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My wife, Anita, exemplified the description of a wife given by the writer of Proverbs during this time, and in addition to her duties as mother and wife, her services as typist, editor, and critic were invaluable.

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CHAPTER I

INTRODUCTION

Since the beginning of the industrial revolution, each fifty year span has brought forth technological achievements undreamed of by the intelligentsia who lived at the start of the period. Technological advances can also be expected over the next fifty year period unless men, through their politics, misjudge each other and misuse the powers they now possess to annul or even destroy the present civilization. Progress in space exploration would be truly fantastic if the momentum generated by the space program within the past decade is allowed to continue into and over this era.

In the next fifty years of the space effort man will have extensively expanded the commercial utilization of near space which began with COMSAT, will have traveled throughout the solar system, will have landed on several of the earth's sister planets, will have established manned bases on several of these planets and the moon, and will have sent unmanned probes into deep space to gather data for future manned missions. For a proper perspective, one must keep in mind

H. G. Wells prediction made in 1902 that "probably before 1950 a successful aeroplane will have soared and come home safe and sound."

Underlying all the other reasons for man's entry into space is his curiosity. This trait has been the primary cause for most of the exploration of this planet and for the expanded storehouse of knowledge concerning these surroundings. Other motives for going into space have been amply discussed and documented over the past two decades. Numerous schemes of space exploration and exploitation have been advanced based upon these reasons. The objectives of these schemes have been concerned with scientific, commercial, or military ends. The advocates of these plans have assumed that the technology necessary to fulfill these objectives exists. In fact, the visions of Arthur C. Clarke, and others of his ilk, have served to stimulate thought about the specific planning efforts and design of equipment that will bring these visions into reality.

The costs of these space goals have been brought home to the American public with the culmination of the late President Kennedy's dream of placing a man on the moon. What effect these high costs bear on the national space program after that epic flight, and the remaining Apollo follow-up flights, is very uncertain in view of pressing national problems. History has shown that there exists a considerable time lag between the discoveries and explorations of new lands and the exploitation phase. The tide of public opinion may delay the exploration phase of the moon at the present, but the path has been blazed. The desire for knowledge and the chance for profits will insure that the exploration and exploitation of the moon's resources will occur just as surely as those acts which stemmed from the sailing of Columbus' fleet in 1492.

The Exploration Process

The steps in this process are similar to those followed by historical man whenever he came to the border of a land possessing an environment different from that to which he was accustomed. The most recent example of this, and the best correlation to the lunar exploration, is that furnished by the polar explorations initiated in modern history, and still in progress. It can be expected that the lunar exploration will follow a similar sequence of events.

After the discovery of the polar regions, man began to explore and search the regional boundaries and surface forms. This first phase of exploration was concerned with the discovery and mapping of the surface features of these two regions. The areas presented a new, hostile environment to man. Progress was often slow because new equipment and technology had to be developed that would conform to the polar environment.

As features and points of interest were noted, the second phase characterized by scientific research was undertaken. In this phase detailed studies were made of the environment, the flora, the fauna, the geology, and the meteorology of the two regions. This second phase is still in progress and has lead now to the initiation of the third facet of exploration.

The last phase consists of man permanently inhabiting the area so that he can exploit the resources found there. This entrance into the third phase has been induced by the discovery of deposits of anthracite coal at Camp Ohio in western Antarctica, and by recent oil field discoveries in northern Alaska. Man's search for energy sources will provide the impetus for this third phase in the land region of the Arctic, and on the Antarctic Continent. It will serve as the lure of gold did for the western United States a hundred years ago. As time passes, additional opportunities for exploitation of the polar regions' resources will arise and provide for the expanded settlement of these areas.

There has been a long period of costly investment by the United States government in its polar investigations. It is doubtful, from a commercial standpoint, whether much return has occurred to our economy. The mineral exploitation phase is just about to begin, and tourism has not yet become important. Great returns have been made on the knowledge gained from the polar expeditions when examined from the public viewpoint. The knowledge of man's life support requirements, of construction techniques, and the behavior of materials and equipment in a cold environment were and are utilized in our national defense efforts. Money values are also difficult to assess when better forecasting of the world's weather results from a more complete knowledge of the polar regions.

Problems Along the Space Frontier

The role adopted by the Federal government in the space program has numerous, historical precedents. Our government and other national governments have in the past supported terrestrial exploration efforts. Some have even sponsored the exploitation phase. Our government, however, has depended on commercial interest to exploit and develop the new lands after government-supported exploration uncovered the resources available.

Public opinion has not played a dominant role in polar exploration because of the lower amount of money spent in comparison with the space program. Unlike the early polar expeditions which were able to take conventional equipment and "cold-proof" it for use in the polar regions, the space program has required the development of complete, new lines of exotic equipment, techniques, and services before exploration could actually begin. Therefore, the initial program costs were high.

A vast, government-directed complex of men and equipment in both private and governmental research, production, and service organizations was initiated to achieve the goals of the national space program. This complex, in directing its efforts toward the achievement of its goals, found its progress delayed by the lack of factual evidence upon which to base its designs. Whole new areas of research had to be opened, with data being collected and analyzed, so that this information could serve as the basis for both procedural and equipment design to achieve the program's goals. The costs of the program have increased correspondingly as the needs for necessary design data grows.

In the aftermath of the orbital flight of Sputnik I, a crash program was begun. Space goals were assigned with such short deadlines that it was impossible to investigate all the feasible methods. Undoubtedly, this has caused unwise decisions during the development of the program. The fact remains that a lot was done in a short time and goals were obtained.

An entirely new form of transportation had to be developed to permit man to travel through space. Life support systems which furnished all the physiological requirements for the astronauts for the duration of the expedition had to be designed and developed. These were penalities with which no previous exploration programs had to cope.

The mode of propulsion for the present family of spacecraft is very inefficient. The method of using multi-stage rockets to launch payloads into orbit requires 100 grams of propellant per gram of payload, whereas, theoretically only 6 grams of propellant are required to launch 1 gram of payload into orbit. This low, thermopropulsive efficiency of rockets, combined with the practice of using disposable rocket motors and spacecraft, has caused the unit cost of launching a payload into orbit to remain high. Even though the cost per pound of payload has decreased considerably since the early stages of the program, it will still take some time before refinements in equipment and techniques drop the cost to $10 per pound. This is the predicted point at which costs will be low enough to permit wide-scale, commercial utilization (Berkner, 1968). The present high costs of placing payloads into orbit have placed very tight constraints on both men and equipment sent into space, and the amounts of their operating time, thereby, delaying the overall program progress.

The costs of the space exploration program have been and continue to be so high that numerous voices have been raised against the government's continuance of the program at this level of expense. The proponents of the program argue that, since this buildup has occurred, any retardation in the program will just increase the costs. Only the government has the resources to conduct this phase of the exploration, and if the trained manpower is allowed to go elsewhere, the nation will at a later date have to again train another group to the present state before forward progress can occur.

The Objective

Whether the followup to the present lunar program is immediate or prolonged, certain basic questions must still be answered before progress in the lunar exploration effort can be continued. One of these vital areas in which information must be generated is that of water usage and facilities for this use. It is with this particular area that this study has been concerned. What is done on the moon can, with environmental changes, be adapted for use in other planetary situations.

The specific objective has been to examine the various possible choices that can be made available to satisfy the water requirements of manned lunar bases or colonies under the constraints imposed by the lunar environment.

General Procedure

This study will be composed of three parts. The first part will consist of a discussion of the needs and uses of water by man in space. Next will be an evaluation of the physical characteristics of the moon which pertains to the occurrence and use of water. The last and major part will examine the integration of the physical possibilities with the needs of man to develop various schemes of water supply, water use, and water treatment for the lunar bases.

CHAPTER II

THE NEED AND USE OF WATER BY MAN

Environment and Life

Terrestrial life has developed under many different sets of environmental conditions. As a result, the living organism bears the stamp of its place of origin in its dependency upon given characteristics for maintenance of life. Some of the surroundings under which the organism developed are not as restrictive as others, and successful species adaptations can be made at times to changes. This adaptiveness enables it to invade new territories where the altered conditions exist, to inhabit the area, and to multiply the species. There are, however, certain basic qualifications of the original environment upon which the specific species of organisms is dependent that cannot be varied without drastic changes in the species itself.

As a biological organism man has been very adaptable as he encountered different physical conditions and social situations in his movements over the interface between the gaseous and liquid-solid phases of this planet. Travels by man into areas above or below this boundary necessitate his taking an atmosphere and climate similar to that of the interface, because human life developed there under conditions of free access to the earth's atmosphere and to the temperature regime found in the Mediterranean regions. Man, as evolved, is now highly dependent upon both particular levels and conditions of these two factors for life itself.

The minimal levels of man's physiological requirements have been determined. These low levels have been used as design criteria for current life support systems. These systems have been developed to provide the basic physiological needs of trained, motivated men who operate for short periods of time in the ocean depths or space. They have been designed around the mechanical equipment that performs the major mission objective rather than planned as entities themselves. Therefore, the design of self-contained life support systems is still in the primitive stages.

Due to cost factors, the design of celestial life support systems will probably also be directed toward the minimal rather than optimal levels of physiological needs until late in the exploration period. Surprises may occur since present adaptive responses to these modified conditions could have hurtful, secondary effects at a later time. Consideration of this factor, along with information being gained through advances in the social sciences, will have an impact on future planning.

It is generally accepted that man must have other amenities in addition to those concerning his physiological needs if he is to retain his humanness and, thereby, his effectiveness over extended periods of time. Research is being directed towards determining these factors, but the full implications of these facets of environment on the continued development of the individual is unknown. It is highly probable that all facets of the terrestrial environment act together in a synergistic manner to shape man. Rene Dubos, the biologist turned environmentalist, advances the thesis that each man is continuously shaped by his particular experiential past through specific social and physical experiences. He advocates that great diversity in surroundings should be provided to enable the maturation of the many latent potentialities within individuals which are needed to further the advancement of man (Dubos, 1968). When permanent or semipermanent settlements in space, or in the ocean depths, are contemplated, provisions for providing environmental stimuli must be engineered into the design of the systems to foster the continued development of the inhabitants.

Man and the Celestial Environment

The spatial environment, and the lunar surface in particular, will be hostile to all forms of life that have developed under terrestrial conditions. Confronted with this predicament, man has three alternatives if he desires to inhabit or to colonize the extraterrestrial bodies (Levitt and Cole, 1963). He can take his environment, but this involves a large penalty since everything needed for life support must be exported from earth. The second alternative is that he can transform the hostile environment into a benign one by synthesizing chemicals and materials needed for life from local sources. The third choice involves the use of mutants or biologically abnormal individuals who can survive serious environmental changes that would destroy normal terrestrial humans.

It is within the framework of the first two alternatives that practical thought and effort must be directed for some time. There will be ample technological and moral problems to solve within the confines of the first two propositions, without the additional problems which would arise from a program directed toward the creation of human mutants for space operations.

As the exploration process occurs for any extraterrestrial body, it is logical to assume that transition from the first alternative to the second will occur. Man will have to take all his basic physiological requirements and the necessary dispensing equipment on the first exploratory trips. As exploration continues local sources which can supply some of his requirements may be discovered and exploited, so that he can hopefully create a local environment that requires a minimum of terrestrial resupply. This sequence of development must be followed if much colonization is to happen.

During the early phases of lunar exploration the astronauts will utilize the self-contained life support systems that are presently used by the Apollo spacecraft and LESA modules. In this frontier situation limited conveniences and levels of physiological support will be tolerated. As exploration continues and the need for more men and longer mission times increase, the life support systems must be designed to provide more optimum conditions and to utilize local sources of materials for life support needs.

Space and the General Physiological Needs of Man

The physiological requirements of man can be divided into static and operative needs. Static needs can be met by design procedures in that lifetime protection against such items as cosmic radiation, noise, or vibration can be built into the life support system. The operative needs are those that must be supplied continuously to man, and generally require periodic, external inputs of energy or material into the system. The most critical of these operative needs are food, water, and air.

