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Man as a Resource on the Moon

INTRODUCTION

All of the objectives for the maximum utilization of extraterrestrial resources will depend upon the performance capability of man under the environmental conditions on the lunar surface. Any discussion of man as a resource must of necessity consider what he will be required to do. In this paper man is viewed as the primary integrator performing those functions for which there is no substitute. These integrator functions fall under the interpretation, judgment, and decisionmaking required to keep a closed loop between man and equipment.

This paper is predicated upon the assumption that the initial Apollo missions have completed the preliminary exploration and geological survey of parts of the lunar surface and have identified a good site for a permanent base installation for exploiting extraterrestrial resources. The timespan for the activities described may begin in 1975 to 1978 and extend over a period of 10 years. This hypothetical base will be used to describe the role of man as a resource and to highlight his areas of activity.

Acknowledgment is made to the members of the Working Group on Extraterrestrial Resources who contributed technical papers to the *Proceedings of the Fourth Annual Meeting*, which provided much useful information for defining the role of man on the Moon, and to the Goddard Space Flight Center for copies of Orbiter photographs of the lunar surface and for advanced data of lunar soil analysis from Surveyor VI.

PROGRAM AREAS OF INTEREST

In considering the resourcefulness of man in the exploitation of lunar resources, 15 major program areas of interest can be identified where man's performance capability can be clearly defined on the basis of known Earth technology (table 1). Each of these areas can be identified with an anticipated work level. Metabolic work levels may be considered to be as follows: light work represents 500 to 1000 Btu/hr; moderate work, 1000 to 1600 Btu/hr; and heavy work, 1600 Btu/hr or more. Many subdivisions of the tasks and each respective task performance capability can be predicted. A complete description can be obtained by detailed functional task analysis. A description of the scope of these areas of interest will assist in obtaining a perspective of the extent of man as a resource and his performance capability for various tasks.

TABLE 1. *Program Areas of Interest*

Area	Work level
Exploring	Light-moderate
Surveying	Light-moderate
Experimenting	Light-moderate
Mining	Moderate-heavy
Tunneling	Moderate-heavy
Processing	Light-moderate
Excavating	Moderate-heavy
Building	Moderate-heavy
Farming	Light-moderate
Unloading	Moderate-heavy
Hauling	Light-moderate
Launching	Light-moderate
Physical conditioning	Moderate
Playing	Light-moderate
Maintaining	Light-moderate

Exploring

The area of exploring is considered to be a continuous activity, because man has never stopped exploring Earth. He will continue to search for additional lunar resources that will be essential in making a fixed lunar base as self-sufficient as science and technology can make it. It is assumed that most of the exploring will be conducted from a rover-type vehicle with a self-contained life-support system. Sorties will be conducted from this vehicle by space-suited men. The overall work level for these activities will be light to moderate. The highest level of activity will occur while they are climbing crater walls and lunar mountains.

Surveying

Surveying is an activity essential to the site layout and construction. It will also be required in support of lunar mapping activities. This task area will probably require the full time of at least two or three men. Some surveying will probably occur concurrently with exploring activities of other lunar areas. The work level will be light to moderate.

Experimenting

Experimenting is another activity that will occur as long as man is on the Moon. It will extend across all scientific areas as man seeks further knowledge and solves problems of living, working, and operating equipment in the lunar environment. All scientific knowledge that will be obtained about the Moon is considered essential to successful exploration of other planets in the solar system. Work level in performing experiments outside life-support shelters will not exceed light to moderate metabolic activity.

Mining

Once proper mineral resources are located, man's performance in initial mining operations may require moderate to heavy work levels. It may be possible, however, by proper man-equipment design, with automation and remote control of various types of mining equipment, to reduce the work level from heavy work to light or moderate. It is estimated that approximately 50 percent of man's time will be spent in life-support cabs, while the rest of the time will be involved in surface tasks such as loading a drill hole for blasting; adjusting, servicing, and maintaining mining equipment; and recovering drill cores for analysis. Logging may be a standard activity of all drilling operations in support of geophysical studies of the lunar crust.

Tunneling

Tunneling was considered a potential part of three base activities. It may be necessary in mining operations in order to exploit a particular vein of high-grade minerals. Tunneling into a crater wall may be required to provide protection for cryogenic storage tanks. Lastly, tunneling into a crater wall may be a more economical means of constructing well-protected life-support shelters. As is true for mining operations, the work level for initial tunneling operations may be moderate to heavy. Again this will depend to a large degree upon the equipment design.

