MOONLAB

A DESIGN FOR A SEMIPERMANENT LUNAR BASE

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ABSTRACT

Under the direction of the authors, the 1968 Joint NASA-ASEE Summer Faculty Course on Systems Engineering prepared a design for a semipermanent lunar base. The base would be for the purpose of scientific exploration, with particular emphasis on astronomy. The site would be Grimaldi. The base would evolve over a 15-year period, requiring 37 launches of Saturn 5 delivery systems. The completed base would consist of eleven interconnected modules. Eight of these are for the shelter of the crew (24 men at base completion) and equipment.

The other three, which are inflated structures partially transparent to sunlight, contain a lunar farm of higher plants. This farm, a significant feature of the design, provides humidity control, oxygen generation, CO_2 removal, and a major part of the calorie requirements in food.

Power is supplied to the base by solar cell arrays during the day and fuel cells at night. Provisions are made for lunar surface exploration, use of lunar rocks and soil for many purposes, and emergency backup procedures.

Background

A 10-week preliminary design study was undertaken in the summer of 1968 by a group of 20 visiting professors at Stanford University and Ames Research Center as a part of the NASA-ASEE Engineering Systems Design Summer Faculty Fellowship Program.

The primary purpose of this study was to acquaint the participants with the educational methods in space systems engineering used at Stanford in the hope that they would introduce similar techniques at their home universities. A second purpose was to acquaint the participants with NASA activities in space technology and research in order to identify areas of importance to engineering students both in course work and in graduate research. A third purpose was to perform a preliminary design of a lunar scientific laboratory. The study was purely for educational purposes and in no way was intended to be a part of NASA planning.

The problem originally assigned to the participants in this study was the design of a "semipermanent lunar surface observatory." The detailed definition of the mission and its objectives was an extremely difficult problem. Because of concern with overall national expenditures a sizeable amount of effort was expended in cost-benefit analysis. Unfortunately, because the benefits were primarily scientific knowledge, a rigorous cost-benefit analysis was not achieved. However, enough thought went into the relative benefits of various lunar missions and experiments and the relative benefits of manned and unmanned lunar, planetary, and Earth orbit missions to enable the study group to converge upon a mission.

Once a specific operational mission and its objectives were defined, the design of MOONLAB proceeded quite smoothly. The decision to include man in the lunar observatory was made fairly early in the program. Human intelligence and skills were considered essential to accomplish the desired scientific investigations. As an exercise in multi-disciplinary communication, the study was successful. As the design evolved the areas of parametric conflict became apparent and resolution by tradeoff was accomplished where possible. MOONLAB, as finally proposed, is designed to evolve over a 15-year period to a size capable of maintaining 24 men and of supporting scientific investigations in astronomy, selenodesy, selenology, selenochemistry, selenophysics, biology, biomedicine, behavioral science and agricultural science as well as particle and field experiments, lunar atmosphere studies, and remote observation of the Earth.

The purpose of this paper is to present a few of the design conclusions which resulted from this study.

Site Selection

The landing site selected for the proposed lunar base (MOONLAB) is in the crater Grimaldi at lunar coordinates 68°00'W, 3°30'S. The selected site is accessible to lunar landing vehicles using lunar orbit rendezvous and also accessible by line-of-sight to Earth bases for the purpose of direct radio and TV communication. Grimaldi was chosen primarily for its suitability as an astronomical site, although the site has many selenological features of interest as well. The site is just south of the lunar equator, a location characterized by extremes in thermal conditions. The polar regions are much more favorable from thermal considerations, but were rejected on the grounds of poor astronomical promise and unfavorable abort capability and plane change requirements in these phases of the program where lunar orbit rendezvous will be used.

MOONLAB Buildup

The early stages of the evolutionary phase of MOONLAB employ the Lunar Orbit Rendezvous (LOR) technique for personnel delivery and return. The study assumed the launch and landing vehicle configurations proposed by the Lockheed Missile and Space Company in Reference 1. Two assumptions concerning these delivery vehicles were made which were of paramount importance in establishing the abort capability for the base. These assumptions were:

1) The LOR personnel carriers are capable of 180-day duration operation, and

2) The direct-mode personnel carrier is capable of 270-day dormancy on the lunar surface.

An alternate program was investigated which did not use LOR techniques. The results of that study indicated the total cost of a direct-mode-only evolutionary program would be the same as the program described in the following pages; however, as the manned operations would occur over 5 years in the direct mode (instead of nine in the LOR mode), the peak annual funding of such a program would be larger. The direct mode would also not return scientific data until a later date. Accordingly, the evolutionary program using LOR was selected.

A profile of the MOONLAB buildup is given in Table 1. A total of 37 launches is required, of which 23 are manned launches and 14 are cargo launches. The buildup of astronaut staytime from 6 months to a year is accomplished in three steps, with a period of one year of Earth post-mission observation of the astronauts before the lunar staytime is increased.

Abort during the first 3 years of the program is continuous since the astronauts will be able to return to Earth via the same vehicle that delivered them. As personnel lunar staytime grows beyond the vehicle staytime in the ninth year, return from the Moon is accomplished by launching a personnel carrier from Earth. In the case of abort the launch time reaction capability of this method (minimum of 3 days) may be unacceptable. By developing vehicles with staytimes equal to personnel staytimes, or vice versa, this problem may be avoided.

The total mass delivered in the evolution of MOONLAB is shown in Table 2. Table 3 gives the delivery requirements during evolution.

Since the requirements do not fall exactly into units deliverable by the cargo vehicles (16,000 and 23,000 kg), early delivery, particularly of expendables, allows the cargo to be partitioned into the specified units.

During the MOONLAB evolution eight shelter modules and three "farm" structures are to be delivered. The deployment of these shelters and farms is illustrated in Fig. 1. Also indicated is the post-evolutionary function of each shelter. The total cost for the MOONLAB project was calculated to be 17.4 billion dollars. Figure 2 shows the annual cost as a function of the year from project initiation (assuming the project were initiated in the early 1970's).

MOONLAB Layout

During design of MOONLAB, it was considered extremely important to minimize the effects of isolation and maximize the effectiveness of the crew at their assigned tasks. Equipment layout and facility arrangement were carefully considered and habitability factors (odor, noise, illumination, temperature, humidity, recreation, etc.) were considered when it was demonstrated that they were potentially significant to the lunar crewman's total performance.