Man must have gaseous oxygen to breathe. He can live only thirty seconds without it. Deprivation of oxygen for periods less than this can cause immediate, irreparable damage to the brain, or can effect long range damage. Since man can survive several days without water and even months without food, the critical design factor for the life support system must be the one that pertains to oxygen and the atmosphere which contains it.

Man must surround himself with a pool of air which is maintained within a critical range of temperature, pressure, and composition. The oxygen must be kept at a specific level and pressure so that the human body can consume and utilize it. Contaminants must be kept dispersed and at low levels if man is to live and function effectively. Water vapor must be held at a certain level to prevent extreme desiccation of the body.

Since minute or hostile atmospheres are found in space, the requirement for the pool of air restricts human habitation to an air bubble form of existence within the confines of a space suit, or more vast surroundings, such as would be found in a space station. The structure for the bubble must be strong enough to prevent collapse due to the pressure differential that exists between the exterior and the interior. The skin of the bubble must be made of an impermeable material so that minimal loss of the artificial atmosphere by diffusion occurs.

The air bubble must also be protected against possible puncture by meteorites. The lack of an atmosphere will enable proportionately more meteorites to strike the surface than occurs on earth. On the moon a layer of lunar material will protect the bubble against impacts by particles the size of cosmic dust or small meteorites. As on earth there will really be no protection from a direct hit, or near direct hit, such as the 1908 fall of the Tunguska meteorite in Siberia. The need for protection against meteorite falls will require man to build his life support facilities underground. Small excursion and "outdoor" activities can be undertaken with less shielding, but permanent underground quarters will be a necessity to insure the survival of a lunar colony.

The Uses of Water by Man

The primary need of water by man is based on the requisite of the human body for a stable fluid balance. Total body water is equal to about 40 to 65 percent of the body weight. This proportion varies as to the age and sex of the individual. Water is continuously lost from the body through metabolic processes, and at periodic intervals, water must be ingested to replenish this loss. The fluid level must be maintained within a specific range for each individual, since with only a moderate dehydration of 2 to 4 percent of the body weight, the heart rate increases, the deep body temperature rises, the individual may develop overbreathing, and the onset of mental instability and depression can occur (Wolf, 1958).

Each human loses water by the same body processes, but the exact amount will vary from person to person due to differing individual characteristics. Average losses of water have been determined under varying stress conditions (Wolf, 1958; Licht, 1964; Best and Taylor, 1966; and Roth, 1968). A man of medium size engaged in light work loses an average of 2500 grams of water per day. The daily output of water from the various sources would be as follows:

urine--	1300 ml
sweat--	650 ml
lungs--	450 ml
feces--	100 ml
Total--	2500 ml (Grollman, 1969)

Water losses in the body are replenished by the ingestion of liquids, semi-solids and solid foods, and by water synthesized by the metabolic processes that take place in the body. The amount of metabolic water synthesized varies according to the composition of the diet, but averages about 300 milliliters per day. Liquids inbibed and water from semi-solid and solid foods amount to 1200 and 1000 milliliters per day, respectively. Thus, the total daily intake balances the average daily loss, but this too varies widely in individuals and their conditions.

Water is by far the most abundant chemical in the human body and diet. It has no equal in the number of functions it performs in the body. The absence of water from the diet will cause a quicker death than that resulting from the withholding of any other dietary need.

Man's dependency on water caused settlement near water supplies, and this biotic relationship led to the employment of water in many secondary roles. Man employs water in the growth and preparation of food. He uses it to clean his body, his garments, his tools, and his places of habitation. He utilizes the properties of water in the manufacture of items and in the provision of services that are necessary to the support and maintenance of human life as is known today. It is used for the development of pleasant surroundings and as a source of recreation. Water serves as a transport medium for items of consumption, for wastes generated from man's body, and for processes directed by man. These wastes are transported from the point of origin to the point of disposal.

The amount of water used in these secondary roles is determined by the volume available at any one terrestrial location and the kind and sophistication of the competitors for water there. The water actually consumed by man in the fulfillment of his basic needs is but a minute fraction of the water used otherwise.

High per capita use at any particular location, therefore, does not necessarily reflect that the local population has a better environment, or a better standard of living than a neighboring site with lower per capita consumption. It may indicate these facts, but human life and the functions associated with it can be maintained efficiently at lower per capita consumption levels than those projected for future planning in the United States. The figures given in Table 1 give the ultimate daily

TABLE 1

ULTIMATE DAILY CONSUMPTION

Average Family of Future:

4 persons
2 automobiles
2 bathrooms
1 garbage disposal unit
1 dishwasher
1 automatic laundry

Family Use/Day

		gal/day
Drinking and water used in kitchen: 2 gal/per. x 4	=	8
Dishwasher: 5 gal/load x 3 load/day	=	15
Toilet: (2) 4 flushes/pers. x 6 gal/flush x 4	=	96
Bathing: 20 gal/bath x 4	=	80
Laundering: 6 loads/week x 40 gal/load	=	34
Automobile Washing: $\frac{\text{2 cars x 1 wash/car/mo. x 150 gal/wash}}{30}$	=	10
Lawn Watering: 2 hr/day x 90 days/yr x 200 gal/hr	=	100
Garbage Disposal Unit: + 1% x 343	=	3
		346 gal/day

Unit Consumption (Domestic) - $\frac{346}{4}$ = 86.5 gcd

Source: G. W. Reid, Water Supply and Sewerage (Lecture Notes) (Norman, Oklahoma: University of Oklahoma Book Exchange Duplicating Service, 1967), Table 1, p. 4.

consumptive use for a member of a future terrestrial family (Reid, 1967).

These factors must be kept in mind when water requirements for space are discussed. Man based away from earth will require water to fulfill his primary needs in like manner of his earth-living counterparts. He will not have a large supply of water available for employment in secondary purposes at any time in the forseeable future. The relatively high cost of lifting a pound of mass into space, even at the time of commercial exploitation, will still predetermine water usage at rates lower than common terrestrial levels.

The inhabitants in the controlled environment of the space station will not be affected by the extremes of heat and cold which raise terrestrial consumption rates. The smaller water consumption rates in space will still provide a high standard of living which is important in view of the scarcity of space water supplies. An adequate water supply will be essential to promote group morale and health in space, as has been the case on earth.

The definitive amounts needed to enhance space living have not been established. Estimates of the water necessary range from 6 to 20 gallons per man per day (Breeze, 1961). IGY Antarctic personnel used about 11 gallons of water per day in a facility which provided the conveniences of hot and cold showers and washing machines. The diversity exhibited in personal tastes, habits, and background will tend to increase the amount of water used for domestic purposes with the addition of more base inhabitants. A hundred-man base in outer space will require much more than the minimal 2500 milliliters per capita required for satisfying physiological needs. New uses and new technology could alter future requirements considerably. The needs in space could possibly reach higher levels than those predicted for earth.

It is uncertain whether the figures listed are plausible for planning in space. Other factors cannot be evaluated with preciseness, but at the rate of $10.00 per pound, the amount of water that has to be imported for use attains immediate significance. Assuming that a man is provided with 2 gallons of imported water per day for personal consumption, the cost of water transport alone for a six months mission amounts to $27,000. This figure would be increased substantially if weight for containers and water facilities were added. When reuse is planned, savings in weight can be expected. If 200 pounds is allotted as each man's share of water system facilities, and 50 gallons are provided for his daily use, the cost of water support will be about $5500. The total expense will be less, and the intangible benefits gained from the extra water use will be more than in the former case.

In planning to meet human requirements for water on the moon, one of two routes can be selected. The planners can take terrestrial formulated philosophy and technology and adapt it for lunar water use. They could, however, re-evaluate man's needs for water, form a new philosophy of water use based on these needs, and then develop a new technology based on the constraints imposed by the lunar environment. It is this latter approach which promises rewards in reducing weight exported from earth during the establishment of manned lunar stations.

A simple model can illustrate the variations of transport costs for different schemes of spatial water use. On short missions water requirements can be minimized, but as stay times increase, more elaborate diets and higher standards of personal hygiene will incorporate greater usage. Table 2 pictures the variations in costs for supporting a man with the basic life support items on missions requiring 180 days when individuals are rotated every 10 days, 30 days, or at the end of the mission. Water use is restricted regardless of the length of the period on-station since the water is wasted after use. The consumable items cost $22.00 per kilogram for transport to the space station. The cost of shipping the storage containers, treatment units, dispensing units, and equipment for processing lunar minerals is ignored for the purpose of this comparison. The transport costs for each man is based on $33.00 per kilogram for the round trip.

TABLE 2

VARIATION OF TRANSPORT COSTS WITH TIME SPENT IN SPACE

Items Transported	10 day		30 day		180 day	
	kg/day	cost per stay	kg/day	cost per stay	kg/day	cost per stay
Man (68 kilograms)		$ 2,240.		$ 2,240.		$ 2,240.
Water drinking	1.2	264.	1.2	790.	1.2	4,750.
wash	1.0	220.	3.0	1,980	4.0	15,800.
food reconstitution	1.0	220.	.7	460.	0	0
Food	.7	154.	1.2	790.	2.1	8,300.
Oxygen	.9	198.	.9	594.	.9	3,570.
Cost per rotation period		3,296.		6,854.		34,660.
Total cost to support a man for the 180 day mission		$59,324.		$41,124.		$34,660.

The source of the station's water supply and the schemes of use, likewise, influence the cost of supplying the life support materials. Through comparing various strategies which utilize different sources and practices of water use, the magnitude of differences is exhibited. Each inhabitant requires a daily allotment of .7 kilogram of food and .9 kilogram of oxygen. The food allotment contains an average of about 50 grams of water. The amounts of liquid water furnished will vary as to the plan of water use. The strategies are structured as follows:

Plan A--Each inhabitant is provided initially with 59 gallons of water (i.e. 222 kilograms). This amount is recycled daily through the system. The value is obtained from Table 1 after deleting the portions for the lawn, car, and garbage disposal. Feces and the urine associated with bowel movements are wasted from the system since it gains this approximate amount through metabolism and inputs from food.

Plan B--This is the same as Plan A except water allowed for toilet use in Table 1 is deleted. Urine, except as noted above, is treated and the product water is reused. Each person is provided with 34.2 gallons of water (i.e. 129 kilograms).

Plan C--The inhabitant is provided with 11 gallons (i.e. 42 kilograms) which is the amount used by participants in the Antarctic IGY study. The use scheme follows that of Plans A and B.

Plan D--Each inhabitant is provided with daily allotments of water which consists of 1200 milliliters for drinking, 950 milliliters to reconstitute the food allotment, and 2000 milliliters for washing. All used water, sanitary wastes, and water vapor are ejected from the station. The system requires 4.15 liters of imported water daily for each inhabitant.

Plan E--Same as Plan D except the humidity control system reclaims some 1100 milliliters of water from vapor produced by each inhabitant, and 100 milliliters of water from vapor that results from washing activities. The system requires 2.95 liters of makeup water daily for each inhabitant.

Plan F--Same as Plan D except all vapor produced and waste wash water is reclaimed for use. The water system required 1.05 liters of makeup water daily.

Plan G--Same as Plan D except all vapor produced, waste wash water, and urine, except that associated with the bowel movement, is reclaimed for use. A backup supply consisting of 10 kilograms of water for each inhabitant is carried initially into space.

Plan H--This is the same as Plan D except cryogenic hydrogen is carried into space and combined with locally produced oxygen at the space station. A weight savings is made since hydrogen constitutes only 11.2 percent of the weight of water. The imports of oxygen are discontinued.

Plan I--This is the same as Plan E, but with the provisions of Plan H.

Plan J--This is the same as Plan F, but with the provisions of Plan H.

Plan K--Local water and oxygen supplies are available for use at the space station.

A comparison of the plans is shown in Figure 1. Plan K is the most desirable. It can be seen that with time the greater amounts of water provided in Plans A, B, and C become feasible. The other plans can be used initially, however, and the wastes stored. At some time in the future, these wastes could be regenerated and Plans A, B, or C could be instigated.