Processing

The processing of ore and its reduction to usable products encompass a large number of subtasks that will require man to operate in the external lunar environment. Many of the activities can be identified as being at the location of surface mining equipment, rock crushers, and the ore-conveying systems where service and maintenance activities will be required to maintain a steady flow of ore into the processing facility. Once the ore has been graded, the extraction process may take place in a semivacuum by use of a large solar furnace or in a special pressurized building or fractionating unit.

Excavating

Various types of excavating activities are considered fundamental to all lunar building construction. Many concepts have been proposed such as surface shelters, buried structures, and structures installed in tunnels made in crater walls. In this analysis it is assumed that many permanent structures will require excavation in order to obtain a firm foundation for buildings. The type of excavating considered requires vehicles related to present bulldozers and earthmovers. In some instances, surface mining equipment might be used to prepare construction sites. Another type of required excavation is ditching, which will be primarily for the purpose of burying power cables running from remotely located powerplants. Man will perform these tasks in much the same manner as he does on Earth. The work level will range from light activity while driving to moderate activity while performing equipment maintenance.

Building

Initial building construction was considered to be primarily an assembly task. Prefabrication of various types of buildings on Earth is considered the most feasible means of establishing the initial base capability. Erection of these structures was considered on a modular concept. In all probability the base layout will evolve from scale models on Earth with each step well planned in advance. Eventually, the base should reach a capability of manufacturing additional buildings from lunar materials as well as interplanetary exploration vehicles and other supporting equipment. The work level will be moderate to heavy when muscular effort is required in alinement and joining tasks.

Farming

As the capabilities of the lunar base are extended, farming will become an essential activity. A farm and food-processing facility will probably begin in a module separate from the main life-support shelter. It will initially provide staple vegetables to supplement the basic food supp es. As the base grows in size, the farming facility will gradually grow until it reaches the level of a balanced closed ecology. At this point, selected animals will be raised within the complex for dietary protein. The work level will range from light to moderate. No lunar-surface activities are visualized for this area except for external building maintenance.

Unloading

This activity is associated with unloading logistic supply vehicles. The operation may initially consist of placing an unloading ramp in position and pulling the supply modules from the vehicle. Eventually the launch site will have mobile service towers that will reduce the turnaround time for supply vehicles considerably. The workload for man can range from light to heavy and will depend upon the type of support vehicle equipment and its multipurpose capability.

Hauling

Numerous hauling activities will move throughout the entire base from the launch complex. Several types of personnel and equipment carriers will be required. Movement of ore from mining sites to processing facilities will depend upon the multiplicity of mining operations. Hauling and erecting numerous communication antennas around the crater rim will be required to provide maximum coverage for exploration and landing and launch control. Specialized experimental instrumentation will probably be placed at preselected sites for geophysical studies on a continuing basis.

Launching

The launching of logistic vehicles and eventually manned interplanetary exploration vehicles will certainly be one of the major facility requirements for a permanent lunar base. Up to the time that the service towers and landing pads are constructed, the major launch operation is viewed as primarily a refueling activity. Later capability will include maintenance and checkout of entire vehicles much as is accomplished at Cape Kennedy today. When the full capability of the launch complex is attained, interplanetary vehicles will be assembled and launched to explore the solar system further.

Physical Conditioning

Long periods of living in a 1/6 g environment represent an unknown in human physiological adaptation. The greatest physiological area of concern is centered around the body muscle and cardiovascular system. Maintenance of body muscle tone by a prescribed series of physical exercises will probably be necessary at least three times a week for all lunar-base personnel.

Playing

Various types of light recreation should be provided as a means of relaxation. All work and no play will eventually make sluggish men. As we learn more about the prolonged effects of lunar gravity, a recreational program will evolve that will provide body conditioning as well as relaxation. Games and competitive sports may evolve that are peculiar to the 1/6 lunar gravity.