Table 1

MAJOR MILESTONES IN THE EVOLUTIONARY PROGRAM

Year	Development
0	Start Development Programs
3	Site Certification Mission
6	Deliver First Cargo Establish 3-Man, 3-Month Staytime Base
7	Staytime Extended to 6 Months Science Program Starts
8	Base Grows to 6 Men Hygiene Shelter Delivered
9	Staytime Extended to 9 Months
11	Staytime Extended to 12 Months Base Grows to 12 Men Sleeping and Command Shelters Delivered Direct-Mode Personnel and Advanced LLV Used
12	Physical Science and Off-Site Activities Shelters Delivered Start Phase C Science Program
13	Agriculture Shelter Delivered Base Grows to 18 Men Deliver Lunar Surface Transportation
14	Astronomy Shelter Delivered Farms Delivered 14 Metric Tons of Science Equipment Delivered
15	Base Grows to 24 Men

Table 2

MASS BUDGET FOR MOONLAB EVOLUTION

System	Weight (kg)	Percent of Total
Shelters, Life Support, Farm and Radiator	99,000	36
Water: Use, Reserves and Packaging	45,000	16
Power Equipment and Replacement	31,300	11
Lunar Transportation and Off-Loading Equip.	26,600	10
Gas: Use, Leakage, Reserves and Packaging	30,400	11
Food: Use, Reserves and Packaging	19,400	7
Science Equipment	19,200	7
Tunnels	2,700	1
Communications Replacement	2,400	1
TOTAL	276,000	

Table 3

MOONLAB EVOLUTION ANNUAL DELIVERY REQUIREMENTS
(Mass Are Given in Units of 10^3 kg)

Item Year	Shelters, Farm and Life Support	Water	Power	Atm.	Off-Loading and Lunar Trans.	Food	Science Equip.	Misc.	TOTAL†
6	16	*	*	*	10	*	2.4		28.4
7		4	.6	2.8		0.8		.3	8.5
8	8	5	3.6	2.8		1.0		.6	21.0
9		8	1.2	4.4	5	1.6		.3	20.5
10		8	1.2	4.4		1.6		.3	15.5
11	18	8	7.2	4.4		2.8		1.2	41.6
12	16	8	2.4	3.6		3.2	2.8	1.2	37.2
13	10	2	7.8	3.6	11.6	3.6		.9	39.5
14	31	2	7.3	4.4		4.8	14	.3	63.8

† Included in First Shelter.

* Payload Constraints Enforce Early Delivery of Cargo.

Some of the important design features which resulted from consideration of human factors were:

1) Separation of noisy (off-site activities module) from quiet zones (sleeping).

2) Normal activity "flow" routines designed into adjacent canisters (e.g., sleeping, personal hygiene, eating).

3) Provision for a continuum of social activity (individual quarters in M-3 to 24-man group meetings in dining/conference area M-4) and for individual and group recreation.

4) Work stations all radiating out from the central command station.

5) Location of primary water storage (M-2) adjacent to the maximum security habitat (M-1).

6) Emergency air locks to and from every shelter. Emergency monitoring of all shelters for air pressure fluctuations. Techniques of locating personnel and diagnosing their physical condition. Protection against sudden decompression, fire, explosion, and radiation, and provisions for search and rescue outside of the base.

The habitat, or base module, used for all base operations is the space canister used to carry cargo and men to the Moon. This decision was made after a tradeoff between various methods of building shelters from lunar material, designing erectible shelters, utilizing lunar geological features, and operating without shelter. The first canister delivered (M-1) is to contain life support and science equipment and facilities to accommodate 3 to 6 men. This structure is to be covered with lunar soil to a minimum depth of one meter in order to minimize micrometeorite and radiation damage. As other canisters are added, changes in module function will occur. For instance, by the fifteenth year, module M-1 is to be the bioscience laboratory, hospital, and maximum security habitat. However, functional changes have been selected so that minimal effort will be required for modification.

The principal parameters and/or constraints encountered in the design of the lunar shelter modules included internal pressure, temperature extremes, protection against ionizing radiation and meteoroid impacts, the dynamic structural loading of launch and landing, and the man-hour construction load on the lunar surface. These factors interacted directly with weight, size, and cost.

The base as designed consists of eight habitat/work-area modules connected by short tunnels of inflatable rigidized material. The modules are to be completely prefabricated on Earth and configured to fit atop a standard, direct landing lunar descent stage. Raceways in the tunnel floors will house plumbing, power, and gas ducting. Deployed over the eight-module cluster will be a flat shield, acting both as a meteroid bumper and a heat moderator. Figure 3 is a drawing of the base configuration.

Power and Communication

The power subsystem selected for the MOONLAB supplies electrical energy directly from solar cells during the lunar day. During the lunar night electrical energy is produced from fuel cells. Hydrogen and oxygen for fuel cells is obtained from electrolysis of water during the lunar day with cryogenic storage. Electrical power for electrolysis is supplied from the solar cells.

The power subsystem choice was influenced by the assumptions that (a) large quantities of fuel for Radioisotope Thermoelectric Generator's (RTG's) will not be available, and (b) the useful life of a SNAP 8 reactor system at full power is approximately one year. If either of the above conditions were changed significantly, the power subsystem choice might be altered.

This system is the least expensive of the five systems considered. The system has other inherent advantages,

1) It is highly modular and can be supplied in units of essentially any size desired,

2) Redundancy is readily achieved by adding units or by accepting a lower availability of power in event of failure of part of the system,

3) Expansion of the system for additional power or for electrolyzing water to provide fuel for mobile vehicles of Earth return is readily achieved,

4) Buildup of the system on the Moon is simple since components can be packaged in nearly any size desired and can be carried on any launch,

5) There is no problem of radiation, thus allowing convenient location of the system relative to shelters,

6) A peak power of 225 kW is possible if all electrolysis is shut off.

Fuel cells for the power system will be available from the navigational packages on the landing vehicles. Each vehicle has two cells, each of 2 kW capacity. With 40 or more landing vehicles there will be more than enough fuel cell capacity, including replacement as necessary. Also there will be ample cryogenic tankage which can be salvaged from landing vehicles. Fuel cells, tanks, and vehicles should be designed with this future use in mind.

The base proper will require 50 kW (electrical) during the lunar day and 40 kW during the lunar night. This does not include power for electrolysis of water to supply fuel for mobile vehicles or for return to Earth. Specific requirements are shown in Table 4. Subsystem characteristics are shown in Table 5.

Figure 4 shows modes of communication provided on the lunar surface. Because of the diverse nature of the MOONLAB mission, the communication subsystem design necessarily included a large amount of flexibility. Lunar equipment must be adaptable to changing needs of investigators. A new Earth-based network is required consisting of three ground stations spaced approximately equally around the Earth.

Table 4

MOONLAB POWER REQUIREMENTS

System	Power (kW)
Lunar Day	
Atmosphere circulation	5
Lighting	10
Heat rejection (living-working space and farm)	6
Water pumping (farm)	1
Harvesting and food processing	1
Waste processing	1
Communications	3
Experiments	15
Miscellaneous and contingency	8
	50
Lunar Night*	
Emergency life support	25
Lighting	4
Heating	10
Communications	1
	40

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*Requirements determined by emergency conditions in the event of loss of the farm.