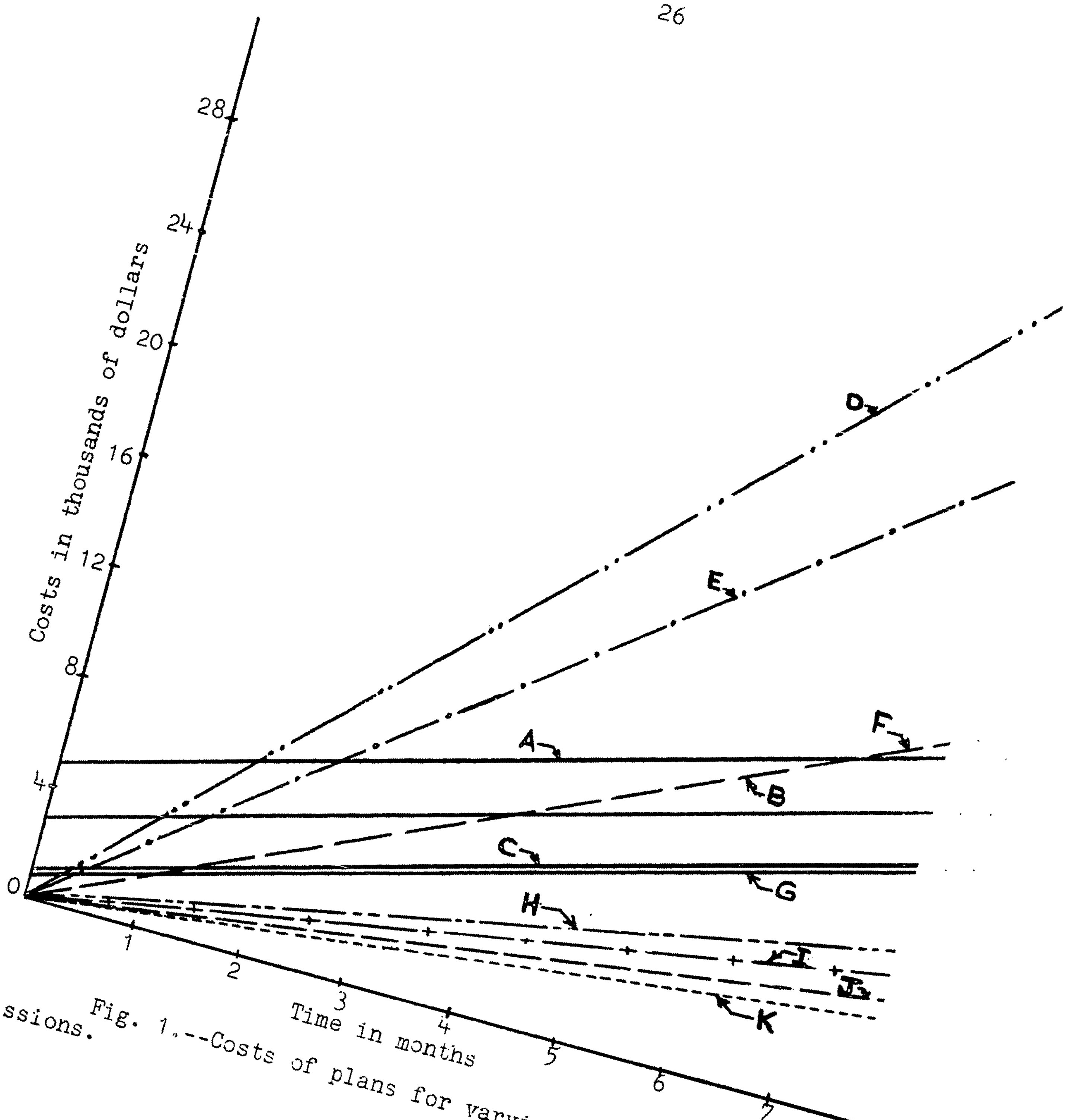

Fig. 1.--Costs of plans for varying lengths of missions.

CHAPTER III

WATER AND THE LUNAR ENVIRONMENT

Physical Properties Affecting the Occurrence and Nature of Water

The effects of the hypotheses of origin upon the occurrence of water

The probability that water bearing materials are found on the moon's surface are based upon hypotheses of the origin and history of the earth-moon system. These theories are in the conjectural realm since the evidence presented in the lunar rocks is still obscured. The photographs, rocks, and personal observations obtained from the Apollo flights, and the data garnered from the earlier unmanned lunar probes, should indicate the most plausible theory of origin.

The three hypotheses generally advanced are: the moon was removed from earth by tidal action; the moon was captured by earth at some time after each had been formed and attained their present mass; and the moon and earth originated as a double planet.

The escape process would have resulted in a breaking and mixing of surface and deep terrestrial material, followed by extensive collisional processes. Therefore, it would seem probable that the moon is highly contaminated with water since so much of the outer mantle of earth is composed of water. Surface fragments of sedimentary rocks may be found if this escape took place some $1X10^9$ years or more after the earth was formed. Residuals of organic matter might be located if the latter were present at the time of rupture.

The capture hypothesis entails the belief that the moon was formed some place other than that of its present position. The place of origin could be in this solar system, or in some far-off galaxy. The moon was then captured by earth as a result of a chance encounter. If this hypothesis is correct, the possibility of water on the moon is based on current theories of the composition of primordial material. Perhaps some water, other than the primordial water, will be found on the moon because of violent activity at the time of capture. Since water covers such a large portion of the earth, copious amounts must have been ejected into space in the collision. The moon should have captured a portion of the material ejected into space from the earth. The water that was caught could have formed temporary streams and lakes on the moon's surface and some could have percolated downward into the surface layers of the moon. It could have reacted chemically with the moon material, or maybe free water remains as ice in the sub-surface layers.

The last hypothesis is based on a double planet origin. The conditions for the existence of water rest on the estimation of the constituents of the pre-existent solid materials which formed the mass of the moon. Under the conditions of the agglomeration of solid particles which comprise the moon, the chemical forms should be those of the primordial matter from which the solar system originated. If the moon material is essentially the same as that of the earth, the most abundant elements should be O, Si, Mg, Fe, S, Al, Ca, Na, Ni, and Cr in that order (Urey, 1958). This matter should include a finite concentration of volatile compounds such as water. At low temperatures, volatile compounds could have been absorbed into the crystal lattices of many minerals and could have been existent in the new-born moon in a solid state.

If, however, the composition of the moon corresponds to that of the carbonaceous chondrite type of stoney meteorites, the moon should have contained considerably more water than that of the former model. This type of meteorite has been said to represent the closest approach to the primordial dust from which the solar system originated (Moore, 1962). Though representative of only 4 percent of the observed terrestrial falls, Urey has pointed out that these types are probably more abundant in the composition of asteroidal matter. These chondrites are extremely fragile and would not survive their atmospheric entry as well as other types. (The amounts of primary, volatile components in these carbonaceous chondrites contain from zero to

20 percent water, 7 percent sulfur, and 5 percent carbon and its derivatives.)

A broad analogy drawn between moon and earth shows the possible magnitude of water contained within the moon (Kopal, 1966). If the waters of the earth's oceans had been released by the uniform desiccation of the whole mass of the earth (equal to 5.98×10^{27} grams), each gram of mass would have contributed 1.54×10^{-4} grams of juvenile water. The volume of water contained within the earth's oceans is capable of covering it with a uniform layer of water nearly 1800 meters deep. Applying the corresponding portions of water to the mass of the moon (equal to 7.35×10^{25} grams), a layer of water nearly 300 meters deep would cover its surface.

The lunar atmosphere

Early astronomers noticed that the moon never had clouds over its surface as did earth and Mars. With the development of better equipment and techniques, the atmosphere of the moon was further studied. Dollfus, in his experiment with polarized light, established the upper limits of density of the lunar atmosphere as 1×10^{-10} that of terrestrial atmosphere. Later work by Elsmore with radio emission studies depressed the value of the lunar atmosphere to a value of about 2×10^{-13} that of earth (Costain, 1956). This is a much better vacuum than ever obtained on earth, but is many times larger than that found in deep inter-planetary space where some 10 to 1000 particles per cubic centimeter are found.

The reasons for this lean atmosphere are due to several factors. The continuation and composition of an atmosphere around a celestrial body are due to the equilibrium established between two opposing forces. This is the gravitational force which ensues from the attraction of the central body on each gas molecule, and the force which results from heat pumped into the gas by the sun and by the reflected heat from the surface of the central body. This heat maintains the kinetic energy of the gas molecules and extends the atmosphere. The conditions of small mass, low escape velocity, and large temperature fluctuations have resulted in the moon having little appreciable atmosphere at any time in its history. Estimations show that molecules with atomic weight of less than 60 will escape during the hot lunar day (Kuiper, 1949). From theoretical and observational evidence, it is likely the gases escaped as rapidly as they appeared. In places that are shadowed from the sun's rays thicker atmospheres possibly are present, but even these will not be of much greater magnitude than the atmosphere in the sunny sections.

There are three other consequences to the lack of an atmosphere to manned exploration and settlement besides that of restricting man to an air bubble existence. The first consequence is the harsh temperature environment as compared to earth.

Here the atmosphere acts as a shield that protects life from the extreme temperature variations resulting from earth's rotation. The atmosphere is nearly transparent to incoming short wave radiation from the sun. Oxygen and ozone in the top layers trap some of the incoming ultraviolet radiation. The major deterrent to high surface temperature is caused by the clouds, dust, and water vapor reflecting the incoming radiation back into space. These same agencies also scatter portions of the incident radiation so that it reaches the ground as diffuse sky radiation. The part that reaches the earth's surface is not all converted into heat because of surface reflectiveness. The average albedo of the earth's surface has been estimated to be 36 percent (Ostling, 1964). The net effect of these agencies on the incident radiation is that less than 50 percent available at the top of the atmosphere actually penetrates to the surface. This causes a lower day temperature than would be expected if there were no atmosphere. Day surface temperatures of 70°C to 80°C have been observed on earth (Geiger, 1950).

Extremely low night temperatures are also prevented by the atmosphere. The short wave radiation able to penetrate the earth's surface heats the upper layers, and the earth becomes a source of long wave radiation. Approximately 9 percent of the long wave radiation that is radiated outward is trapped by the atmosphere. It then radiates the absorbed heat back to earth and out into space. This green house effect helps to maintain the temperature of lower layers some 30°C to 40°C warmer than would be possible under perfectly translucent conditions.

The atmosphere helps to keep a relatively small range between average, annual maximum and minimum temperatures. It does this by moving the heat absorbed in warm regions toward the colder, polar ones. A milder temperature gradient between different terrestrial locations is kept because of this atmospheric phenomena.

The temperature regime of the moon is much different. The sun's rays hit the moon's surface undiminished in strength. The full value of the solar constant can be used in determining the amount of heat received. The albedo of the moon is only about 7.2 percent so the rest of the incident radiation is absorbed by the surface and converted into heat. Theoretical estimates and observational data have shown that the lunar day temperature reached 390°K at the midsolar point (i.e., 117°C). The temperature should decrease from this point poleward due to the increasing inclination of the lunar surface with the sun's rays. Comfortable temperatures will be found in the vicinity of the poles. The temperature range of some 300°K corresponds to the earthly range of temperatures between the boiling points of water and liquid aid (Kopal, 1966). There is extreme gradiation between neighboring locations in the sun and shade. A piece of lunar material taken from a sunny location and placed into shadow would drop nearly 200°C in a relatively short time (Baldwin, 1963). The temperature gradient measured during a total eclipse of the moon illustrates this. It has been found that when the surface of the moon is obscured by the shadow of earth that the temperature of the surface drops from 390°K to 180°K during a 40 or 50 minute period. The following emergence of the sun may incite a heat wave with a temperature gradient of 5°K per minute compared to the cold wave gradient of 2°K per minute which preceded it about an hour.