Maintenance

Maintaining and repairing equipment is considered to be the second largest area of activity in the entire lunar-base operation. The base complex is visualized as growing via the "bootstrapping" technique beginning with the initial landing of equipment. It will be absolutely essential, in the interests of self-sufficiency and minimum logistical support, for the lunar-base personnel to develop the capability for maintainability. Initially, equipment may have to be serviced and maintained in a vacuum by space-suited mechanics. It may be good design philosophy to consider replacement of major modular components; the modular units could be replaced and taken into a small pressurized shelter for maintenance and repair. Maintenance of full-size vehicles inside a pressurized facility will be an early objective in construction the base complex. The organization of a fabrication facility should consider the requirements of repairing existing equipment as well as the manufacture of replacement parts and new equipment assemblies. Maintenance logs and component failure identification for all lunar equipment items throughout the program for lunar exploitation will be essential in planning for maximum self-sufficiency. Space-suit workload will be moderate and maintenance workload in the shelter will be light to moderate.

OPERATIONAL LUNAR BASE

Concept

A concept for a fully operational lunar base is shown in figure 1. The site chosen for this base is representative of numerous lunar craters observed on Orbiter photographs. The crater as shown is approximately 20 miles across and about 2500 feet deep. The minerals in this area are located in accessible surface deposits along the walls of the crater. This mining site contains minerals with abundant quantities of oxygen, magnesium, aluminum, silicane, and iron. Previous core analyses have indicated that the mineral deposits extend to 50 meters or more into the crater wall. It is economical to consider extensive exploitation of these lunar resources by use of surface mining techniques. A study of this facility will indicate the following types of installations and equipment erected by man:

(1) Living shelters
(2) Powerplants
(3) Landing pads
(4) Equipment sheds
(5) Launch control center
(6) Surface vehicles and support equipment
(7) Mining equipment
(8) Cryogenic storage tanks
(9) Processing plant
(10) Communication and radar antennas
(11) Launch towers and equipment
(12) Farming shelter and equipment
(13) Telescopes
(14) Maintenance shop
(15) Fabrication plant
(16) Recreation area
(17) Research laboratory
(18) Sewage and waste disposal plant

Note that the units are modularized, for growth and flexibility. As a result of integrated functional planning, a stepwise programed increase in lunar-base capability can occur. In figure 2, the site is shown during the initial stages of construction.

General Construction Tasks

Site Preparation

After the landing of the first logistic vehicles, civil engineers will begin the specific activities in preparation of the site:

(1) *Surveying.*—The entire crater will be surveyed and the location of each permanent facility marked out.

(2) *Mapping.*—Concurrent with the survey-

FIGURE 1.—Concept of fully operational lunar base.

FIGURE 2.—Concept of lunar base site during initial stages of construction (exploring and surveying).

ing activity, maps will be prepared to facilitate building construction. These maps will include pertinent data describing terrain composition and geological structure for the site of each major facility.

(3) *Excavating and/or tunneling.*—Some excavating may be required to provide a level site for each building; this will depend upon the nature and depth of lunar soil. Excavating or tunneling may be required for protection of cryogenic storage tanks because the frequency of meteor fall on the lunar surface is unknown.

(4) *Hauling.*—The movement of equipment of all types from logistic vehicles to all parts

of the lunar base is considered to be a continuous activity. Multipurpose vehicles will be required so that maximum flexibility can be obtained.

(5) *Drilling and Blasting.*—Although these activities are primarily associated with mining operations, some drilling and blasting may be required in the preparation of building foundations and access roads.

Assembly and Erection of Building Forms

In the foreground of figure 3, two spacesuited workmen are shown fastening an anchor cable on the research laboratory located on the crater rim. In the background various assem[illegible]ivities can be seen. In the foregrou[illegible] crater floor can be seen the prim[illegible]pport shelter. This unit has been [illegible] from eight prefabricated units. The adj[illegible]t farming dome is provided with shutters to control solar energy for optimal photosynthesis. The cryogenic tanks of life-support gases are being buried by the bulldozer to the right of the main building. In the center of the crater is located the beginning construction of the launch and landing complex. One supply vehicle is seen being unloaded while another is landing. A third pad is unoccupied. A centrally located service tower is being assembled in the launch complex. Note the vehicles with telescoping erection devices supporting major structure during joining and mating activities. To the right are located three maintenance sheds. These have been erected from nine prefabricated unit modules. Specific task areas for building construction will include:

(1) Hauling
(2) Lifting or erecting
(3) Bolting and joining
(4) Welding
(5) Cutting
(6) Plastic spraying

Plastic spraying to achieve pressurized joint integrity is considered a feasible lightweight technique for sealing these pressurized units once physical joining is completed. The plastics industry has the capability of developing a technique for spraying plastics in a vacuum.