Table 5

MOONLAB POWER SYSTEM

Development cost	$110 million
Hardware cost	$115 million
System mass	21,500 kg
Deployment time	200 man-hr
Annual replacement rate	20 percent

The cost of electrolyzing 2000 kg of water per year will be 3.16 M$.

Life Support

The life support subsystem for MOONLAB is unique for several reasons,

1) It uses higher agriculture to both close the O_2-CO_2 cycle and to provide food.

2) Because higher plants are used, man's waste products are almost all completely used efficiently.

3) By careful choice of crops, it is possible to operate with a minimum of mechanical equipment. Fundamentally only a fan and a dehumidifier are needed.

4) A large fraction (75%) of the total food available is in a relatively fresh and aesthetic form.

5) Resupply from Earth is greatly reduced.

6) Water purification is greatly simplified, and as a consequence more water for washing and laundry is available because of the multiple use.

Some idea of the interrelationships in the life-support system can be seen in Fig. 5. A material balance is shown in Fig. 6. During the lunar night the agriculture is dormant and shelter air is bypassed through an absorber bed to keep the CO_2 from exceeding 1.5% during the lunar night. The CO_2 is then desorbed into the agriculture during the lunar day. A backup system requiring standby electrical power is available if the agricultural system should fail.

Atmospheric leakage from the shelter will be principally due to air lock operation. Assuming that air locks will bound the tunnels and that there may be as many as three openings per day, losses have been calculated as 10% of a tunnel volume per day per opening. Farm leakage is based on probability of 3 punctures per year of meteorites 1.5 mm in diameter, and the loss of one shelter volume (18 m shelters) at each hit before repair can be made.

During the base evolution all food will be from Earth-supplied stores. The diet will be 2,800 k-cal with roughly 12% protein. As the agriculture develops, harvest of crops will begin to contribute to the diet. On the basis of 0.63 kg/day/man of dried food, the 24-man base will require 15.1 kg/day or k, 520 kg/yr. This relatively small weight makes it feasible to keep a year's supply of food on hand as backup for possible agricultural failure.

The MOONLAB water requirements are quite extensive, due to initial requirements for charging the farm and the necessity for an inventory for fire protection. Once the base reaches steady-state operation, a surplus of some 5,000 kg will be produced each year due to metabolism by the farms and by the crew. This surplus will be electrolyzed to H_2 and O_2 for fuel and breathing air. However, during the evolutionary phase some 45,000 kg of water must be brought to MOONLAB.

Waste is to be disposed of by feeding it to the farm, in various forms. During construction and if the farm is temporarily out of operation, waste will be disposed of by more conventional means. An electrodyalysis system will be used for urine reclamation and solid wastes will be heat-dried, sterilized, and stored.

The Lunar Farm

The reasons for developing MOONLAB agriculture are as follows:

1) The MOONLAB farm provides the basis for a pleasant, expandable permanent colony on the Moon, and is also economically justifiable. For 75% food recycle, about 2 years time at a base level of 24 men justifies the weight of the farm over the weight of required imported food and a CO_2 removal system.

2) Development of a system for maximum photosynthesis with minimum space and labor requirements.

3) Development of new plant forms, new genetic makeup, and new soils by exposure to unusual light, hard radiation, gravity, magnetism, and atmospheric composition. Useful plants produced in such an environment may produce seeds which are advantageous elsewhere.

4) Crop adaptation and exploitation methods on the Moon may provide means for unlimited colonization of the Moon without dependence on Earth.

5) Moon farming may yield knowledge and techniques which can be applied on Mars without the need for shelters. Mars farming could lead to eventual conversion of the entire planet to useful purposes.

Several farm units are provided for safety and for variation in growing conditions. Figure 7 shows a plan view of a typical farm unit.

One 18 m diameter farm unit will be programmed for perennials, one 18 m diameter unit for annuals and diannuals, one 10 m diameter unit for vegetable crops, and one 6 m diameter agrilab for new work in hydroponics and tissue culture. The total farm area for a 24-man MOONLAB was calculated to be 500 m^2 (1/8 acre).

Figure 8 shows the layout of the farm and the nighttime environment. Leaf crops will be removed from the 18 m farms at dusk. Highly reflective shades will be deployed over all windows to minimize heat loss at night.

Soil conditioning must be considered as a primary factor in designing the farm. Moon soil must be made from Moon dust since 160 tons are needed for the total farm assuming a 10-in. soil depth. Soil will be loaded before putting the window in place. Aggregate will be loaded first, followed by finer material. The soil will be watered by coarse sprays and drained into a sump. Water holdup of the entire farm in the soil will be 8,000 kg.

The floor of each farm unit will consist of a sloping, gastight pan of high-density plastic placed on properly contoured Moon dust. Tables 6 and 7 summarize various characteristics of the agriculture complex. Figure 9 shows a cross section of one of the farm units.

Table 6

CHARACTERISTICS OF THE AGRICULTURAL COMPLEX

	18 m	18 m	10 m	6 m	TOTAL
Window Area	250 m^2	250 m^2	75 m^2	25 m^2	600 m^2
Enclosed Volume	800 m^3	800 m^3	450 m^3	50 m^3	2100 m^3
Window Mass	370 kg	370 kg	110 kg	37 kg	900 kg
Floor Mass	1000 kg	1000 kg	300 kg	n.a.	2300 kg
Beam Mass Number	1400 kg	1400 kg	800 kg	n.a.	3600 kg
Total Structure	2800 kg	2800 kg	1200 kg	40 kg	6800 kg
Night Power	0	0	2 kW	2 kW	4 kW
Soil Mass	65 tons	65 tons	25 tons	5 tons	160 tons
Soil Moisture	2000 kg	3000 kg	1200 kg	300 kg	7500 kg
Maximum Biomass					10,000 kg
Total Plant Dry Matter					1,000 kg
Nitrogen in Biomass					200 kg

Table 7

LIFE SUPPORT SYSTEM--AGRICULTURE PEAK POWER REQUIREMENTS

	kW	Mass
Feces Dryer	0.22	10.0
Water Heater	0.08	1.0
Agriculture Machinery	4.0	100.0
Wash Water System	0.50	12.0
Air Circulation	3.8	320.0
Pumps at 0.093 kW each*	1.6	20.0
Lighting, UV sterilizers, adsorber	10.0	800.0
TOTAL	20.2	1263.0

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*Includes agriculture processing pumps.

Possible annual and biannual leafy crops which the farm will include are rye, swiss chard, endive, lettuce, and Chinese cabbage. Other plants of interest are tomatoes, peas, beans, sweet potatoes, peanuts, and alfalfa. The various foods to be processed are leaves, cereals, root crops, vegetables, and hydroponic crops.

