electric heaters are required to insure an operating temperature of 27°C. Some conceptional designs have been made of lunar farms with volumes up to 160 000 m^3 and floor spaces of 8 000 m^2. This would lead to a closed system in which all bio-mass would be recycled.

During the first years of a lunar base, or in case of a small temporary lunar outpost, an open ECLS system will probably be used due its simplicity, requiring the smallest possible number of scarce labor hours.

<u>LF14: Assembly facilities and equipment (tools, jigs, shops).</u>

As the elements of lunar facilities are transported to the Moon, some require assembly to larger units. This assembly can take plave in the open requiring extravehicular activies (EVA) or within a protected area. Also the expansion of lunar facilities in due course of the development will lead to production of facility elements on the Moon which have to be combined with imported components. This work has to be accomplished in the lunar "assembly facility". It must also allow to do part of the work under shirtsleve conditions (IVA). It is clear that this activity requires also fixtures and special equipment, mostly imported from the Earth.

6.LUNAR BASE SYSTEM STATE VARIABLES AND PERFORMANCE INDICATORS

The operation of a lunar base will be characterized by the values of time dependend variables. It is essential to define these system variables to be able to compare the behaviour and performance of any lunar installation and/or activity.

1. STATE VARIABLES

The following one dimensional state variables of a lunar base on an annual and/or life-cycle basis, determined by system evaluations of individual concepts and models, are deemed desirable for comparisons:

Population:

01. Total lunar population (persons)
02. Lunar workforce (persons)
03. Death rate (% of total population)
04. Birth rate (% of total lunar population)
05. Average yearly labor-hours performed by lunar workforce (hours)
06. Share of lunar science labor-years (%)
07. Share of lunar production & manufacturing labor-years(%)
08. Passenger transportation volume on lunar surface (passenger * km)

Infrastructure:

01. Total mass installed within the lunar complex (t during LC)
02. Masses of individual lunar facilities (t)
03. Share of facility mass imported from the Earth (%)
04. Total power installed within the lunar complex (MW)
05. Total power installed on the Moon(MW)
06. Total power installed in lunar orbit (MW)
07. Consumption of thermal power (kWh)
08. Consumption of electric power (kWh)
09. Length of power lines available on the Moon (km)
10. Length of soft roads available on the Moon (km)
11. Length of hardened roads available on the Moon(km)

Products:

01. Total mass of lunar products (t)
02. Total mass of lunar products for lunar base use (t)
03. Total mass exported or returned to Earth from the lunar base (t)
04. Total mass of lunar propellants produced for space vehicles (t)
05. Total mass imported to the lunar base (t)
06. Total mass of propellants for space vehicles imported (t)
07. Facility & equipment mass imported (t)
08. Other imports for consumption (t)
09. Freight transported on the lunar surface (t * km)
10. Total mass of operating gases lost to the lunar environment (t)
11. Total mass of propellants injected into the lunar environment (t)
12. Total mass recycled within lunar base (t)
13. Number of books,patents and other intellectual products of lunar origin(-)
14. Amount of data stored on the Moon (MB)

Economical variables:
01. Total sales of lunar products and services ($)
02. Total investments in the lunar base program ($)
03. Total commercial investments in the lunar base program ($)
04.Total no.of labor-years on Earth in direct support of the lunar complex (years)
05. Distribution of lunar base acquisition and operation costs versus time ($ p.a.)

2. INDICATORS OF ECONOMICAL PERFORMANCE
of a lunar base composed of *two state-variables* (excluding space transportation) - Cumulative or per annum:

01. Annual budget of the lunar base/ lunar population ($/person)
02. Annual Earth support budget for the lunar base/global military expenditures (%)
03. Annual Earth support buget for the lunar base / global expenses for research & development (%)
04. Commercial investments in the lunar base/ total lunar investments (%)
05. Investments in the lunar base infrastructure/ mass of lunar infrastructure ($/t)
06. Total sales of lunar products and services/annual budget of the lunar base (%)
07. Specific cost of lunar products ($/kg)
08. Specific labor-cost for lunar services ($/labor-year).
09. Earth labor years/lunar labor-years (Earth years/lunar years))
10. Cost of a labor-years performed on the Moon/cost of a labor-year on Earth(-)

3 . OTHER PERFORMANCE INDICATORS
than economical- or of the space transportation system performance indicators, cumulative and/or cumulative over the life-cycle:

01. Degree of goal achievement for the entire lunar development program (%).
02. Share of self-sustenance (internal manufactured supplies/total supplies) - (%).
03. Share of lunar fabricated products used on the Moon (%).
04. Share of lunar produced facilities(%).
05. Share of lunar produced supplies (%).
06. Mass of lunar products exported/mass of products imported (-).
07. Total mass of lunar facilities/lunar population (t/person).
08. Productivity of the lunar crew (t/labor-year or per person-hour).
09. Productivity of lunar facilities (total products p.a./t facilities installed).
10. Energy consumption/ lunar population (kWh/person).
11. Energy consumption/mass of lunar products (kWh/kg).
12. Total length of hardened roads on the Moon /lunar population(km/person).
13. Freight volume transported to the Moon/ mass of lunar products (t *km/t).
14. Labor years performed on the Moon / lunar population (%).
15. Data rates on communication links between Moon and Earth (MB/year)

After defining in which way the performance of a lunar base including all of its possible activities, we can now go to the description of such activities with emphasis on the early years.

7. TYPICAL ACQUISITION SCHEDULE

The aquisition and the operation of a lunar installation, whether a small lunar laboratory or a lunar settlement is a rather complex process. This is best illustrated by an example of what kind of activity is likely to be required if and when such a lunar base is realized. A relatively modest lunar base is selected as an example to illustrate the development sequence and the initial activation activities. These are described below up to the point of initial beneficial occupancy. It sketches also the first 1000 days of the lunar base.

Tab.7-1: Typical schedule for base activation during the first lunar day

STEP	Time period - from -to	ACTIVITIES
1	x - 13 years to x-4	Project initiation: Planning, research, pre-development
2	x-4 years to x+3 years	Primary development: module & equipment development, site preparation, placement of infrastructure elements
3	x-1 year to day x	Deployment of initial modules: transportation of initial equipment to the lunar site,manned scouting trips from orbit
4	day x	Landing of the first permanent crew The first 6 members of a 12 person crew arrives at the base site
5	day 2 to 12(1st lunar day)	Assembly of initial base complex: positioning of modules,equipment and supplies,checkout and activation of base
6	day 13 to 90	Infrastructure development: completion of initial infrastructure development phase
7	day 91 to day 274	Initial lunar science program: Priority lunar science facilities are set up and activated, long term experiments are activated after arrival of the 2nd 6 person crew
8	day 275 to day 640	Lunar Base extension: the lunar infrastructure, facilities and equipment are extended to a capacity of 24 lunar crew members,
9	day 641 to day 1000	Pilot plant activation: A major production facility to produce liquid oxygen and construction material is activated and operated to full capacity
10.	day 1001 and after	Lunar Base utilization

The events during the fifth step of the initial base activation covering the first lunar day would see typically the following activities:

Tab.7-2: Acquisition timeline and labor-hours during the first lunar day

event	Activity	labor-hours	day number
1.	landing of 1st permanent crew	12	1
2.	activation of permanent communication links	10 EVA	1
3.	assembly of thermal radiator	20 EVA	1 +
4.	assembly of airlock and prime habitat module	10 EVA	1
5.	checkout of crew return vehicle for emergency oper.	16	2-3
6.	preliminary checkout of (nuclear) power plant	8 EVA	2-3
7.	unpacking supplies and equipment	24 EVA	2
8.	assembly and checkout of solar power subsystem	24 EVA	2
9.	tele-ckeckout of lunar modules	24	2
10.	unloading and checkout of lunar rover	8 EVA	2
11.	unloading and checkout of lunar truck	16 EVA	2
12.	siting of lunar spaceport	16 EVA	2
13.	ckeckout of nodes and remaining airlock modules	24	2-4
14.	siting of all remaining modules at final location	16 EVA	3
15.	preparation of road between base site & spaceport	40 EVA	4-6
16.	preparation of spaceport site	40 EVA	6-12
17.	siting and preparing site for nuclear power plant	24 EVA	4-5
18.	moving return vehicle to lunar spaceport	24 EVA	6-8
19.	checkout of return vehicle at lunar spaceport	40	9-10
20.	secure propellant reserves near return vehicle	24	11-12
21.	transport of remaining modules to final site	40 EVA	4-5
22.	installing nuclear power plant at prepared site	16EVA	6
23.	checkout of additional modules & equipment	32	4-5
24.	connecting nuclear power plant to user facilities	8	7
25.	activating nuclear power plant	8	8
26.	integration test of all elements of lunar power plant	8	9
27.	installing radiation shields on habitat modules	24	5-6
28.	ckeckout of integrated facility modules	32	5-7
29.	integrated ckeckout of completed lunar base	20	9-10
30.	preparation of waste storage facility for operation	24	10-11
31.	increase radiation shielding in critical areas	36	11-12
32.	final external inspection of lunar base elements	30 EVA	12
33.	celebration of initial operational capability at sunset	12	13