Powerplant Assembly

The power supply for this lunar base is visualized as coming from three possible sources: solar, nuclear, and geothermal. The initial power plant will probably be a nuclear unit or units. As the base capability grows, these will be augmented by batteries of solar cells to generate power during the lunar day. It may be necessary to locate a nuclear power plant adjacent to each major facility. In any event, all power cables will be laid in underground ditches for maximum protection. This will require that at least one of the multipurpose vehicles have a unit attachment, much like a ditcher for laying drain tile, that will dig ditches 3 to 4 feet deep.

Exploitation of lunar geothermal power based upon the increasing evidence for volcanic activity on the Moon provides a fertile area in which man can exercise his resourcefulness in the hostile lunar environment. It will be assumed for this discussion that a geothermal deposit has been identified and will be exploited. This was accomplished during the initial surveying and mapping for the base complex and is the result of geophysical analysis of the lunar-surface strata within the crater. The first plans call for drilling and capping a test well in order to determine the content of the geothermal fluid and to establish the "in-the-well" pressure. This phase of the operation is viewed as a two-man job. Once this task is accomplished, the operating pressure of the geothermal fluid will be utilized as a power source to drill a larger and deeper well. It is assumed that processing equipment will be provided to recover all essential minerals and gases from the geothermal fluid. At this point in the exploitation of lunar geothermal power, the operational feasibility should be established. Further expansion will depend upon lunar base demands and the nature of the geothermal fluid.

Service Area and Support Equipment

The equipment and maintenance area for the lunar base is shown on the right in figure 3. The small units are among the first permanent

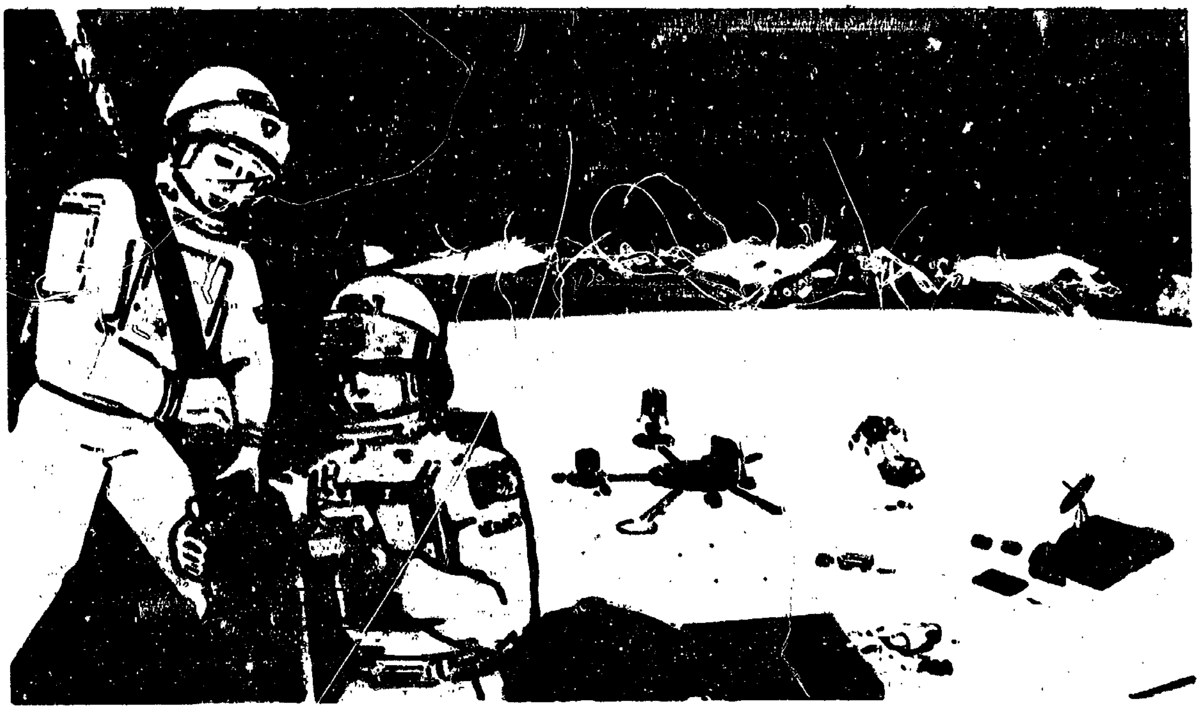

FIGURE 3.—Concept of lunar base site during construction.

facilities established. Initially, only two units comprised a small workshop where equipment components were maintained and repaired, while the other served as a life-support shelter until the main shelter was completed. Gradually, the facility grew to nine prefabricated modular units. The workshop would then provide service and maintenance for all heavy work equipment such as bulldozers, drills, cranes, trucks, rovers, and service and maintenance space suits. This facility may contain a small concrete-processing plant. The power supply for the lunar vehicles will be provided by fuel cells. The water produced by these fuel cells would be removed from storage tanks on each vehicle and stored in the service area for use by the base complex.