The second point, discussed briefly in Chapter II, concerns the lack of protection from meteorites that are swept from space by the moon on its passage. On earth the atmosphere protects man from all but the largest of these particles. The friction resulting from the passage of the meteorite through the atmosphere vaporizes the meteorite, or retards its speed considerably, except in the case of the truly large particles. The weak atmosphere of the moon does little to de-accelerate the meteorites that smash into its surface. There seems no reason to suspect that the moon intercepts proportionately less meteorites than earth. Estimates of the number of meteorites that can be seen by the naked eye approach the figure of 4×10^9 per year. This figure would be greater if those able to be seen by telescope were added. Their mass has been estimated to be some 2×10^9 grams per year or 4 grams per square kilometer per year (Dauvillier, 1961). Since there is no atmosphere to burn the smaller meteorites, the mass accumulating per square kilometer on the moon's surface would be larger than that of earth. This bombardment by these unimpeded meteorites occurs at speeds up to and beyond 72 kilometers per second.

The third consequence resulting from a weak lunar atmosphere is that the moon cannot maintain any liquid on its surface. The near vacuum of the moon surface and the hot temperature experienced during the lunar day would rapidly, if not explosively, evaporate any liquid. The experiment performed during a test of a Saturn first stage rocket in which 100 tons of water were dumped from a height of 90 miles portrays what would happen in the lunar environment (Baldwin, 1963). The atmospheric density was 1×10^{-8} that of sea level which is still several orders higher than that of the moon. In this test the water expanded at about 6600 feet per second.

It is apparent that at no time in its history was the moon under a hydrologic regime such as that which shaped and sculptured the face of earth. The surface is dry and probably always has been. Since water cannot exist there, or even in the surface layers that are exposed to the temperature increases of the sun during the lunar day, water is limited to the interior of the lunar globe.

The thermal regime

Due to the lack of knowledge about the thermal history, the form and location of the water in the interior becomes a matter of conjecture. Argument swirls as to whether the moon is hot or cold inside. The thermal history leads to an array of possibilities as to how and where water will be found in the interior. If the moon has remained cold, the water in the lunar material is in the same state and place as at the time of formation. At this extreme the total water content will be the highest, but it will be difficult for man to utilize the water due to the dispersed state in which it will be found. Scarcity will subsequently exist if the moon has been molten during its past, for large amounts of water vapor would have expelled into space.

Any stage between the two extremities is possible. A point closer to the lower extreme would seem more useful to man. At this stage the lunar interior would be heating from its original, cold state and might be molten. From physical chemistry it is known that at temperatures above $1000^{\circ}K$, water will be driven from all solid hydrates in the form of super-heated steam. As the temperatures increase, chemical compounds with lower boiling points and minerals with lower temperatures of crystallization will migrate upward through the melt as the solids settle downward. If melting has advanced to the stage where the surface and near surface layers have become water-rich, this would be the most advantageous water regime for man.

The accumulation of heat could have resulted from several sources including the premise that the moon was formed by the condensation of a hot, vaporous cloud. Under this concept the early moon was originally at a high temperature. This hypothesis will be ignored in accordance with the current ideas of lunar formation.

Gravitational energy released during the original accumulation of particles would have been a source of heat. If under the improbable circumstances that objects always struck each other with a velocity of 2.38 kilometers per second, and with no loss of mass, the average energy of accumulation would have been 1,685 joules per gram. Now, a particle arriving at the lunar surface with an impact velocity of 2.38 kilometers per second would have a collision energy of 2800 joules per gram. When silicates are heated and melted, the energy required is about 2000 joules (Urey, 1960). Therefore, toward the end of the terminal stage of collection, gravitational energy could have provided sufficient melt heat. The rapidity of the collection and the burial of the earlier particles would play a large part in the amount of heat retained by the primitive moon. The full value of heat per gram shown could not be applied for heating purposes. Energy losses from vibration and fragmentation at the time of impact would decrease the amount to be converted into heat. Radiant heat losses to space would also occur.

Heat could have been generated as a by-product of chemical reactions between materials, or by the pressure increases in the interior. The initiation of heat by one factor might also have caused heat to be generated by the other. The increases in core pressure induced by the accumulative processes would raise the interior temperature. This increase in pressure could have caused additional reactions between adjacent materials. Heat released could have then increased the pressure to bring about yet another temperature increment.

The viscous dissipation of bodily tides raised by the attraction of earth could provide another significant heat source for the lunar interior. The varying tides on the moon's surface are caused by the eccentricity of the moon's orbit (e = .0549) around the earth. This, coupled with a coefficient of viscosity of 1×10^{18} grams per centimeter second for the lunar materials (as suggested by terrestrial experiments with silicate rock materials), leads to a specific relaxation or "breathing" time in the interior. This period is short enough to permit visco-elastic flow dissipation of a part of the energy from the tidal motion by conversion into heat (Kopal, 1966).

The efficiency of this process is proportional to the orbital eccentricity, and is inversely proportional to the cube of the distance between earth and moon. The mechanical heating of the moon by tides could have been greater in the past, if the moon was closer to earth, or if greater eccentricity of the lunar orbit has occurred. Significant heating by interior shearing stresses would have happened if there had been a time when lunar rotation was not synchronized with its revolution.

Radioactivity should have played a role in the thermal history also. If radioactive materials were scattered uniformly throughout the moon as was assumed in primitive earth, and found in meteorites, it is logical to assume that the succeeding history of these materials would be similar to that followed on earth. This heat has been charged in large part with the development of the molten, inner earth, and with the development and maintenance of the present surface features. The process occurred possibly in the following manner (Hurley, 1959).

In the radioactive breakdown of materials, alpha, beta, and gamma particles emitted by an unstable nucleus disrupt and distort the atomic structure of the near neighborhood. The energy producing this disruption is transformed immediately into heat. The damage and excitation of the structure may be so intense locally that the heat generated is equivalent to a temperature of tens of thousands degrees centigrade.

A sufficient number of local radioactive disintegrations, or the insufficient dissipation of heat, will cause an increase in local temperature so that melting of the materials within the high temperature areas will occur. As radioactive material has a lower crystallization temperature than magnesium, silicon, or iron, the liquid radioactive material would be forced to the outside as the heavier, solid materials sank to the center of the molten area. The radioactive material becomes concentrated around the peripheral area initiating local melting with the heavier solids again sinking to the center, while the previously melted radioactive material, and that newly acquired in the last melt, subsequently migrate outward. This process continues to a point where the conduction of heat outward is fast enough to prevent further melting temperatures. A stable mantle is maintained at this stage.

It is assumed that the above process occurred in the earth's interior, and that a concentration of radioactive materials has accumulated in the near surface layers. Around this peripheral area of heat-producing material, a large temperature gradient exists between the earth's crust and the molten area rather than extending onward to the center of the earth. This results in a more uniform temperature within the molten area. Relatively little heat is lost from the interior because of continuous heat production at the border of the molten volume.

A uniform flow of heat amounting to 1.2 microcalories per second per square centimeter comes to the mantle surface in the oceanic and continental areas. If the flow of heat is blocked by poor conduction, such as might be caused by a regional cover of deposited sediments, local heating can happen. The dissipation of this generated heat may result in volcanic eruption or mountain building. Previously, the flow of heat through the earth's mantle was much higher, and consequently the earth's mantle was not as thick due to the greater heats within the interior. The nature of radioactive material assures a larger supply of uranium 238, uranium 235, thorium 232, and potassium 40 during the past.

Besides these quantities of long-lived radioactive materials, heat could have been contributed by short-lived nuclides of which no trace remains. The contribution made by these short-lived nuclides, and those with 1 X 10^5 to 1 X 10^8 years per halflife, are not known. Studies of radioactive decay have helped man to understand earth, but much is not understood due to limitations in present techniques and equipment. There also remains conflicting hypotheses as to the evolution undergone by the earth.

Extrapolation of terrestrial data has been used to study the radiogenic heating of the moon. Kopal, in summarizing the works of several authors in this field, states that unless the proportion of radioactive elements in lunar matter has been badly estimated by analogy to those found in chondritic meteorites, considerable radiogenic heating has taken place. The heat applied by a corresponding proportion of radioactive materials in the moon would have been sufficient to raise the average temperature of an initially cold moon in excess of $1000^{o}K$ (Kopal, 1966). This is sufficient to maintain a molten interior within a distance of 300-400 kilometers of the surface (Gold, 1965).

The roles played by these different sources of heat is unknown. Each of these factors probably aided in raising or maintaining the heat of the moon's interior. It is a matter of conjecture as to whether the moon is warming from an initial, cold condition; whether the moon melted at an early stage and is now in a cooling period; or yet, whether the moon has undergone several cycles of heating and cooling. Answers to some of these questions will appear as data is analyzed from seismic and petrological studies.

The information obtained from the Apollo XI flight will expand knowledge of the lunar composition gained from the Surveyor program. The experiments performed during that program gave first evidence of the surface properties of the moon by close-up photography, mechanical digging in the lunar material, and chemical analysis of this material by alpha scattering equipment. The photographs revealed pebbles and stones on the surface and imbedded in unconsolidated material finer than sand. The mechanical digger dug trenches, broke pebbles, and was prevented from digging by the hardness of hidden objects. The alpha scattering equipment provided the most interesting information from a water standpoint. The limited, sample analyses (a sample area is 10 centimeters in diameter and a micron deep) have indicated that the maria are similar to terrestrial basalts, and that the lunar highlands might be of acid silicate composition (Turkevich, 1968). Important genetic considerations arise since the lunar material seems like its earthly counterpart.

Basalt is derived by chemical fractionation of an ultramafic rock such as the chondritic meteorites. The acid silicates of the highlands may resemble those found on the continents of earth, as the continents are a layer of acid rocks floating on more dense rocks in the earth's mantle. A partial or fractional melting of the moon will cause a differentiation between the materials so that the heavier material would be concentrated at the center, and materials of lower crystallization temperatures would be located at progressive distances away from the heavier core.

The heat sources sufficient to melt these substances into lava-like forms must be from internal rather than external sources such as solar radiation or meteorite collisions. The impact of large meteorites on the surface of the moon could provide enough energy to heat the local areas to melting if the energy is converted to heat. It has been deemed inconsistent that the mare basins could have been filled with molten lava which was contemporary with the crater formation (Gault, 1967). It seems more logical that meteorite craters and lower surfaces of the moon were the paths of least resistance between a molten interior and the surface.

The thermal emissions of the moon have been studied with infrared and microwave techniques. These studies have led to the observation that a constant temperature of $240^{o} \pm 6^{o}K$ prevails at a surface depth of about one foot. This thinking limits the role that solar radiation plays in heating the interior of the moon.

The Nature and Occurrence of Water

The consequences of the temperature gradient

It can be assumed that temperatures were attained within the lunar interior which were adequate to drive the water as steam from the hydrates if it has undergone a similar heating process to that of earth. The temperatures were sufficient to raise the vapor pressure so that the steam could bubble outward from the molten center. This process on earth caused the formation of the oceans, and in like manner, should have enriched the surface layers of the moon with water. The atmospheric thermal regulation keeps the ocean water in liquid state on earth, but lunar water which happens to reach the surface boils away. That which does not reach the surface should remain underground since the temperature decreases toward the lunar surface. The hot steam seeping outward will condense into liquid and eventually form ice.

The amount in the near surface layers will depend on whether the moon has undergone several cycles of heating and cooling as stated previously. If several cycles have occurred, all the surface and near surface layers will not have undergone similar heating, differentiation, or degassing processes. Differences between lunar areas exist as evidenced by thermal emission measurements, surface structure forms, color, and chemical composition. It is likely that the amount of water contained in these dissimilar areas will vary in the same manner that variations occur among areas on earth that are geologically different in origin.

Ice

Moonquakes resulting in crustal fissures or volcanic action could allow rapid venting of water vapor or water through the low temperature zone. These fissures or vents could be only temporary passages due to the cold of the nights and the vacuum of the atmosphere. Ice layers would eventually span the fissures, and the surface would again be sealed.