The first lunar night will be used for resting, maintenace and repairs, preparation of scientific activities and detailed planning for the second lunar day. Detailed communication with the Earth support base will take a great amount of time. There must also be ample time to relax and communicate with family members of the lunar crew.

A critical parameter is the availability of thermal and electric power on the Moon. Also in this case an example illustrates the power level and growth rates required.

Tab. 7-3: Estimated growth of lunar power demand :

time period - day no. x +	1-12	13-90	91-274	275-640	641-1000	total
solar subsystem power level	+75	+75	+150	+600	+900	1800
fuel cell subsystem power level	+30	+30	+40	-	-	100
nuclear subsystem power level	+100	+100	+100	+300	-	600
tot.installed power level(kW)	205	+205	+290	+900	+900	2500
solar subsystem mass	16	16	32	135	200	400
fuel subsystem mass	4	4	5	-	-	13
nuclear subsystem mass	5	-	-	6	-	12
total mass of power plant (MT)	25	20	37	141	200	425
solar subsystem labor	30	30	50	150	200	460
fuel cell subsystem labor	80	80	100	-	-	260
nuclear subsystem labor	90	-	-	90	-	180
total man-power (hours)	200	110	150	240	200	900

These power demands and other demands require a certain growth of the mass of lunar facilities. This growth is a function of the atate of the art available at the time prior to the acquisition. In the selected case, the mass of lunar base facilities, including equipment, but excluding the lunar soil used for radiation protection will grow along the folowing lines:

Tab.7-4: Estimated growth of lunar facility mass

At day x + 12 = 320 t
during the period from day 13 to 90 growing by 140 t to a total of 460 t
during the period from day 91 to 274 growing by 180 t to a total of 640 t
during the period from day 275 to 640 growing by 460 t to a total of 1100 t
during the period from day 641 to 1000 growing by 300 t to a total of 1400 t.

In addition to power and mass the labor demend will drive the rate of lunar base growth. Our example shows the following characteristics.

Tab.7-5: Distribution of labor-hours over the individual periods and activities:

TIME PERIOD	ACTIVITIES	labor-hours	sub-total lab.hrs.
day x + 1	checking modules site preparation communications	10 80 10	100
day 2 to 12	installing modules road preparation power system maintenance	300 250 230 12	792
day13 to 90	road construction science maintenance	3680 1000 72	4752
day 91-274	workshop modules schience power system road construction spaceport maintenance	100 1000 1600 2000 2800 4000 164	11664
day275 to 640	pilot production mining modules science waste processing power system maintenance	15000 5000 2000 15000 1300 6000 628	44928
day 641 to 1000	production mining modules science waste processing power system road construction spaceport maintenance	30000 10000 500 25000 5000 10000 4600 4000 756	89856

This adds up to a total of 152 092 labor hours during the first 1000 days of the initial lunar base. With a crew of 12 in the first year, of 24 in the second year and 48 in the third year, there are approximately 84 labour-years available,leading to about 1800 hours per year per crew member, which appears realistic for this early phase of development.

8.TYPICAL LUNAR SCIENCE PROGRAM

As shown above, this first major task after arrival of-the first lunar crew will the the activation of all facilities. Bebeficial occupancy is the primary goal. But the next urgent task is the initiation of a science program, that has distinct priorities. These are presented in this chapter for a more complete understanding of the skills required early the the lunar base development program. This phase of the program is part of the overall lunar science program the structure of which is shown first.