Leaf processing will include harvesting, packaging, and freezing at dusk. Leaves not directly edible will be cooked with hot water while fibrous leaves will be crushed and fiber pressed out for return to the soil. The serum will be frozen for direct consumption if palatable, and unpalatable serum will be boiled to coagulate protein, which will be pressed out and dried. A safe scheme for removing leaf serum taste should be found as soon as possible.

Root crops and vegetables will be eaten after the usual preparation, and cereals will be boiled or dried and malted to improve taste. Hydroponic crops will be eaten as is or dried during the day, since dusk harvesting is not needed in this case. Tomatoes will be consumed immediately and sweet potatoes will not need preservation.

Concluding Comments

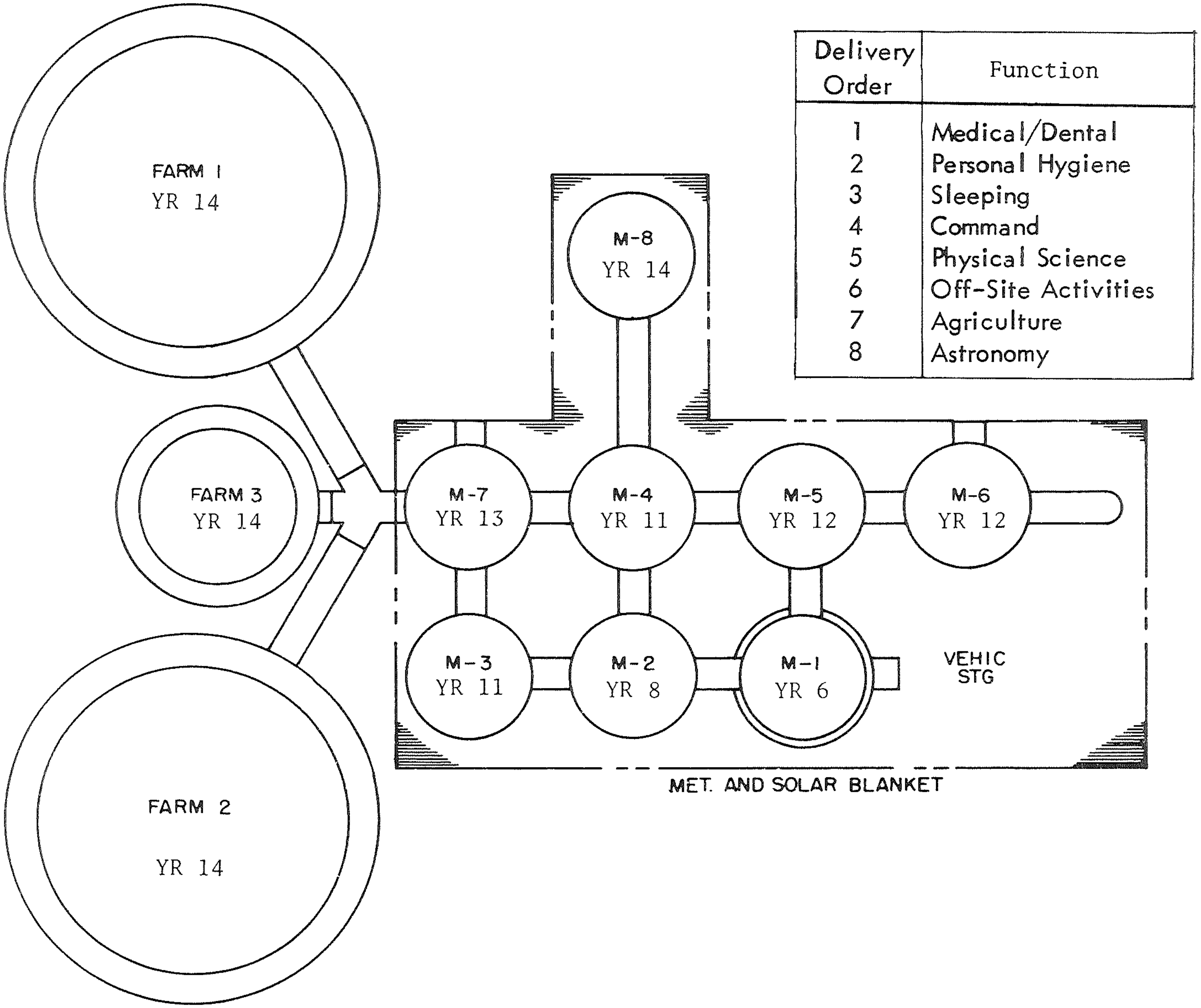
The MOONLAB study, insofar as possible, was a complete system study. It included detailed considerations of scientific mission activities, experiments and equipment, personnel selection, training and organization, structural and thermal design, emergency procedures and backup subsystems, mobility, lunar resources exploitation, and post evolution logistics. It is not possible to go into all of these considerations in this paper. Interested readers may refer to Reference 2 for the complete study results.

References

1. "Improved Lunar Cargo and Personnel Delivery System," LMSC Report 7-28-64-4, June 28, 1968.