Water vapor or water ejected by way of the crustal fissures would not last. If vented during the lunar night, some would fall on the surface as ice. Exposure to sunlight during the lunar day would soon remove all traces of the ice. If, however, ice fell into a crater or a mountain valley sheltered from the sun's rays, the ice would last indefinitely. The low temperatures found in the shadows, and the low rate of sublimation of ice into a vacuum at this temperature (3.1×10^{-14} grams per square centimeter per second), would have evaporated only 46 meters of a primordial ice layer that had been shaded from the sun. The percentage of surface area in permanent shadow is very small. Land areas near the poles are subjected to the slanting rays of the sun, and would permit exposed ice to last for many years. If chunks of ice could be discovered during the first exploration trips, early benefits from this resource could be realized.

Permafrost

The form of ice in the frozen underground may be similar to forms found on earth. About 20 percent of the earth's land area is underlain with a layer of perennially frozen ground called permafrost. The thickness of this layer varies with the mean air temperature of the region. The permafrost may be only a few centimeters thick when the average temperature is $0^{\circ}C$ to over 600 meters thick, as found at places in Siberia where the average air temperature is $-15^{\circ}C$.

The permafrost layer includes bedrock, soil, ice, sand, and any other material that has been below $0^{\circ}C$ for more than 2 years. The amount of ice varies with the porosity and permeability of the surface layers. Ice occupies the pore spaces in bedrock, partially or completely filling them, and fills the fissures as veins of ice. Ground ice may form 20 percent of the rock volume. In the soil mantle above the bedrock ground ice may be present in larger volumes. It occupies the volumes between the fragments and cements them firmly together. Layers and wedges of ice up to 4 meters or more in thickness exist in some locations.

In localities containing similar material and average temperatures, variation exists in the thickness and orientation of the permafrost layers. There are places that are never frozen, localities that allow surface water to drain between and under adjacent permafrost layers, and situations where permafrost regions are isolated from each other. Fossil permafrost regions are those where permafrost beds are overlain by an unfrozen layer outside the normal permafrost region, or where a deep permafrost layer is separated from a surface permafrost zone by an unfrozen zone. With such variation in terrestrial underground ice, it is probable that this condition would occur on the moon.

Gold gives an analysis of what might be found (Gold, 1965). He assumes that the water which came from the interior flooded the maria, the large craters, and the lower regions of the moon since these places offer to water, as to the lavas, the paths of least resistance between the interior and the surface. Thus, water trapped in the surface layers would freeze and eventually form an internal ice layer. This would be impermeable to the passage of water since any liquid or vapor which subsequently filled the empty pore spaces would freeze.

With a heat flow rate akin to that of earth coming from the lunar interior, the following temperature structure might be found. Moving from the lunar surface at a temperature of 230°K, a temperature gradient of 200° per kilometer is used in the top 50 meters of loose, uncompacted material. A gradient of 100° per kilometer will be used for a 50 meter thick layer of compacted material underneath the first. The temperature at the bottom of this 100 meter layer will have risen to 245°K. The ice will have evaporated from these debris layers, and the thickness of the surface layer is now adequate to prevent rapid evaporation of ice from below. Underneath the debris layers, a gradient of 28° per kilometer is used. With these conditions it is possible to have a layer of ice or permafrost that is one kilometer thick since the temperature at a depth of 1100 meters is 273°K (i.e. the melting point of ice).

The above temperature zones, based on the value for the terrestrial heat flow, give an indication of what might be found. As differences exist in the occurrences and thicknesses of the permafrost layers on earth, many lunar variations can be expected. It would take thousands of years, and an adequate supply of water from the lunar interior, for the given structure to have reached a stable thickness where the heat losses at the surface would have been balanced by the heat gain from the freezing of water at the bottom.

Porous material under the permafrost would determine whether liquid water could be found. If the lower layers are impermeable, the surface zones may have served as temporary passageways between more permeable, adjacent areas which later had frozen. Liquid water should be found since heat forces the steam liberated in the interior outward. The thermal and electrical gradients should aid in keeping a layer of water underneath the permafrost that could be tapped for water supplies. Water wells have been drilled through the permafrost to supply Yakutsh, a town in Siberia, where the mean January temperature is 46°F below zero (Dyson, 1962).

Combined water

In addition to occurrence in free forms, water could be found in combination with various lunar materials. The venting of water vapor along crustal fissures, or the outward seppage of water through the porous surface material, will provide adequate contact for chemical reaction. Lunar material could absorb water hydroscopically. Succeeding evaporation or lowering of local temperatures could have trapped water in the combined state as hydroscopic water, hydrates, or lattice water. If deposits of these materials are found, they could provide water supplies as heat is sufficient to liberate water in the above listed states.

Water enrichment could occur from volcanic action. Most terrestrial lavas have a chemical composition that contains less than 1 percent of water. Some differentiated products of primary magmas, however, that erupted under the ocean have as much as 11 percent water in their composition (Rittmann, 1962). Eruption under the lunar permafrost might provide sufficient contact between the melted ice and the magma to form a similar type material. If the lava was extruded onto the surface, rapid devoltolization would occur due to the high temperatures of the lavas. The lack of an atmosphere would probably reduce the water content below that of terrestrial forms.

The chief constituent of terrestrial volcanic gases is water vapor. Steam spouts, carrying hydrogen sulfide at temperatures between 90°C and 300°C, are widely distributed in all the volcanic regions of the world. These solfataras deposit sulfur in sufficient quantities to be worked economically. The steam and solutions formed by oxidation decompose the rocks surrounding the vents. These solutions leach the bases, replace them with sulfates, and leave the silica from the original silicates as porous opal. The decomposition products remaining often contain enough quantities of useful sulfates, such as alum and aluminite, to be worth exploitation (Rittmann, 1962). These hydrated products would emit water vapor if reheated.

Green has reaffirmed earlier findings of sulfur rich areas on the moon. He took telescopic shots through a filter that absorbed light at wave lengths of 3100 angstroms. This is the wave length at which light reflected from sulfur is absorbed. His pictures showed black spots near the crater Aristarchus where other astronomers have reported gaseous activities. This is a possible sign of volcanic activity. According to Green, sulfur is the most prominent indicator of volcanic material. When found on earth it is surrounded by hydrous rock. Areas of lunar volcanic activity might also be a source of hydrous water from which water might be extracted (Time, 1968).

Formation of Surface Features by the Action of Water

Photographic analysis of the lunar surface

In this century the development of photography and the giant telescopes have aided the study of the lunar surface. During the recent decade, however, it became necessary for more detailed studies as preparations were advanced to place a man on the moon. American and Russian spacecraft have provided thousands of photographs taken from the lunar or near lunar surface. These photographs have been used to select potential landing sites, and to make elaborate maps which have enhanced the studies of the lunar features and forms.

Most of the features have no terrestrial homologues, and there remains a large degree of speculation as to the interpretation of their causes and histories. Some are of interest from a water resources standpoint because they indicate possible formation by the action of water.

Lunar domes

Dome formations are located on the plains of the maria and in the mare-like interiors of the large craters. They are usually found clustered as small, inconspicuous hills that are circular in diameter and gently convex in cross section. To date, the altitudes of the domes do not attain more than 2 to 3 percent of their diameters which indicates gentle slopes. Many show evidence of summit craters. The largest of this type is approximately 48 kilometers in diameter and has a height of about 760 meters. The majority of the domes are much smaller than this.

The origin of the domes has been assigned to shield-type volcanic action, trapping of lava underneath the surface by a laccolith mechanism, and mineral phase changes (Salisbury, 1961) in which olivine and water are changed to serpentine and heat. The latter is accompanied by a 25 percent increase in volume. The shield volcano hypothesis has been discarded due to the lack of evidence of lava flows from the domes. The other two hypotheses of formation are possible. Both models permit the surface forms observed, and the absence or presence of a central craterlet (Baldwin, 1963).

There is another class of domes located inside many of the craters. This type has been compared to the pingos which are found in the permafrost regions of the earth. In these structures the central dome is formed by a laccolith mechanism using ice, rather than lava, as the extrusive material.

<u>Wrinkled ridges and rilles</u>

Wrinkled ridges are found in the lunar maria. The ridges may be several kilometers in width, but are not more than 200 or 300 meters high. They are often hundreds of kilometers in length. Cracks have been observed along the tops. White material, observed in the cracks, has been considered to be incrustations of salt deposited by escaping water. Another possibility is that the wrinkles on the maria overlie fissures through which water rises from the interior. The escaping water hydrates the material and forms the wrinkled ridges by the volume expansion accompanying the hydration process (Urey, 1960).

Another feasible explanation of wrinkled ridges and their accompanying forms has been given (Baldwin, 1963). Since a wrinkled ridge on the surface implies a compression effect, they should, therefore, appear at the center of the maria rather than at the edges as in actual occurrence. The lunar crust should bend, and isostatic adjustment should take place, if lava heavier than the surface material is extruded upon the surface. Tensional pressures would develop at the edge of the depressed area with compression in the center regions. If some of the lava still in a liquid form is drawn into the interior, the crust will again by isostatic adjustment tend towards a larger radius of curvature. The lava surface, during the crustal springback, will become smaller and wrinkled ridges must form. The ridges seem to have formed in places where the lavas were thinner, and where subsurface obstructions may have inhibited uniform adjustments to the changing stresses. The bending of the crust, the isostatic adjustments due to the superposition of masses of dense lavas, and the partial withdrawal of lavas into the body of the moon, if operating concurrently, seem to explain the present variation in lava levels, wrinkled ridges, and rilles in the maria.

The long cracks or rilles avoid the wrinkled ridges. This is as expected since the rilles are assumed to be caused by tensional stresses in the surface layers. Baldwin's explanation of the formation of these features is based upon the occurrence of lava flows and associated volcanic activities such as the chain craters. These craters are closely associated with rilles in numerous instances. The craters have been thought to be some form of volcanic vents.

The features attributed to the action of lava by Baldwin are considered by others to be derived from the action of ice (Gold, 1965). Since the rille system is concentrated in the maria or to the flat bottoms of the craters, the deformations taking place are of a weaker material than that of the surrounding highlands. If the floor had been filled with lava, distortions other than those observed should have occurred in the surrounding area. Ice can account for the distorting, uplifting, and collapsing of the mare ground. An ice layer is less stable than a sheet of debris or rock. In time it will be capable of suffering deformation if the amount of water in the ice layer varies or changes as more water accumulates at the bottom, or as water evaporates off the top. The plastic movements and adjustments to the varying ice conditions would produce collapse conditions, fissures, and crevasse patterns in the top debris layer.

An additional hypothesis on the formation of some particular lunar rilles has been projected (Lingenfelter, et al., 1968). The evidence for a lean lunar atmosphere discounted earlier theories concerning the erosion of the landscape by water. Examinations of photographs taken during the Lunar Orbiter program have disclosed features that lead to renewed consideration of erosion by running water. If this is true, the presence of the rilles is interpreted as evidence that a subsurface permafrost layer might exist, and have considerable amounts of water contained underneath it. These authors contend that the lunar surface could be eroded by water since an overburden of ice can provide the pressure required to maintain water in the liquid phase. Their reasoning is based upon the following circumstances.

It is assumed that a permafrost layer has been formed by the degassing of water vapor from the lunar interior during geologic time. The impact of a large meteorite forms a crater and shatters the permafrost layer. Liquid water, trapped underneath the permafrost, is released and floods the impact crater. If the pressure of the overburden, the trapped volatiles, or hydrostatic head is great enough, the water can overflow the crater and cut a rill.

The exposure of water to the moon's atmosphere causes it to boil. Surface ice formation supplies the latent heat. The boiling of water continues until the weight of the overlying ice is sufficient to maintain the triple point pressure which under lunar conditions is equal to 37 grams per square centimeter. Experimental work has confirmed that ice will form under vacuum conditions to a thickness such that liquid water can exist beneath it (Adler and Salisbury, 1969). Liquid would continue to freeze rapidly at the ice-water interface until a thickness was reached in which the mass loss at the ice surface by sublimation was balanced by the mass gain at the bottom of the layer due to freezing. The sublimation of the ice surface would vary because of the changes in energy applied over the lunar day.