Life-Support Station

The main life-support station will contain the following activity areas:

(1) *Emergency safety areas.*—Such areas will be provided to isolate modules in the event one is penetrated by a meteor.

(2) Living quarters will combine the recreation area, sleeping area, rest area, and food preparation and dining areas. It is possible that each major facility will also contain a smaller life-support station for use of each respective work crew.

(3) Adjacent to the living quarters will be a hospital and dispensary.

(4) Communications will be a very important function for work integration throughout the lunar base. It is visualized that the main life-support station will contain a central work site control center. Eventually this will become the base operating control center.

MINING AND PROCESSING OPERATIONS ON THE MOON

Exploitation of lunar mineral resources will be in progress concurrently with the activities which have just been described. Figure 4 shows a concept for open-pit mining of minerals located on the crater rim. The mining vehicles shown are multipurpose units containing life-support cabs. The vehicles perform the inte-

FIGURE 4.—Concept of open-pit mining for minerals located on crater rim.

grated functions of drilling and loosening the ore, grading and conveying it into a crusher, and then loading the ore into a transport carrier. The ore-processing facility can be seen on the left side of figure 4. Other mining-site tasks not shown in the figure that may be required are outlined as follows:

(1) Drill rigs:
  - (a) Setup and assembly
  - (b) Drill monitoring
  - (c) Geological survey
  - (d) Drill core recovery
  - (e) Logging and data recovery
  - (f) Blast preparation
  - (g) Blasting

(2) Additional mining support or excavating equipment:
  - (a) Bulldozers
  - (b) Scoop shovels or diggers
  - (c) Earthmovers
  - (d) Conveyor belts and/or buckets
  - (e) Rock crushers
  - (f) Mineral hoppers
  - (g) Trucks and trailers

From time to time, ore samples for mineral assay will be collected at the mining site to assure that mining operations are concentrated on the highest grade ore deposits. A space-suited geologist is shown in the right corner of the figure performing this task.

After the ore has been mined, it is transported to the processing and extraction facility. Figure 5 shows a processing and extraction facility primarily concerned with the recovery of oxygen and hydrogen for use as rocket engine fuel and life support. Other types of extraction processes will be required to reduce ore to basic minerals such as iron, aluminum, and magnesium. Extraction of gases from minerals was considered to be a process similar to that used by the oil industry to fractionate petroleum. The gas mixture is collected in the storage tanks, which may be either fixed or mobile. The space-suited workmen seen in the fore-