1. STRUCTURE OF AN EVOLUTIONARY LUNAR SCIENCE PROGRAM

PHASE A : ROBOTIC EXPLORATION

1. Orbital investigations:
   - Imagery with 10 m resolution of the entire Moon
   - Gamma ray spectrometry
   - X - ray spectrometry
   - neutron spectrometry (composition, including water at poles)
   - infrared spectral imaging in support of mineralogy
   - altemetry
   - gravity field measurements
2. Surface investigations:
   - Local composition in special areas (Copernicus central peak,Reiner Gamma)
   - characterization of permanently shadowed regions
   - atmospheric detectors
   - seismology
   - robotic telescopes, sensors
3. Sample return from special and common areas
4. Technological demonstrations
   - science rover
   - resource extraction

PHASE B : PILOTED EXPEDITIONS

1. Local to regional geological investigations and sample collection
2. Emplacement and testing of intermediate scale prototype telescopes
3. Subsurface investigations
4. Advanced seismology; heat flow; remanent magnetism experiment

PHASE C : TEMPORARY LUNAR OUTPOST

1. Larger telescopic facilities (initial interferometer array)
2. Lunar environment monitors (during human occupancy)
3. Regional geological investigation and sampling
4. Demonstration of iterative sampling/analysis to address detailed problems
5. Deep sub-surface sampling (drilling)
6. Physics experiments (heat, cold, vacuum evaporation)
7. Resource extraction technology demonstrations

PHASE D : PERMANENT LUNAR BASE

1. Astronomical observatory with several instruments
2. Long-distance exploration
3. High energy physics demonstration experiments (X-ray telescope,cosmic ray, neutrino detectors),
4. Closed ecological system studies, bio-diversity studies, psychologigal studies,
5. Geophysical characterization of lava tubes
6. Navigational network associated with Earth-Moon dynamics measurements,
7. Lunar particle flux detectors, characterization of micrometeorids, secondary impact ejecta,
8. Solar wind observatory.

PHASE E : LUNAR INDUSTRIAL PARK

1. Manipulation of lunar environment
2. Three dimensional studies of lunar regolith associated with lunar mining
3. Environmental monitoring
4. Active experiments - behaviour of lunar materials to support agriculture
5. Closed ecological life systems, biological system research, continuation and eleboration of previous experiments.

PHASE F : LUNAR SETTLEMENT

1. Specialized scientific experiments
2. Very large arrays of optical interferometers
3. Detailed exploration of large impact craters
4. Exploration of young vulcanos
5. Search for active lunar phenomena

2. AN ILLUSTRATIVE LUNAR SCIENCE PROGRAM FOR THE FIRST 1000 DAYS AT A LUNAR BASE

Lunar Base Planning requires representative information on the mass and volume requirements for the equipment of the lunar science sub-program. Also an estimate of the human labour required on the Moon to install and operate this equipment is needed to arrive at the total logistic requirements. A typical lunar science program for the first three years may look as shown in the next table.
Deriving the relative priorities for these science activities, the following selection criteria were used:

- expected utility to lunar development
- expected utility to the general public on Earth
- expected economic utility
- expected gain of knowledge within the scientific community
- required resources on the lunar surface
- required resources on Earth
- availability of scientific skills of the lunar crew
- availability of suitable scientific equipment
- probability of successful experimentation.

Tab.8-1: Illustrative example of the structure, mass and labor requirements for an initial lunar research program

SCIENCE FIELD	labor hours	mass (kg)	Prior. 1.yr	Prior. 2.yr	Prior.- 3.yr	Aver. Prior.
A. ASTRONOMY	5000	15000				
A-1 Optical, UV/IR astronomy interferometry	1000	5000	11.	3.	4.	4.
A-2 Sub-mm astronomy interferometry	1000	5000	19.	18.	19.	22.
A-3 VLF Radio astronomy	3000	5000	18.	14.	18.	20.
B. LIFE SCIENCES	9300	9000				
B-1 Sociology,psychology man-machine interactions	950	400	2.	2.	2.	2.
B-2 Health support	2300	3100	6.	1.	8.	6.
B-3 Medical sciences	2750	400	1.	1.	2.	1.
B-4 Exobiology	1300	3200	15.	16.	17.	16.
B-5 Biology	2000	1900	17.	8.	16.	18.
M. MATERIAL SCIENCES	8400	23000				
M-1 Metallurgy	2500	10000	9.	17.	5.	10.
M-2 Applied technology	2500	10000	10.	9.	13.	15.
M-3 Material sciences	3400	3000	5.	5.	15.	9.
G. GEOPHYSICAL SCIENCES	15100	60000				
G-1 Cartography	1950	4000	4.	7.	6.	5.
G-2 Gravity	500	10000	13.	20.	1.	11.
G-3 Lunar atmosphere	850	4000	16.	13.	12.	14.
G-4 Mechanical experiments	1800	7000	3.	4.	3.	3.
G-5 Radiation	750	4000	8.	12.	7.	7.
G-6 Radio waves propagation	900	7000	21.	13.	9.	17.
G-7 Geology,petrology	6800	15000	7.	6.	11.	12.
G-8 Meterorites	850	6000	21.	15.	20.	19.
G-9 Vulcanism	700	3000	14.	10.	14.	13.
GRAND TOTAL	37200	127000				