The thickness of the idealized ice layer would be reduced by the expected form of lunar water as a carbonated, muddy brine. Ice will be produced which will have a reduced transparency and thermal conductivity to that of pure ice. Upon sublimation, the non-volatiles once held would form a surface layer that would absorb most of the solar radiation after a short period of time.

If the water breached the crater wall, it would flow downslope under a quickly forming blanket of ice. Since the rilles are wider and larger than the equilibrium thickness of the ice, the rivers were not restricted as to their course, nor in the development of meanders.

The boiling water, as it flowed downslope, would churn the porous material to produce a slurry of mud and ice. As the water penetrated the ground, it is preceded by a vapor whose pressure prevents underground boiling. This vapor would produce frost which raises the subsurface temperature to $0^{\circ}C$. The high porosity of the subsurface material limits the void spaces blocked by the frost. Water seepage and the accompanying piping action in the subsurface material would be sufficient to open channels able to erode to underlying permafrost layers.

The time required for the erosion of the rilles would depend on the flow rate and the load carrying capacity of the lunar rivers. The authors correlated some terrestrial measurements and conditions to those exhibited by several selected rilles. The Surveyor measurements and the slope angles of the rille bank materials, determined from the

Orbiter photographs, indicate a fairly fine-grained, loosely-packed material which would erode quickly. Since the energy required by fluids to support particles is directly proportional to the square of the gravitational acceleration, the load factor of the rivers should be increased by a factor of 36. Due to the erodibility of the material and the high load carrying factor, they would be able to erode materials faster than terrestrial rivers under the constraints of higher friction losses by the overlying ice and a lower value for gravitational acceleration.

CHAPTER IV

CONSIDERATIONS OF WATER RESOURCES IN SPACE

As a result of present technological limitations, efforts at base establishment during the next decade will be directed toward attaining lunar objectives. This study has, therefore, been oriented toward the problems placed by the lunar environment on water system design. In this chapter these general constraints will be examined to determine the alternatives available to the designers of water systems. Various schemes and techniques based on lunar suppositions and believed to be applicable to the areas of water supply, treatment, and reuse will be discussed in following chapters. Since this study is futuristic in that bases and colonies are still years away, advances in knowledge of the environment, technology, and material science will disclose new lines of approach for solving the problems associated with water. The ideas engendered in this part of the study are intended to open new vistas of thought rather than furnish finalized solutions.

The Effects of Water on Space Exploration

The problems associated with water supply and water reuse will comprise a continuing major research effort for the designers of space stations. The daily water requirements of the station occupants will involve a heavier flow of materials through the system than that of any other item supplied for life support. The rate of space exploration will be partially governed by answers to questions such as: (a) Is the water obtained from a local source or must it be supplied from earth? (b) If local sources exist, how difficult is the task of extracting water? (c) What is the distance between the base and the local water source?

If water has to be imported from earth or some adjacent body, the transport burden will be increased to the point that little manned development can be expected. Short visits to gather data, or to service unmanned data collection systems, could be permitted using present spacecraft water systems which are able to provide for minimal water needs.

Full scale exploration and development will require water in large amounts. Restrictions on water use can be tolerated during the first exploratory trips when stay times are of limited duration. To envision a permanent base requires a local water supply, unless the gains obtained are of such high value that it is worthwhile to import all needs. A base on an extraterrestrial body should be able to exist with a minimum amount of support after the equipment and tools for utilizing the local resources are landed.

Water will be required in material form to fulfill its utilization by man. These uses will not only include the primary and secondary needs which were discussed in Chapter II, but water can serve as a raw material for production of hydrogen, oxygen, and rocket fuel. The moon will be an ideal launch pad, and much time and effort has been spent in hypothesizing the location of water and mechanism for extracting water from the possible sources.

If water cannot be located in sufficient quantities to merit exploitation, future colonization of the moon is doubtful. In the event that water is located, the development of a lunar colony can be attempted. The set of conditions on the moon are as difficult as any that will be encountered on nearby planets. When life support systems can be developed to operate there successfully, only moderate modifications should be required for operation at other locations in the solar systems which have appreciable atmospheres, higher values of gravity, and less extreme temperature variations.

The Restraints of Space on System Design

The design, construction, supply, and maintenance of an extraterrestrial base will be more complex and costly than any similar terrestrial program yet undertaken. The high cost of transporting material, the difficulty of mounting a space rescue mission, and the inability of man to survive for even short periods of time without a fail-safe, artificial environment impose substantial design constraints.

Terrestrial environmental systems are not true life support systems since they can effect some exchange of materials with the atmosphere. Hazardous gases, vapors, and wastes can be dissipated through earth's atmosphere, or in the limitless volumes of her oceans. Extraterrestrial life support systems are forced by resupply difficulties or specific environmental characteristics to be a closed system in which materials are recycled. With a larger number of factors entering the design, the system becomes increasingly more complex and smaller ranges of negative interactions are allowed among the components during operation. Requirements used in the selection of any one component or subsystem will determine in part the standards and requirements for the other system components. The constraints imposed by the parts on the safe operation of the whole system may not permit the optimal design of any of the particular subsystems. Therefore, the requirements impressed upon the total system will have to be accepted and understood before proposing the design criteria.

During the early stages when so much dependence is placed on earth exported supplies, actions influenced by human intervention must also be examined. The space environment will require disciplined responses from personnel.

Personnel actions and the consequences resulting from these actions, whether in the performance of normal station duties or in the conduct of scientific experiments, will have to be investigated at the planning stage since survival depends upon the existence of a fragile balance among the components of the system. For years to come, the hope of survival will rest upon the actions taken by the base personnel rather than upon earth staged rescue missions.

Material and equipment must be examined to determine whether the role envisioned for their employment is the most opportune for the total system. This evaluation should be undertaken and co-ordinated among all the areas of planning and be applied to the later action phases. Before any material or equipment is incorporated into the design, it should be classified as to priority of purpose. With its importance established, further examination should be made to determine whether the item could serve any further beneficial use after fulfilling its primary function. After a thorough examination of secondary uses has been made, the ultimate disposal of the item should be considered. The most efficient method of space colonization will come from a system that is able to incorporate together a grouping of equipment that maximizes the use of multifunctional materials in an amount just necessary to perform the desired ends.

Returning to the specific area of interest, studies of the equipment and processes upon which water acts, equipment and processes which act upon water, and water as a material itself must be examined in light of the following discussion. It does not seem feasible that indiscrimate wastage of water can be tolerated even if large supplies are located at extraterrestrial locations. The local environment under which the water is found will be different from earth, and the amounts and types of chemicals in solution will probably differ from that normally encountered under terrestrial conditions. It has been proved that waste waters can be treated and reused at less expense than treating a local water source with a high mineral content for one time use. In space water will be a precious resource. If the true cost of water production is used as the pricing factor, conservation procedures will be adopted. Water and water bearing substances are most amenable toward performing a somewhat continuous role as a part of a chain of reactions. Therefore, after the water system is filled initially, inputs of water will be made only to replace water actually consumed through electrolysis, chemical processes, or other irretrievable losses.

In a base located on the moon, water would necessarily be confined to the environs of the space station or the lunar interior. The lack of an atmosphere and the cold ground temperatures create an unfavorable hydraulic regime. Water released on the surface would be wasted to space. Its use in this manner would be comparable to that made of hydrocarbons on earth. The cold ground will necessitate the use of heated storage unless it could be injected into a free water zone in the lunar interior.

Some materials or equipment that will be necessary components of the base will have no further use after fulfilling their original role. A few will pose special disposal problems. Others may have new-found uses. Purposes for which one material has always served satisfactorily may, under the conditions of the space environment, require new and different forms to serve the same ends. Large volumes of paper as newsprint, towels, and containers are used in everyday terrestrial life to perform many functions. Microfilming could replace the printed page, textile products could take the place of paper towels, and containers could be made of reformable metals. The use of paper in a secondary form such as insulation might justify the continued use in its fundamental application. As another alternative, the composition of paper could be changed so that this new form could serve as a chemical source, or as a food ingredient in its secondary role.

Hydraulic Properties in the Space Environment

Man's requirement for an atmosphere that is maintained at specific conditions has been established in the previous chapter. Atmospheric pressure, necessary to provide oxygen, will prevent boiling of liquids, and permit utilization of other liquids besides water which are essential to man's environment--chemicals, fuels, lubricants, and food components.

The physical properties of water will not be altered if optimal conditions for man are sustained within the space base. Temperature will influence most of the physical properties and will dominate the behavior of water in space just as on earth. Man can effect the desired changes in water temperatures and should be able to create and control the conditions desired for any particular water regime.

The effects caused by differences in viscosities, densities, vapor pressures, and surface tension among liquids should be observed in the various space stations. The absorption of light and heat, the solution of solids, and the molecular diffusion of dissolved substances should also be unchanged despite planetary location.

Forces in fluid systems

The laws of mechanics can be employed to analyze the forces occurring in the fluid systems. The common forces are centrifugal, inertial, surface tension, viscous, and gravitational. The centrifugal and inertial forces are unaffected by location in space since units of velocity, length, and mass do not change. The factors promoting velocity, however, can change due to spatial position.

Viscous forces are molecular phenomena which result from friction generated by molecular particles in opposition to motion. These forces become influential only when relative motion occurs within a fluid. Their magnitude depends upon the rate of motion and the subsequent deformation of the particles. The coefficient of viscosity is independent of the state of motion, but is a function of temperature. High pressure will change the coefficient, but the pressures expected within the life support systems will bring about minor changes in comparison to those resulting from temperature fluctuations. Viscous forces should, therefore, be independent of location.

Molecular attractions cause surface tension forces to develop. The values for surface tension forces deviate in response to changes in the conditions of the interface between different phases of matter. Since the value of surface tension is proportional to the pressure differential existing across the interface, this force will vary as to position in space. For example, if the atmosphere within the lunar base is maintained at standard conditions, this will require an atmosphere that is six times more dense than that of earth. This will decrease the differences in density between the liquid and gas phases and cause a reduction in surface tension. An additional effect is that the boiling point of water will be increased. Variations of surface tension, due to changes in pressure, will also be minor in comparison to contrasts caused by temperature.

The nature of mass attraction insures that the operations of fluid systems in which gravitational forces act will vary in response to spatial position. In the solar system the force of gravity ranges between apparent weightlessness, commonly called zero gravity, to a force of 2.738×10^4 centimeters per second squared that is exerted at the solar surface. This value is 28 times the terrestrial value, and it is doubtful whether man for several generations to come will encounter situations where gravitational forces of this magnitude exist. Most extraterrestrial bases will be located in gravitational fields of much lower magnitude. The lower extremes will be encountered in bases located on asteroids, or in orbit about planetary bodies. The lower gravitational region will be examined further as discussed by Berenson (Berenson, 1963).

Newton's equation stating the relation between force and acceleration is given in Equation (1)

$$\Sigma F = ma \tag{1}$$

where "ΣF" is the sum of the forces acting on a body, "m" is the mass, and "a" is the body acceleration as defined by the L-T-M system of dimensions. This equation is valid relative to a nonaccelerating coordinate system, and for absolute velocities that are negligible in comparison to the speed of light. Forces in contact with the body, and forces which act at a distance, such as the gravitational force "mg," combine to influence the state of motion. The quantities of the equation above are vector quantities. Each of the forces on the right side must be added vectorially to yield the resulting acceleration vector.

Equation (2) expresses the influence of gravitational attraction of any body due to the mass of a second body where "g" is the acceleration of gravity.

$$g = \frac{Gm_1m_2}{s^2} \tag{2}$$

"G" is the gravitational constant, "s" is distance, and the other factors are as previously defined. From Equation (2), it can be seen that "g," the force of gravity, cannot be made zero by the addition of other forces or accelerations. The meaning of "zero gravity," therefore, is that the net contact force on the system is zero. If all forces at a distance other than gravity are zero, zero gravity is said to exist when the system acceleration, "a," equals "g" as calculated by Equation (2). This state is rarely approached in actuality.