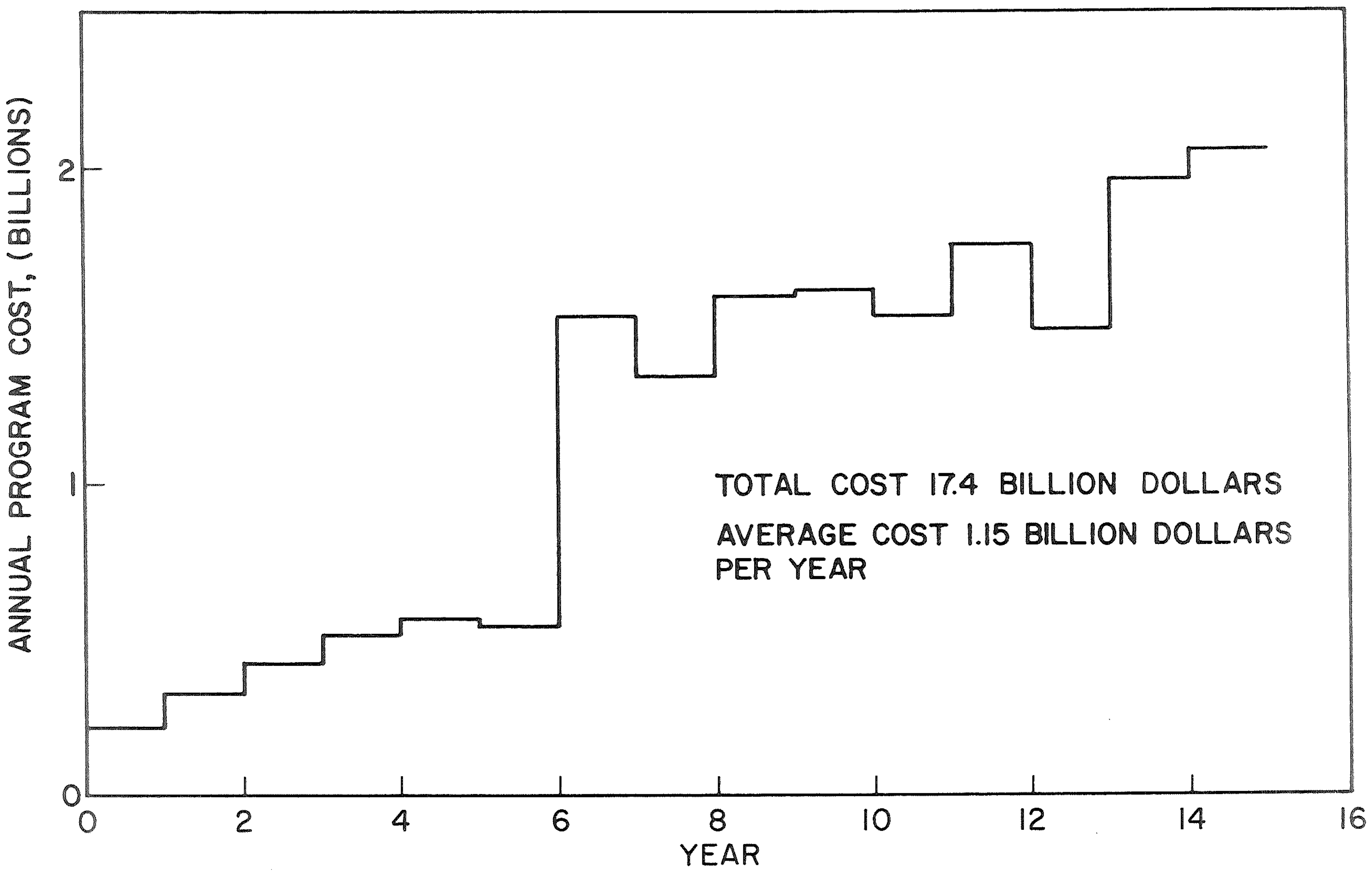
2. "MOONLAB," Final Report of Stanford University-Ames Research Center Summer Faculty Program in Engineering Systems Design, NASA Contract NSR 05-020-151, 1968.

FIGURE TITLES



Delivery Order	Function
1	Medical/Dental
2	Personal Hygiene
3	Sleeping
4	Command
5	Physical Science
6	Off-Site Activities
7	Agriculture
8	Astronomy

Figure 1.


ANNUAL PROGRAM COST, (BILLIONS)
0
1
2
YEAR
0
2
4
6
8
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TOTAL COST 17.4 BILLION DOLLARS
AVERAGE COST 1.15 BILLION DOLLARS PER YEAR

Figure 2.

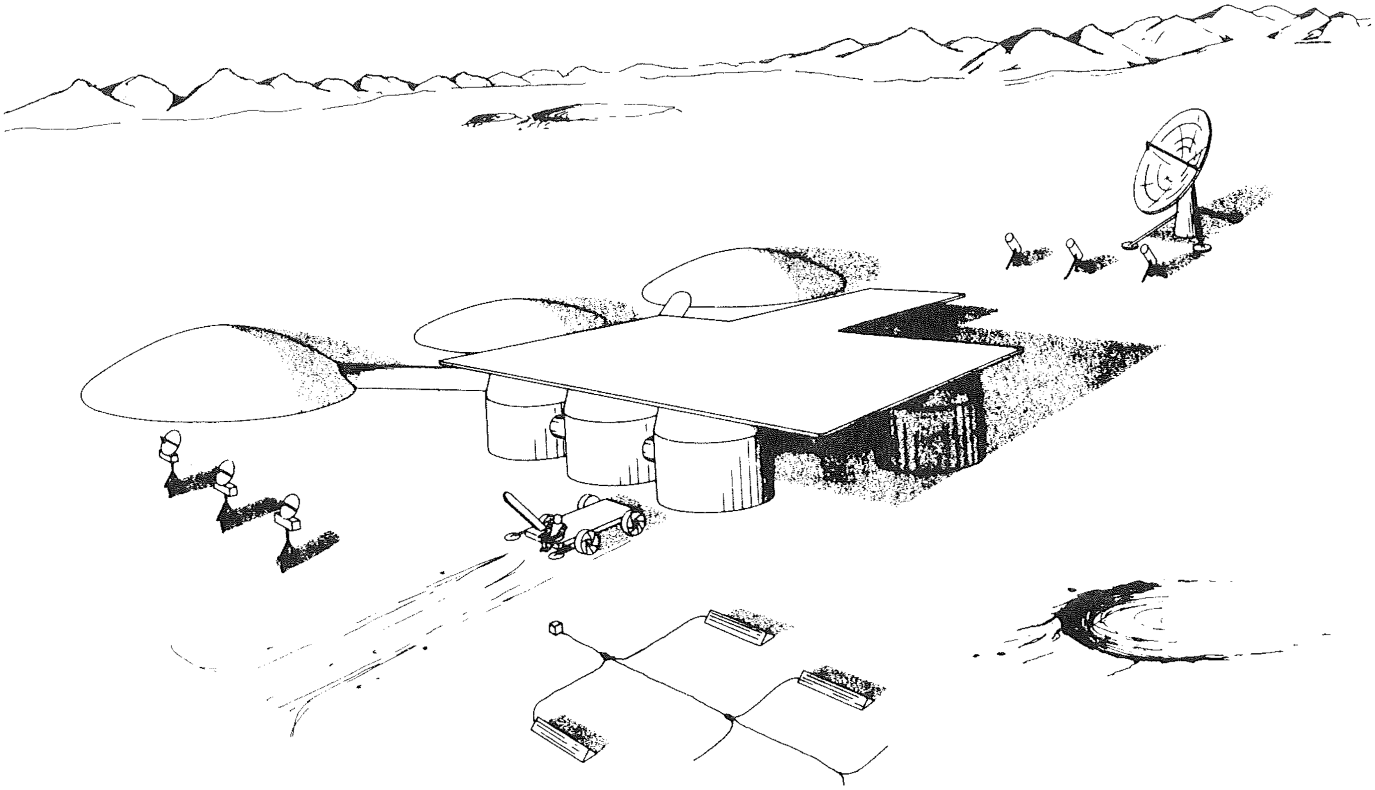
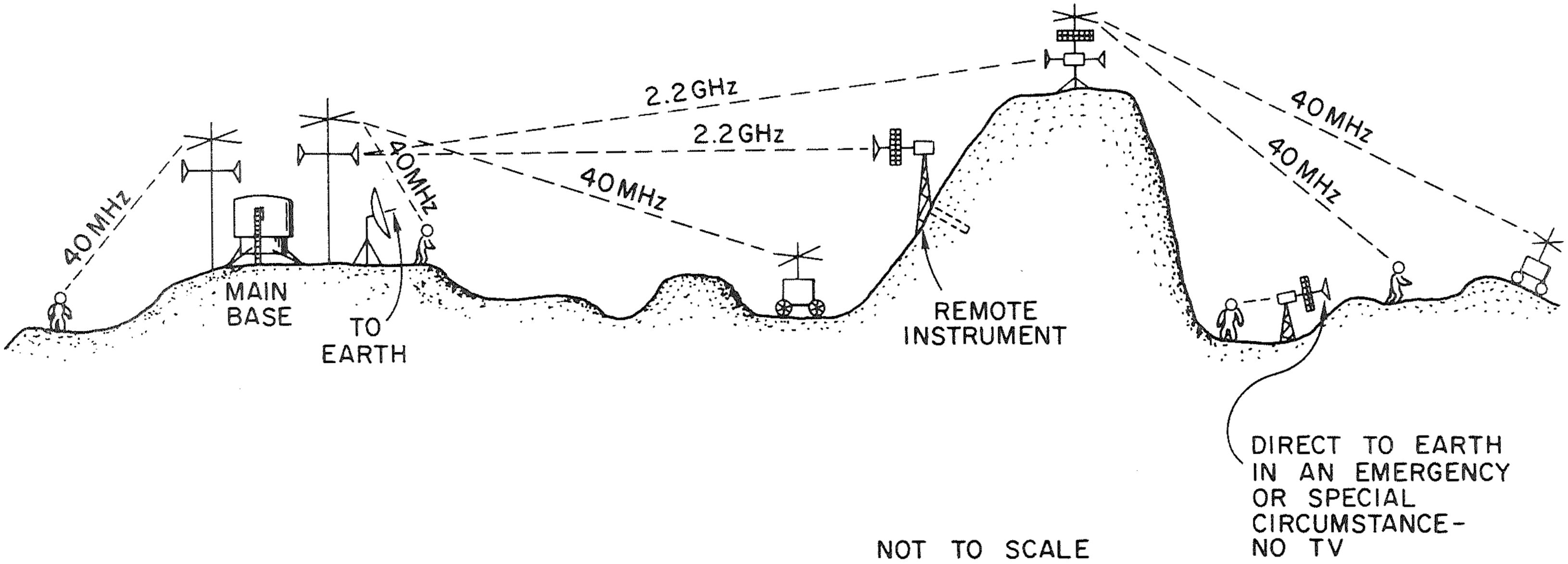