With the help of the selection criteria defined above a tentative program was developed for the four time periods of this initial lunar science program, allowing 5 200 hours during the first nine months, 14 000 in the 2nd year and 18000 hours in the third year:

Tab.8-2: Research activities versus time at the initial lunar base

FIELD	1st Quarter hours/kg	2.+3.Quarter hours/kg	2nd year hours/kg	3rd year hours/kg
A- 1	-	500/2000	500/3000	100/100
A-2	-	-	500/2000	500/3000
A-3	-	-	1000/2000	2000/3000
sub-total	-	500/2000	2000/7000	2600/6100
B-1	50/100	100/100	400/100	400/100
B-2	100/300	200/800	1000/1000	1000/1000
B-3	350/100	400/100	1000/100	1000/100
B-4	-	100/500	600/900	600/1800
B-5	-	-	1000/900	1000/1000
sub-total	500/500	800/1500	4000/3000	4000/4000
M-1	-	-	500/2000	2000/8000
M-2	-	-	500/3000	2000/7000
M-3	-	400/1000	1000/1000	2000/1000
sub-total	-	400/1000	2000/6000	6000/16000
G-1	150/1000	400/1000	1000/1000	400/1000
G-2	-	-	-	500/10000
G-3	50/1000	200/1000	400/1000	200/1000
G-4	100/1000	200/1000	500/2000	1000/3000
G-5	50/1000	100/1000	400/1000	200/1000
G-6	-	200/1000	500/5000	200/1000
G-7	500/4500	900/5500	2400/3000	3000/2000
G-8	50/1000	100/2000	400/2000	300/1000
G-9	-	100/1000	400/1000	200/1000
sub-total	900/19500	2200/13500	6000/16000	6000/21000
TOTAL	1400/10000	3800/18000	14000/36000	18000/69000
% of available resources	23/30	32/6	33/8	19/24

These are "rough order of magnitude" (ROM) estimates to be improved upon.

3. DRAFT OF A LUNAR SCIENCE SUB-PROGRAM FOR THE SECOND 1000 DAYS OF A LUNAR BASE.

An analysis of such a phased program following the first 1000 days was carried out be a group of graduate students of the Technical University Berlin in 1989. This supplemental program to that described for the first 1000 days looks as follows:

Tab.8-3: A typical follow-on quarterly lunar science program for the years 4 to 6

	Research Field	labour hours	equip. mass-kg	average priority
A	**Astronomy**	273	1310	19
A-1a	- optical astronomy	30	110	20
A-1b	- optical astronomy	50	200	21
A-2	- infrared astronomy	20	100	23
A-3	- ultraviolet astronomy	35	200	21
A-4	- radio astronomy	30	450	20
A-5	- X-ray astronomy	38	150	18
A-6	- particle physics	70	100	13
B	**Life Sciences**	1140	1360	7
B-1	- sociology,psychology	180	80	2
B-2	- health support	300	500	7
B-3	- medical science	280	80	1
B-4	- exobiology	180	450	19
B-5	- biology	200	250	8
M	**Material Sciences**	1100	1500	5
M-1	- metallurgy	350	600	3
M-2	- applied technology	350	500	5
M-3	- material science	400	400	6
G	**Geophysical Sciences**	1380	5010	12
G-1	- cartography	120	250	10
G-2	- gravity	25	600	11
G-3	- lunar atmosphere	80	350	14
G-4	- mechanical experiments	120	650	9
G-5	- radiation	80	280	15
G-6	- radio wave propagation	60	580	16
G-7	- geology,petrology	800	2000	4
G-8	- meterorites	65	200	12
G-9	- vulcanism	30	100	17
	GRAND TOTAL -average per quarter	3893 hr	9180 kg	