In a freefalling body the size of a spaceship, differences in gravitation can be detected (Bondi, 1968). A gravitational gradient exists across the spacecraft being strongest on the side of the attracting body. A strain is impressed on the vehicle which attempts to elongate the body along the direction joining it with the center of the attracting mass. The small difference in gravitational attraction, between the most distant points along the gradient within the spaceship, can be measured and utilized. Thus, there is a little gravity left over even in free fall which can't be abolished in any manner.

The net contact forces on a system are rarely zero. Atmospheric particles and photons exert contact forces on systems in space. Low gravity is said to exist when the net contact force is less than the force of gravity (i.e., the weight of the system on earth).

In hydrodynamic systems where the motion is defined by solid boundaries, the influence of gravity is limited to changes in pressure intensity in direct proportion to the change in distance along the gravitational gradient. If the liquid is unconfined in any zone of the system, the gravitational forces present can affect the form of the free surface, thereby, influencing the entire pattern of motion.

Analysis of liquid systems in space

Fluid forces on earth can be analyzed through the use of dimensionless numbers which are measures of the ratios between the forces involved. Ratios that can be used and the order of magnitude of the critical value are given in Table 3. For each specific problem a more accurate estimate of the pertinent dimensionless parameter should be different by at least a factor of ten from the estimated critical figure for the other force to be ignored.

The strength of the forces will change according to specific planetary conditions. Until experimental evidence

TABLE 3

DIMENSIONLESS FORCE PARAMETERS

Force Ratio	Definition	Name	Symbol	Critical Value
$\frac{\text{Gravitational}}{\text{Surface Tension}}$	$\frac{g(\rho_l - \rho_g)L^2}{\sigma}$	Bond Number	Bo	1
$\frac{\text{Inertial}}{\text{Gravitational}}$	$\frac{\rho V^2}{g(\rho_l - \rho_g)L}$	Froude Number	Fr	1
$\frac{\text{Inertial}}{\text{Surface Tension}}$	$\frac{\rho V^2 L}{\sigma}$	Weber Number	We	1
$\frac{\text{Inertial}}{\text{Viscous}}$	$\frac{\rho V L}{\mu}$	Reynolds Number	Re	1000
$\frac{\text{Viscous}}{\text{Gravitational}}$	$\frac{V}{g(\rho_l - \rho_g)L^2}$			10^{-3}
$\frac{\text{Centrifugal}}{\text{Gravitational}}$	$\frac{V^2}{g L}$			1

Source: Berenson, P. J. "Fundamentals of Low Gravity Phenomena Relevant to Fluid System Design," Vol. XIV of Advances in the Astronautical Sciences. Edited by Benedikt, E. T. and Halliburton, R. W. Tarzana, California: AAS Publication Office, 1963. Table 1, p. 124.

is procured as to the actual effects of forces in an extra-terrestrial environment, these dimensionless numbers can be used to indicate the influence of each force on a system operating under specific conditions at any position in space. For instance, the residual aerodynamic drag on a large booster in free flight might be on the order of 9.80×10^{-4} centimeters per second squared (Reynolds, et al.; 1964). Because of the low surface tension of liquid oxygen, gravity effects, even at this low value, are still important in the oxidizer positioning problem. The Bond number indicates the importance of gravity in situations of this type. Liquid oxygen in a tank with a diameter of 109 centimeters has a Bond number of one when "g" equals the value listed above.

The magnitude of values obtained in the preliminary analysis by the dimensionless parameters will determine the particular regime under which the liquid system must be further analyzed. After these analyses have been completed, and the importance of the various forces established by the values of the ratios, the possibility exists that the effects of certain forces can be neglected. Design capabilities can be employed to change the system makeup or operation in the event that the initial design characteristics have unfavorable ratio values.

In fundamental hydromechanics the studies of the force properties of weight and pressure was facilitated by arbitrarily setting the viscosity, surface tension, and compressibility of the fluid under investigation to zero. A large sector of terrestrial, hydraulic practice has been based on work developed from those assumptions. Hydrostatic systems are described by characteristics imposed by gravitational forces. The surface and pipe flows normally encountered in hydraulic practice have been in the range where inertial forces were dominant, therefore, these assumptions have been valid on earth. The changed conditions in space will require an evaluation of the forces at each site. In areas where local gravitational forces are greater than earth's, continued dominance of inertial forces can be anticipated. Where low gravity is encountered, greater influence by the forces of surface tension and viscosity will be noted. The fluid systems can be made to operate in the force regime desired with proper design. Other constraints previously discussed may dictate the final system form and operating range.

A liquid, unlike a gas, may be considered incompressible in the types of flow usually encountered in hydraulic engineering. In the confines of the space station it is logical to assume that if liquid flows can be induced within pipes or along channels, the continuity equation as given in Equation (3) will be applicable with "e" the mass density, "v" being velocity, and "A" the cross sectional area.

$$\rho_1 v_1 A_1 = v_2 A_2 \rho_2 = \text{"}\underline{\text{mass}}\text{" per second} \quad (3)$$

Water will not be expanded or compressed noticeably during motion within the pipe or along an open channel if conditions permit their employment.

On earth natural and the majority of man-made systems are powered by gravity. The flow velocities obtained are in direct proportion to the rate of change of the pressure gradient along the path of flow. Work is done on a volume of water that flows between two points since the pressure is different at each point. The amount of this work is equal to the change in potential and kinetic energy. The following equation developed by Bernoulli holds for frictionless flow systems using a nonviscous, noncompressible fluid.

$$\frac{P_1}{\rho} + gh_1 + \frac{1}{2} v_1^2 = \frac{P_2}{\rho} + gh_2 + \frac{1}{2} v_2^2 \qquad (4)$$

In examining Equation (4) it is apparent that regardless of the magnitude of the gravitational force involved, flows can occur as a result of pressure differences between points along the flow path. Therefore, base water systems can be analyzed by Equation (4) if flow characteristics have Reynolds values in the appropriate range. It can also be concluded that if liquid weight cannot be utilized to provide flow, pressure forces will be required. Closed systems, as provided by pressure conduits, will be needed for normal water transmission duties between the treatment facilities and use points in the base rather than utilizing open channels.

With the need for flow in pressurized conduits established in low gravity environments, the problems associated with pipe flow will be examined further. Equation (4) is not correct since frictionless systems and nonviscous liquids are not encountered in real situations.

The effects of viscosity on flow depend on the boundary geometry and velocity. For fluids flowing at low velocities viscosity effects can be seen across the plotted profile of average velocities found in the conduit. Flows at higher velocities exhibit characteristic profiles that are less dependent on viscosity. At the higher velocities analyses of flow by Equation (4) is permitted due to the greater uniformity of the average velocity profiles, and the restriction of viscous influence on flow to areas in the immediate vicinity of the boundary.

Viscosity does play a role during the periods alternating between the initiation and cessation of flow, and the attainment of velocities where inertia forces dominate. The analysis of such flows through the base water system will be concerned with the solution of the basic equation of unsteady flow:

$$\frac{\partial V}{\partial t} = \frac{1}{\rho} \frac{P}{s} \tag{5}$$

The effects of viscosity and the boundary conditions will lead to the addition of terms which together comprise the quantity on the right side of Equation (5).

For the range of velocities which occurs between the initiation of flow and the state of fully developed turbulent flow in the particular conduit, there is usually one average velocity value below which disturbances of any magnitude are eventually dampened by viscous action. Flows at velocities lower than this critical value are inherently stable, and those that are greater develop vortices and become unstable. This limiting velocity must be found experimentally for the various conduit cross sections and operating conditions. The magnitude of the limiting velocity can be disclosed by calculations using the value 2000 found for the lower critical Reynolds number for terrestrial flows through circular tubes.

From this point, the further development of the equations of flow in closed conduits in extraterrestrial situations, based on terrestrial equations, seem justifiable also under the assumptions upon which Newtonian mechanics are derived. The use of equations developed from known information of the spatial site should be sufficient for initial designs of flow systems. After experimentation at the site, more refined and precise equations will be available.

In like manner, the other regimes of flow to be encountered in station water systems can be initially examined and analyzed by techniques formulated on earth. The chemical and petroleum industries have compiled much knowledge and experience in studying viscous flow through pipes or porous media which can be applied to spatial situations. Surface tension and capillary flow phenomena have been studied in conjunction with the space program, and the body of knowledge associated with these parameters continues to grow. The effects of centrifugal forces on flow are known and methods for analysis of systems utilizing this force exist.

<u>Comparison of terrestrial and lunar hydraulic phenomena</u>

The five types of forces would be interacting in fluid systems on the moon. The values for inertial and centrifugal forces would be identical to those in similar situations on earth. Viscous and surface tension forces would differ slightly as a result of the increase in the atmospheric density of the space station. The paramount cause of dissimilarities between the operation of terrestrial and lunar systems is caused by the difference in gravitational attraction. The value for the moon is 162 centimeters per second squared. This is .165 of the terrestrial value. A comparison of the probable effects of gravity on identical systems located on earth and moon is given in Table 4.

Energy for Spatial Use

Man will have to provide the means by which energy can be made available to furnish an environment for life, and to perform the many tasks of modern living. The sources of energy for space stations are the earth or the sun. If the station is located on an extraterrestrial body, local stores might be utilized. The processes through which water is furnished to the lunar station require varying amounts of energy. The sources which can be developed and their potential will be examined since this influences the design of water resources facilities.

TABLE 4

A COMPARISON OF EFFECTS OF EARTH AND MOON GRAVITATIONAL FORCES ON HYDRAULIC PARAMETERS

Factor	Earth	Moon
Weight of water per cubic meter	1000 kg	165 kg
Pressure increase per meter of water depth	100 g/cm^2	16.5 g/cm^2
Velocity head	1	6
Frictional head loss by Darcy-Weisbach equation	1	6
Height of capillary rise	1	6
Orifice coefficient	2.45	1
Celerity of gravity wave	1	2.45
Section factor for critical flow	2.45	1
Critical depth in rectangular open channel	1	1.82
Critical velocity in rectangular open channel	1.82	1
Critical slope in rectangular open channel	1.57	1
Fluid horsepower	6	1
Settling velocity for discrete particles	6	1

Solar energy

The largest source of energy available will be that from the sun. It has been found that the accessible radiation energy at any location on earth is dependent upon the atmospheric clarity, hour of the day, time of the year, and latitude of the body. When comparing earth and lunar values, there is wide variation between all factors except the latter.

The lack of an atmosphere raises the solar constant at midday to a value of 2 calories per square centimeter per minute as compared to terrestrial values which range from 0 to 1.5 calories per square centimeter per minute. The lunar day, which is equal to 29.53 terrestrial days, insures that there is continuous sunshine for a period comparable to fifteen days on the lunar surface. The obliquity of the ecliptic of the earth is approximately 23.5° compared to the lunar value of 6.66°. The lower value for the moon insures protection against long periods of darkness experienced by the terrestrial polar regions in winter. The sun, at the lunar poles, hovers continuously near the horizon and never sets.

The primary methods by which solar radiation can be utilized are through direct application of the radiant energy into electricity by means of heat engines, thermoelectric generators, and photoelectric generators, or through photochemical means such as photosynthesis. The devices used in terrestrial application for capturing the solar energy have been flat plate collectors, or some form of focusing collector. One of the most difficult problems has been the loss of heat that occurred between the collection device and the receiving medium. The development of heat pipe theory promises a solution to that problem (Eastman, 1968). This will raise the efficiency of the solar collectors.

The lunar use of solar collectors will be enhanced by several factors other than the high solar constant. The low gravity force will enable the construction of large collectors that use lighter materials and less bracing than is possible on earth. The lack of an atmosphere will eliminate structural requirements imposed by wind forces, and will also exclude tarnishing of the polished collector surfaces. Tracking devices and procedures for the collectors will be simplified since the sun will cross the horizon 14 times less during the lunar day when compared to terrestrial operations.