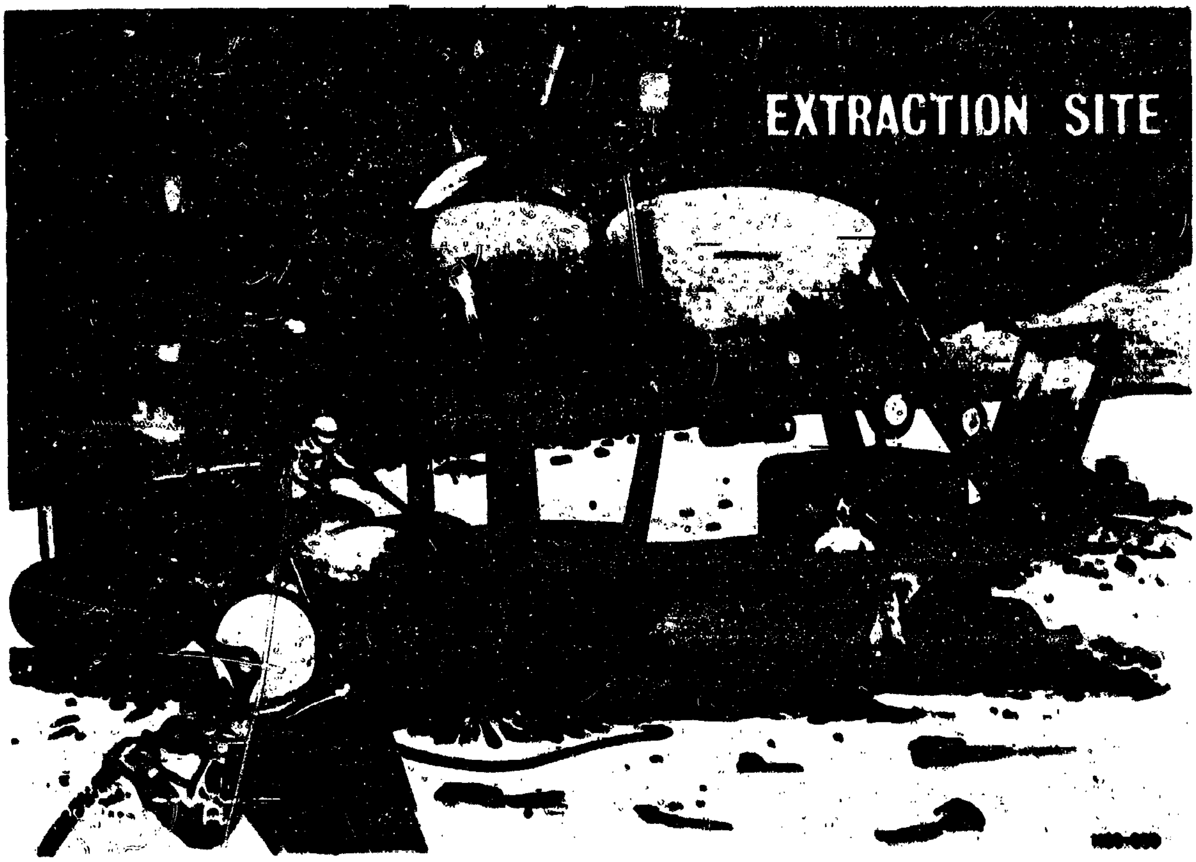

FIGURE 5.—Concept of extraction site.

ground may be completing the connections of a high-pressure gasline leading to a cryogenic facility where the gas is liquefied and stored in underground storage tanks. The portable tanks seen may be used for the purpose of collecting precipitates and sublimates, which will be reduced by other extraction processes to useful minerals. An operation of this type will require three to four men.

When the mining and mineral extraction capabilities reach a level where pure metals are available, then a fabrication facility for the manufacture of all types of equipment will be required. Such a facility is shown in figure 6. The activity emphasized in this figure is the fabrication and assembly of rocket vehicles for further scientific exploration of the solar system. In addition to this important activity, the fabrication facility will be capable of manufacturing new pressurized shelters as well as replacement components for base equipment. In many respects, the manufacturing facility might be considered as a supermodel shop, because many new equipment items could be one-of-a-kind special-purpose units. This is the last step in maximizing the self-sufficiency of the lunar base complex.

CONCLUDING REMARKS

In conducting the analysis of all activities that man will perform on the Moon, no task could be found that could not be performed by the proper man-equipment relationships. This can be assured by extensive planning and sound engineering design of equipment. As a sum-