Figure 3.


2.2 GHz
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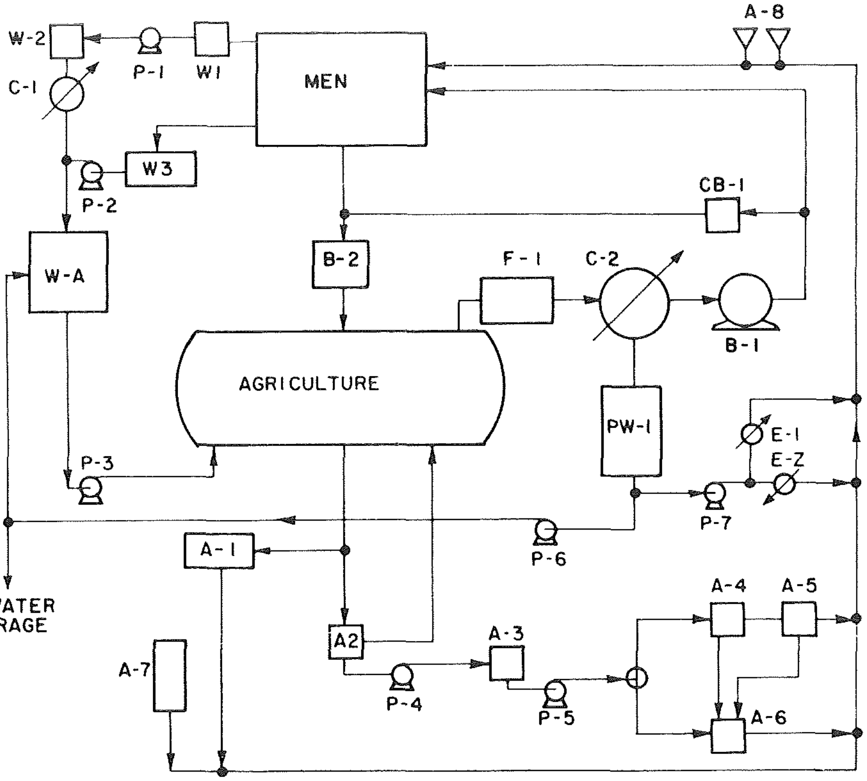
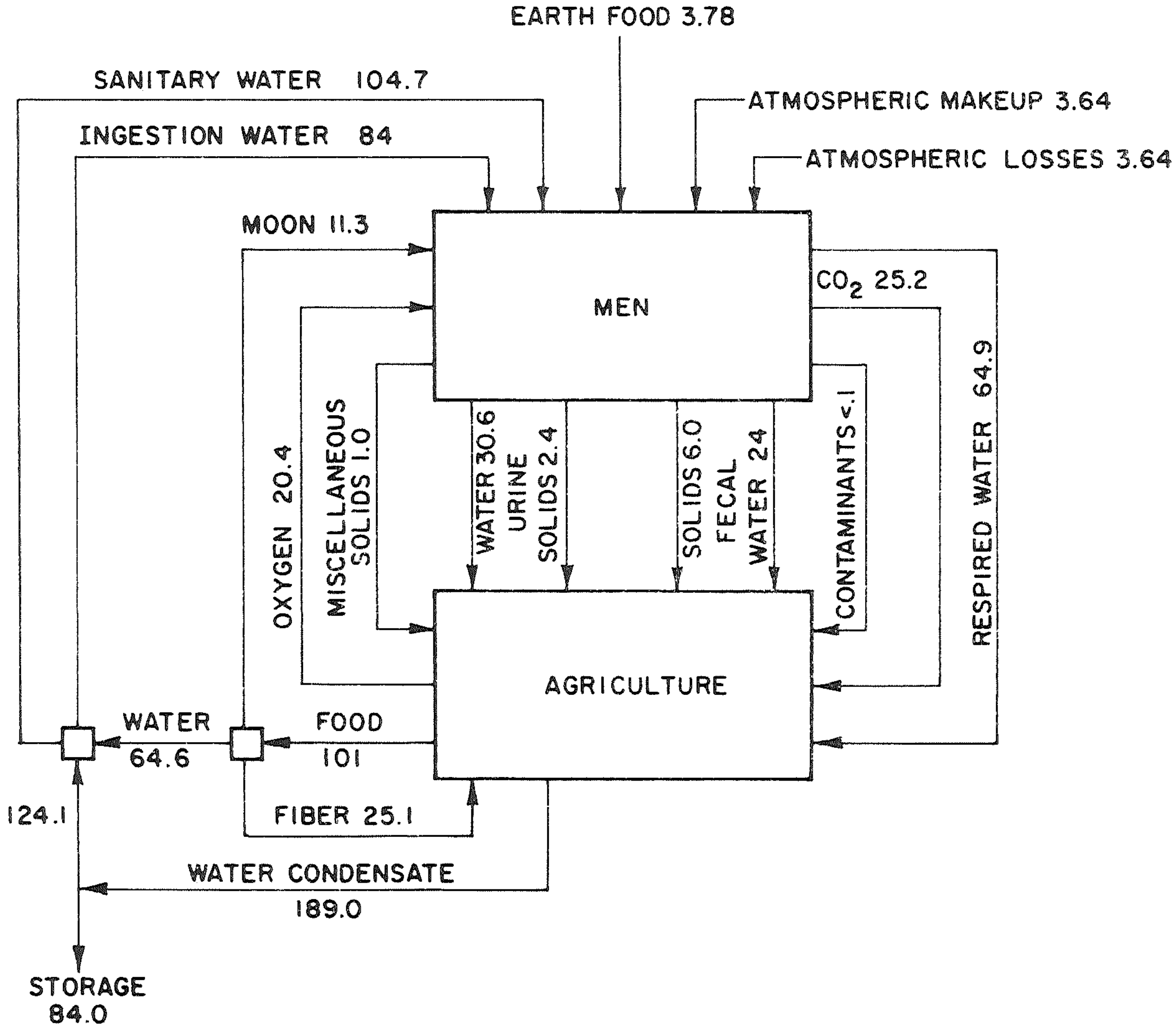
MAIN BASE
TO EARTH
REMOTE INSTRUMENT
DIRECT TO EARTH IN AN EMERGENCY OR SPECIAL CIRCUMSTANCE- NO TV
NOT TO SCALE