All these examples have been selected for the purpose of illustration. Detailed plans have to be derived with participation of the scientists involved at a proper time. Thus these plans are subject to change in such a process. To implement a specific lunar science program a a given time all the details of proposed experiments have to be available to select the most relevant experiments and compose a program for execution. The information required of each experiment is as follows:

4. LIST OF INFORMATION REQUIRED OF EXPERIMENTS PROPOSED

If experiments are proposed for science & engineering of-, on- and from the Moon the following information is required for a complete evaluation and prioritization:

01. Name of the proposed experiment or project.
02. Name of the principal investigator or proposer.
03. Date of defining and describing the experiment or project.
04. Science or engineering field/discipline of the experiment or project.
05. Experiment or project group within field or discipline.
06. Objectives and purpose of the experiment or project, indicating new scientific information expected in the process.
07. Rational / justification of the experiment/project, indicating the probable user of this new information and potential applications.
08. Justification for need of lunar environment versus low Earth orbit environment in a space station.
09. Does the experiment benefit other experiments or projects on the Moon or can the experiment package /project equipment be used for other activities on the Moon with some modifications?
10. Does the expected knew information benefit directly the development or operation of the lunar base?
11. Duration of the experiment/project envisioned.
12. Estimated mass of the complete experiment or project equipment package.
13. Estimated dimensions of the complete package.
14. Estimated electric power required by the experiment or project.
15. Estimated thermal power required and the thermal load on the system originating from the experiment or project.
16. Vacuum or normal atmosphere required by the experiment/project.
17. Estimated data handling capacity required on the Moon and on Earth.
18. Operations and control requirements on Earth.
19. Requirements for consumbles,such as water, chemicals etc.
20. Special safety considerations during transport or operations.
21. Special launch requirements for the required equipment.
22. Special external equipment required for installing the experiment/project.
23. Labor-hours required to set the experiment up, or to install the project, at the desired location and activating it.
24. Labor-hours required on the Moon for running the experiment or project during its active operation on the Moon.
25. Labor -hours required for evaluation on Earth during its active operational phase on the moon and thereafter .

26. Mass and volume of package to be returned to the Earth after completion.
27. To which degree (in percent) does the available knowledge and state-of-the-art allow the preparation of the experiment/project, with the year proposed as the reference year?
28. Lead time in terms of years or months required by the proposer on Earth for preparing the hard- and software from the time of approval and funding of the experiment to date of shipment to the Moon.
29. Estimated number of labor-years and cost to develop, operate and evaluate the proposed experiment/project with the year in which it is proposed as the reference year.
30. If the experiment/project requires stages of scale-up as most engineering experiments will need, state the anticipated stages on Earth and on the Moon.

This tentative list of information required on experiments and projects needs refinement, is a first attempt attempt to determine priorities for each of the development phases.

9. HUMAN ACTIVITIES AND SKILLS REQUIRED

1. ACTIVITIES REQUIRED AT A LUNAR BASE

The following scientific and non-scientific activities are will have to be performed at a Lunar Base:

Grading of surfaces
assembly of facility modules
mining
manufacturing of construction materials
construction of roads and facilities
unloading and loading of space vehicles
landing and launch operations of space vehicles
maintenance and repair of space vehicles
propellant production
propellant storage
housekeeping of habitats
maintenance and repair of facilities
maintenance and repair of stationary equipment
maintenance and repair of surface vehicles
operation of surface vehicles
waste collection and processing
gardening and farming
medical services
food preparation
storage of supplies and spares
communication services
electric and thermal power generation and distribution
field research
laboratory research
administration services
recreation services
clothing

To carry out these activities a certain number of skills are required, most but not all of them are listed below.

2. GENERAL SKILLS REQUIRED :

A preliminary survey has been made of the skills required which resulted in the following list of people required who possess primary and secondary skills in the following areas:

- construction workers
- surface vehicle operators and maintenance specialists
- space suit specialists and EVA experienced people
- versatile people with fast learning capability
- mechanical-, electrical- and electronic specialists
- geologists
- astronomers
- medical personnel (physician,psychologist ...)
- life science specialists
- space vehicle service personnel
- base manager and team leader

There will be a *shift of skills* required during the individual development phases of the base, furthermore within each development phase from year to year, also there will be a need for more than one shift in certain activity areas.