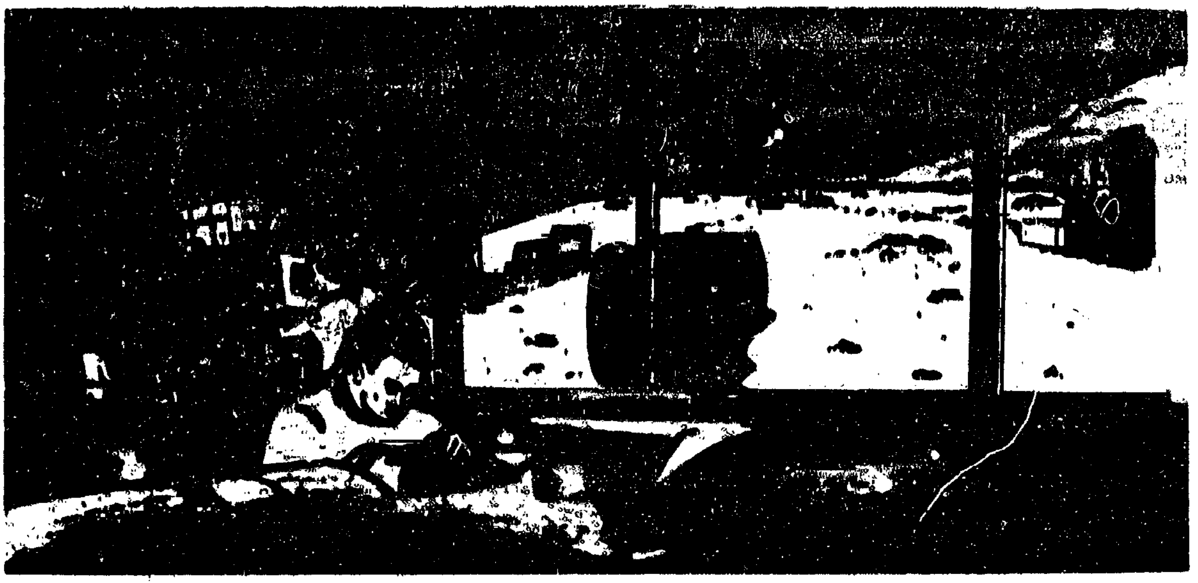

FIGURE 6.—Concept of fabrication plant.

mary of man-equipment requirements, six major areas concerned with the safety of man in the lunar environment are:

(1) Space suits
(2) Life support
(3) Tools, vehicles, and support equipment
(4) Radiation warning system
(5) Integrated communications:
  (a) Work frequencies
  (b) Emergency frequencies
(6) Performance capability

In the next 20 years, space suits will evolve into well-engineered functional units with integrated life-support systems having a minimum of 8 hours' capability. Man will readily adapt to the working environment using this equipment.

Tools, vehicles, and support equipment will be initially designed to maximize their utility on the lunar surface. Yet, knowing man, he will find means of using them effectively for purposes for which they were not intended, so that he can accomplish maximum mission effectiveness. Man's inherent ability to improvise spot solutions for the unexpected is man's greatest attribute.

The lunar research laboratory shown on the crater rim in figure 1 in conjunction with Earth-based observatories will have the primary responsibility of operating and maintaining a radiation warning system. This warning system will be keyed into the integrated communications network. Through assigned emergency frequencies, all base personnel will be informed of anticipated increases in radiation levels that may require temporary cessation of external base operations.

An integrated communications network is considered essential to safe lunar-surface operations. In addition to emergencies mentioned above, all major work parties should be monitored in the base central control. As man extends exploration activities over the lunar surface, communication with these exploring parties may be maintained first via Earth relay and later by lunar-orbiting communication satellites. It is visualized that man will service and maintain these satellites by service vehicles launched from and returned to the lunar-base complex.

What is meant by performance capability? This is a term that means different things to each scientific discipline. When applied to man, it means the capability of accomplishing the general performance functions of walking, running, jumping, climbing, standing, driving,

TABLE 2.—*Space-Suit Performance Capability*

Joint system	Movement if nude, deg	Range of movement, deg		Max torque, ft-lb	
		Present	Future	Present	Future
Shoulder	180	165	180	20	5
Elbow	140	140	140	5	2
Wrist	135	135	135	.75	.75
Waist-hip	120	110	120	40	20
Knee	135	130	135	10	5
Ankle	85	20	35	2	1

Task	Unsuited cost, Btu/hr	Suited metabolic cost, Btu/hr	
		Present	Future
Standing	440	500	450
Walking slow	900	1200	1000
Walking fast	1100	1600	1200
Assembling	680	1600	900

and flying, and the specific performance functions of—

Reaching	Pulling
Grasping	Pushing
Holding	Turning
Transferring	Inspecting
Opening	Probing
Connecting	Squeezing
Locking	Sighting
Stowing	

in any combination. When man is considered as a resource in the accomplishment of a mission, all his tasks and equipment relationships can be detailed in a functional task analysis. These data are then useful in establishing man-equipment requirements for use as design criteria. Depending upon the detail required, each task can be reduced to a range of motion for each one of man's joints. Such data can then be applied in space-suit design, in work-space layout, and providing accessibility for equipment repair and maintenance. We have obtained such data for a man-space-suit system by establishing an overall performance level for the use of the equipment design.

Many of the tasks that have been discussed will require extravehicular performance by man. Table 2 summarizes the present space-suit performance capability for both range of motion and metabolic cost of suited performance. These data lend credibility to the estimates outlined for man as a resource on the Moon. On the basis of improvements in pressurized performance achieved in the last 2 years, it is predicted that the nude range of motion for all suit joints with fairly low force levels and metabolic cost will be accomplished in the next 5 years.

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