Figure 4.



A-1	Freezer
A-2	Crusher
A-3	Cooker
A-4	Coagulum Washer
A-5	Dryer
A-6	Serum Freezer
A-7	Stored Food
A-8	Flavors
B-1	Circulation Fans
B-2	Adsorption System
C-1	Condenser
C-2	Dehumidifier
CB-1	Contaminant Removal
E-1	Water Cooler
E-2	Water Heater
F-1	Filter Sterilizer
P-1	Feces Pump
P-2	Urine Pump
P-3	Dilute Urine Pump
P-4	Juice Pump
P-5	Cooked Juice Pump
P-6	Water Recycle Pump
P-7	Potable Water Pump
PW-1	Potable Water Storage
W-1	Feces Storage
W-2	Feces Dryer
W-3	Urine Storage & Sterilization
W-4	Dilute Urine Storage

Figure 5.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INGESTION WATER 84
ATMOSPHERIC LOSSES 3.64
MOON 11.3
MEN
CO_2 25.2
OXYGEN 20.4
MISCELLANEOUS SOLIDS 1.0
WATER 30.6 URINE SOLIDS 2.4
SOLIDS 6.0 FECAL WATER 24
CONTAMINANTS <.1
RESPIRED WATER 64.9
AGRICULTURE
WATER 64.6
FOOD 101
124.1
FIBER 25.1
WATER CONDENSATE 189.0
STORAGE 84.0

Figure 6.

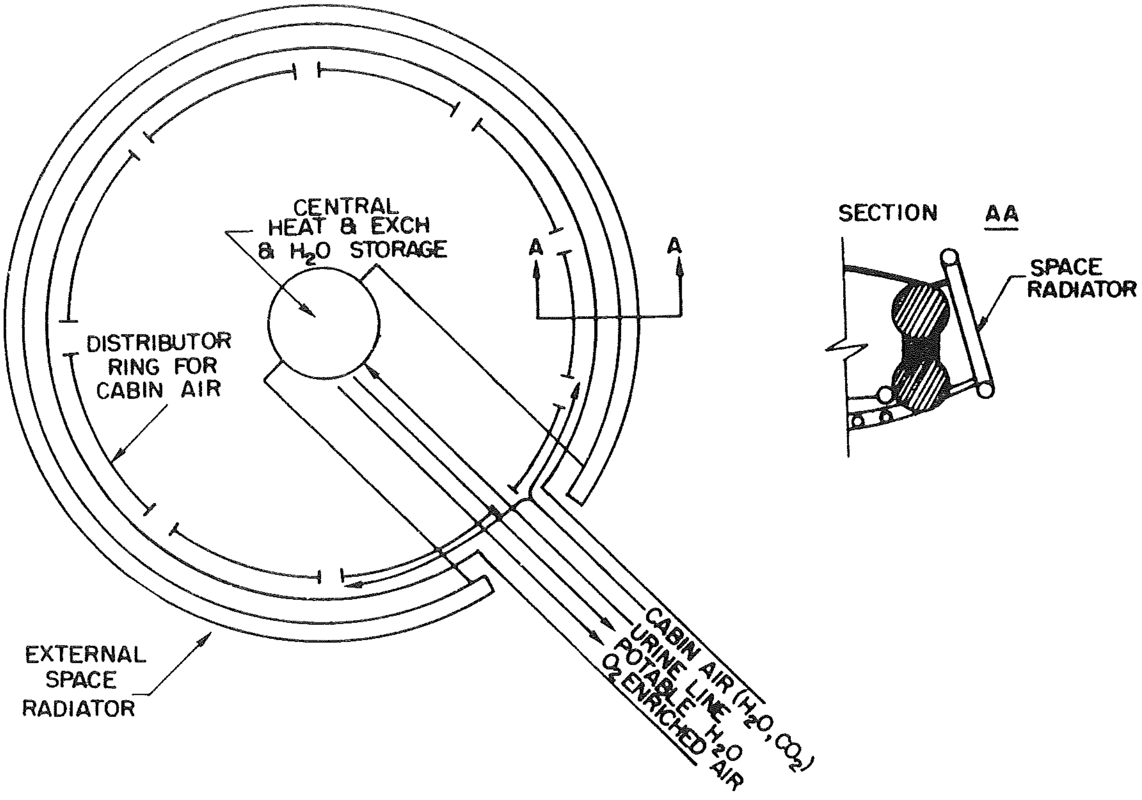
CENTRAL
HEAT & EXCH
& H_2O STORAGE
A
A
SECTION AA
SPACE
RADIATOR
DISTRIBUTOR
RING FOR
CABIN AIR
EXTERNAL
SPACE
RADIATOR
CABIN AIR (H_2O, CO_2)
URINE LINE
POTABLE H_2O
O_2 ENRICHED AIR

Figure 7.