The *weekly working hours* during the acquisition phase will be 50 to 60 and gradually decrease in due course of development, with increasing lunar population and decreasing specific logistic costs .

The *length of the duty cyle* for each individual lunar crew member is expected to be between 3 and 6 months during the acquisition phase, 6 months during the exploration phase and about 12 months during the utilizazion phase, as the crew comfort improves by the enlargement of the facilities on the Moon and greater efficiency of the logistic system. On the long run, some people might even stay on the Moon for several years.

The *issues* to be discussed in more detail in this area in the future are the following:

1. Duration of EVA's
2. Capability limitations during EVA's
3. Phychological requirements
4. Needs for system simulations on Earth
5. Operational models
6. Male/female crew composition
7. Selection process for Base Commander
8. Selection process for international crew composition
9. Job/task definition as function of time
10. Skill mix for each individual development phase

3. INITIAL SKILL MODEL :

A situation was assumed in wich *the participating judges* would have the responsibility to determine the composition of a 12 person lunar crew to be sent to the Moon for 6 months to activate the first outpost facilities, test and make initial use of them. A preliminary list of desirable skills was prepared in a previous opinion poll, as a point to deviate from . The participants were asked to distribute the desirable primary skills (identify by figure = 1), their secondary skills expected (= 2) and their eventual back-up skills (= 3) over the 12 individuals making up the first lunar crew.

Based on the preferences selected by the judges the following ranking order was obtained for the primary ,secondary and back-up skills of the crew members during the 6 month acquisition period:

Tab.9-1: Skills required during the first six month of lunar base acquisition

Primary skills	Secondary skills	Back-up skills
1. Lunar Base manager 2. Medical doctor 3. Electronic specialist (incl.communications) 4. Space vehicle specialist and repair man 5. Geologist (lunar science generalist) 6. Space suit specialist 7. Mechanic (all round) 8. Construction engineer 9. Surface vehicle operator and repair man 10.Electrician for power network 11.Experimental physicist 12.Life science specialist, nutrician	1. Materials science- physicist 2. Biologist 3. Chemist-chemical engineer 4. Psychologist 5. Nutrician- cook 6. Construction specialist 7. Electrician (general) 8. Mechanic (general) 9. Electronic specialist (computer) 10.Life support specialist 11.Geologist 12.Astronomer	1. Space vehicle specialist 2. Medical doctor 3. Base manager 4. Life science specialist 5. Biologist 6. Chemist 7. Psychologist (Human factors) 8. Cook, nutrician 9. Physicist 10. Electrician 11.Construction specialist 12. Surface vehicle specialist

Tab.9-2: Typical workload for the crew members (in percent of labor-hours):

SKILLS:	during activation period	first operational period
construction worker	10	5
surface vehicle operator	10	5
space vehicle specialist	2	2
space suit specialist	6	4
mechanic	10	5
electrician	15	10
electronic specialist	10	10
geologist	5	15
biologist	2	5
physicist	2	5
chemist	2	5
astronomer	2	5
medical doctor	5	5
base manager	6	4
life science specialist	8	10
cook	5	5
sum	100	100

10. LUNAR BASE SYSTEM SIMULATION

The following strategies may be employed to *simulate* the acquisition and operation of a lunar base which is essential to arrive at the best possible solution, based on the objectives and criteria selected:

(1) The dimensionless mass distribution of the individual base elements in percent as a function of time is chosen as the controlling system parameter.
By choosing the lunar base size and its growth as function of time as the second control variable, one can calculate the individual masses of each of the lunar base elements and proceed from there to the outputs and logistical requirements.

(2) The launch rate and annual transportation volume of the space transportation systems are selected as the control variable in connection with a manifest that specifies which modules are transported to the Moon in each year of the acquisition period to satisfy the specified functions of the base. Target values for the desired outputs will then determine the growth rate of each base element observing the capabilities of the space transportation system.

(3) The services to be produced on the lunar surface in terms of labor-hours or labour- years ,plus the desired annual output of lunar products in terms of metric tons per year, are selected as the control variables. An iterative process will than be used to match the growth rate of each facility with the capabilities of the logistic system.

Using the information presented in this report it is possible and desirable to simulate selected lunar development scenarios, determine the systems performance, system cost and thus obtain information on the relative cost-effectiveness of lunar base facilities and their operation.

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