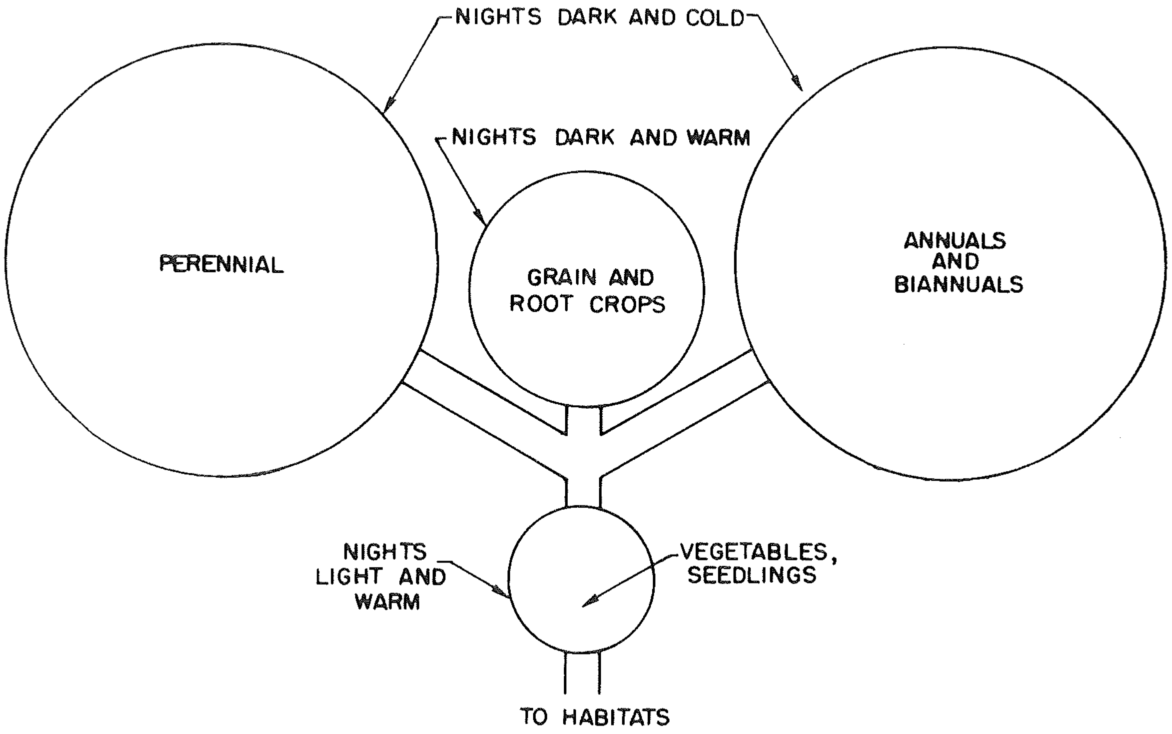
NIGHTS DARK AND COLD
NIGHTS DARK AND WARM
PERENNIAL
GRAIN AND ROOT CROPS
ANNUALS AND BIANNUALS
NIGHTS LIGHT AND WARM
VEGETABLES, SEEDLINGS
TO HABITATS

Figure 8.

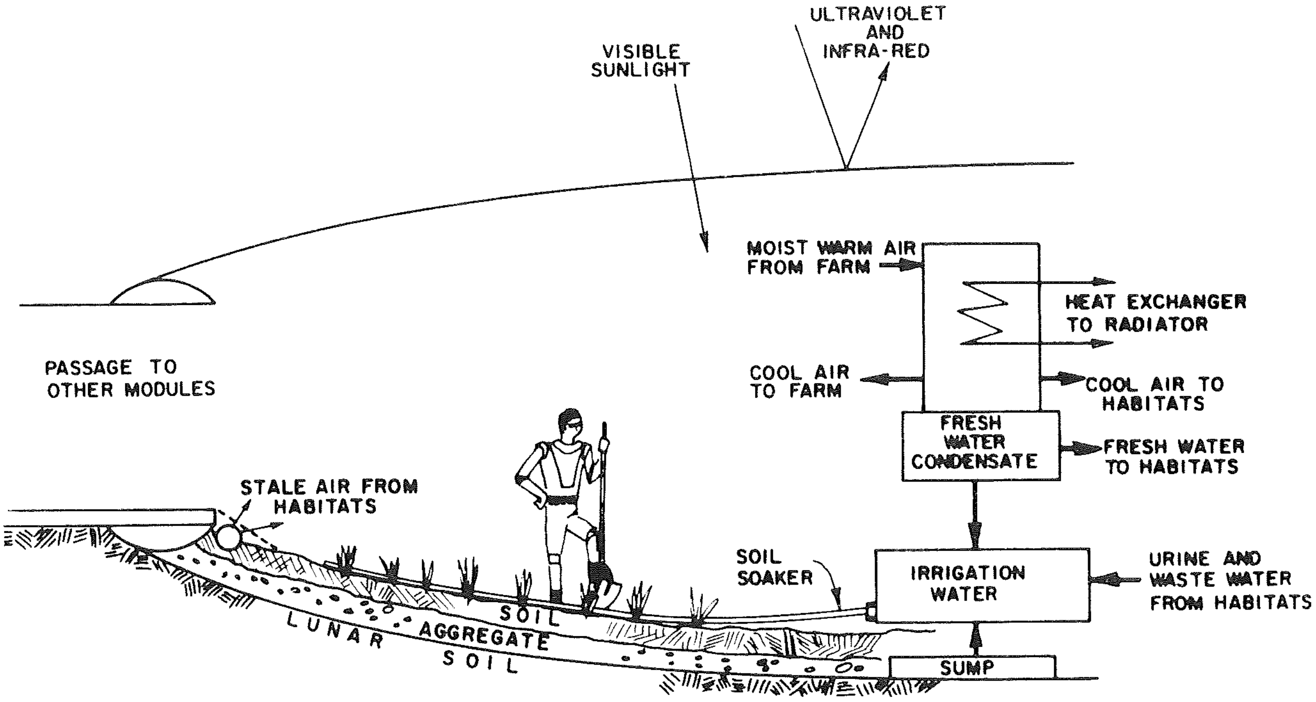
ULTRAVIOLET AND INFRA-RED
VISIBLE SUNLIGHT
MOIST WARM AIR FROM FARM
HEAT EXCHANGER TO RADIATOR
PASSAGE TO OTHER MODULES
COOL AIR TO FARM
COOL AIR TO HABITATS
FRESH WATER CONDENSATE
FRESH WATER TO HABITATS
STALE AIR FROM HABITATS
SOIL SOAKER
IRRIGATION WATER
URINE AND WASTE WATER FROM HABITATS
SOIL
LUNAR AGGREGATE SOIL
SUMP

Figure 9.