There should be no shortage of energy during the lunar day. When the sun is at its midday position, a square kilometer of surface receives enough energy to furnish 5.0×10^9 kilowatts per hour (Kopal, 1964). However, the night poses problems as its duration approximates that of 14 terrestrial days. For sites near the polar regions, the erection of large collectors perpendicular to the sun's rays would insure a continuous supply of solar radiation which could be converted into electricity. This could be transmitted via power lines to the stations which were enveloped in shadow. Line losses might limit the effective distance to which this power could be transmitted. Therefore, stations located near the equator, some 2730 kilometers from the polar regions, would have to rely on other forms of energy during the initial phase of settlement, or until new developments occur in transmission line theory. As stations become more numerous, a power net founded on the great circle principal would allow stations in the day periods to generate electricity by solar radiation sufficient for their use, and for supplying neighboring stations which were in shadow.

The solar energy received by a lunar station could be stored for use during the night. This stored energy could be in the form of heat or chemical potential. The storage of solar energy in the forms of electrical or mechanical energies, however, appears unfeasible at present. The length of the lunar night, and the size and number of batteries necessary to provide a continuous supply of electrical energy during this period, prohibits electrical storage. The mechanical storage of energy, such as the storage of elevated water supplies, appear impractical due to the lunar gravity, mild surface gradients, and the low temperature of the night.

Material in a vacuum can only lose heat by radiation or conduction since there are no convective air currents to carry the heat away. Heat loss through conduction is determined by the size of the contact area between members. Losses through radiation can be reduced if the radiating body is surrounded by a highly reflective material which can direct the radiated heat into the emitting body. Slabs of material could be heated during the day, sealed into aluminum foil envelopes, and placed in a vacuum in minimum contact with other materials. During the lunar night they could be used as a source of heat.

Energy storage through chemical means is feasible also. The utilization of the latent heat of fusion is one method. Materials with high melt temperatures are melted by solar energy, and stored in insulated containers. At night the melted material could be drawn as needed and allowed to cool. The loss of heat by cooling and the latent heat of fusion would be available for space heating, or to boil water for generation of electricity.

Hydrogen can be produced through electrolysis of water using solar generated electricity. This hydrogen can be stored until needed. It can be used as a component of fuel cells for supplying direct electrical energy. Hydrogen could be used in the generation of electricity as a fuel for heating steam boilers, or burned directly with air to supply high temperature steam within a turbine.

The two vessel system in which chemicals are mixed and the exothermic heat of reaction is used offers possibilities. Such a heat production system is found in a water-sulfuric acid combination. When a concentrated solution of sulfuric acid and water is heated by solar energy, the water will be distilled from the solution. The water vapor is condensed in another part of the system. After the residue of sulfuric acid and water has cooled, it has a subsequent, lower vapor pressure than the water located in a nearby vessel. The water vapor from the water supply releases its heat of condensation of 580 calories per gram at room temperature as it re-enters the sulfuric acid. In addition there is the heat of mixing between the water and sulfuric acid. If a valve is between the two vessels, the potential chemical energy can be stored indefinitely without chemical loss. Similar systems that could be used for various temperature ranges are phosphoric acid and water, $Ca(OH)_2$ and water, $CaCl_2$ and water, $NiCl_2$ and NH_3, silica gel and water, silica gel and NO_2, and silica gel and alcohol (Daniels, 1964).

Lunar sources of energy

Photochemical methods using lunar supplied chemicals could also be used as an energy source. These chemicals would be activated by exposure to solar radiation, and during the night would be subjected to chemical reactions which release the absorbed energy as heat or electricity. Photosynthesis, a reaction of this type employed by living plants, will probably be used on the moon in several applications to provide food supplies, to treat biodegradable wastes, and as sources of organic chemicals and medicines. It can not be considered a major source of energy at present.

Under proper conditions the internal heat of the moon could be used as an energy source. If nature has collected the heat as steam and placed it in a suitable location, the steam may be utilized to generate electricity (Austin, et al., 1965). Only a site near Lardello, Italy and one in New Zealand have conditions that are conducive to power generation (Thirring, 1958). Such gifts by nature must be rare, and reliance on other sources should be emphasized.

As there is a large range in surface temperatures, and a great variation exists between the temperatures of the exterior and interior, the heat pump or some modification of the Claude process should be feasible for converting these conditions into useful work. Again, the development of heat pipe theory and equipment may advance this method of energy production in terrestrial and lunar applications.

One of the major properties of the heat pipe is its ability to concentrate or disperse heat. If thermal power is introduced to the heat pipe at a slow rate over a large surface area at one end, the total amount of heat collected can be released at a higher rate over a proportionately smaller area at the opposite end. Dispersion of heat occurs in this situation when the flow of heat is reversed. In a lunar situation the solar radiation could be used to heat a sub-surface layer above its constant 240°K level by means of a grid of buried pipes. At night the heat dispersed over the buried layer could be collected by another buried grid of heat pipes using a different working fluid, and concentrated at the point where mechanical work is desired. Since the thermal properties of lunar materials have been seen to vary, it might be possible to locate spots where this method would work more satisfactorily than others.

Lunar deposits of hydrocarbons may exist (Wilson, 1962). If the moon has been built of a material similar to chondritic meteorites, about 3.6 percent of the mass should be similar to that composition exhibited by the carbonaceous chondrites when based on measurements of terrestrial proportions. About 1 to 5 percent of this type of meteorite is composed of carbon. Some of this carbon is in forms that have heavy molecular weight. Assuming that internal heating has occurred, temperatures above 673°K will have been sufficient to thermally crack these heavy carbons, and drive the fractions toward the surface. The lighter carbons would have been emitted into space, but the heavier hydrocarbons might have left a local skin of vacuum-reduced crude oil or asphalt. Wilson asserted that this could be the reason for the darker colored marias. If the primordial material had an assumed .01 percent hydrocarbon content, a total of 7×10^{15} tons of liquids would have resulted had the original content been cracked with a thermal efficiency of 10 percent. This amount could surround the entire globe with a uniform cover to a depth of over 20 meters (Kopal, 1966).

Since the terrestrial occurrence of hydrocarbons has been in sedimentary material as the result of biochemical action, lunar exploration will help to answer the question as to whether hydrocarbons can occur under abiotic conditions. If they do exist, perhaps in addition to being concentrated in terrestrial-like traps, they may also be caught under the ice. The more volatile hydrocarbons could provide the pressure to raise water and the heavier hydrocarbons to the surface for use.

The vacuum on the lunar surface, although not a source of energy, can provide a means of better utilization of other forms of energy. The pressure differential which exists between the interior of the station and the lunar atmosphere can be used in the venting of air locks, distillation chambers, or in the manufacture of vacuum tubes. The vapors that are evacuated can be drawn through the deep cold of a shadowed chamber and crystallized. The crystals could be collected and returned to the station for reuse.

Energy from earth

Nuclear reactors imported from earth will be used to generate electricity in the lunar stations. Now, they appear to be the most feasible means of providing energy during the night. Since nuclear fuel undergoes continuous disintegration, the reactor can be used to provide the constant demand loads for the station. During the day solar generated electricity could be used for peaking requirements. Some functions might have to be curtailed in the station during the night due to insufficient power.

The use of lunar supplies to provide radioactive material for energy sources will probably occur only during the later phases of colonization. The mining and processing of radioactive material that is suitable for use as reactor fuel will probably be too much for the lunar stations to undertake in terms of facilities and resources. If extremely rich and concentrated surface deposits of uranium are found, it would be cheaper to send the ores to earth for processing. Resupply should be no problem since the fuel elements could be shipped in unmanned, cargo rockets with little or no shielding measures taken.

The importation of energy from earth will probably consist primarily of nuclear fuel elements as mentioned in the previous paragraph. Nuclear fuel and reactors for generating electricity, and concentrated chemical energy in the form of explosives for construction, will have to be sent to the moon. Fuel-type hydrocarbons from earth will probably never constitute a major lunar import since internal combustion engines cannot perform outside the confines of the station. Their use in the life support bubbles will be also limited because of their high oxygen requirements, and the atmospheric pollution that occurs during their use.

Summary

In review, it appears apparent that electricity, because of its versatility, will furnish the majority of lunar energy requirements. This electricity will be generated by solar radiation and nuclear reactors supplied from earth. The use of lunar deposits of hydrocarbons for energy, within the stations, will be limited. They may be used for rocket fuels, but their importance will be from their use as a source of chemicals or food.

CHAPTER V

WATER SUPPLY AND TRANSPORT

Methods to Exploit Lunar Water Sources

It is imperative that local water sources be developed quickly into water supplies for the extraterrestrial bases, because the continued import of a heavy, consumable life support item like water will retard the needed input of material and equipment essential to expand and expedite the habitability of the site. Continued reliance on imports will be required if readily available supplies are not located, or difficulties are encountered in preparing the local source for exploitation. Research should be directed toward determining the best means of shipping water.

Blocks of ice, or tanks of liquid water, would provide immediate supplies of free water at the site. It could be sent in combination with other critical chemicals, and recovered as they were expended. Capillarity may be utilized by shipping water between the particles of an inert material such as carbon. Tanks of hydrogen and oxygen shipped to the site could be advantageous also. The oxygen would serve as a reserve air supply. When water is needed the two chemicals could be combined. The exothermic energy of the reaction could be used to produce electricity or heat. If oxygen can be obtained on the moon, cryogenic hydrogen at a density of 4.37 pounds per cubic foot could be imported from earth, and reacted with the oxygen (Di Leonardo and Johnson, 1965).

The sources and forms of water expected on the moon were discussed in Chapter III. In recapitulation, water could be found on the moon in the following forms. It may exist in the vapor or liquid phases in the lunar interior. Ice formations are possible as surface deposits in locations shielded from the sun, or in lens of varying thickness in the near surface layers. Clumps of ice crystals in a permafrost matrix may be found scattered throughout the cold surface layers. Localized sites near old crustal fissures or volcanic vents could contain water in the form of hydrates or lattice water. The lunar rocks should also contain small quantities of chemically bound water. Means of developing these supplies will be discussed.

A beneficial source of water during the early phases of exploration would be a deposit of surface ice. Even if the ice were located underneath surface debris, it could be developed with a minimum of effort and equipment.

Supply parties could periodically use this deposit. In lunar evening or night periods they could shatter ice and carry it to the life support units. The ice could be melted for use as needed. Di Leonardo and Johnson mention that ice could be a satisfactory form of storage. More elaborate transport procedures would be necessary to convey the ice during the lunar day. It would have to be shielded from the sun to prevent an explosive change in state. In fact, ice could be melted and carried in liquid state inside insulated, pressurized storage tanks to the point of use.

If the deposit of ice is vast, consideration should be given to the establishment of a nearby lunar base so that this supply could be used. With energy available the exploitation of the ice deposits could follow several different routes. Strip mining and quarrying techniques, using chemical explosives or electrically powered equipment, would break the ice mass. The fragments could be loaded into unirail trains or trucks and carried to furnaces which would melt the ice and process the product water.

In another method a domelike structure, similar to a diving bell, could be placed on the surface of the ice deposit. The interior is sealed and filled with a pressurized atmosphere. Heated probes melt the ice underneath the dome. The liquid is collected and pumped through heated pipes to other facilities for further treatment.

The lack of a lunar atmosphere insures that shadowed areas remain cold. Deposits can be preserved during exploitation by the erection of canopies which shield any uncovered ice from the direct rays of the sun. Use can be made of this shadow effect after the ice has been in the furnaces. The product water could, however, be pumped into molds located in a shaded place. The water freezes in the molds and is removed. These ice blocks can be stored in the vacuum atmosphere with only a shade for protection. In this manner stockpiles of water can be maintained at the extraction facility without requiring large, elaborately controlled tank farms to keep a liquid water reserve. Withdrawals could be made at any time to meet the demand for water. Once at the use point the blocks could remain outside the station until needed, thereby, decreasing the storage facilities required at any of the lunar stations.

Shallowly buried permafrost would also be adaptable to quarrying, strip mining, or hydraulic techniques. The yield of water per ton of material would be much lower in the case of permafrost, than in the previous case, unless thick ice layers within the permafrost zone were located and utilized.

Valuable by-products might be obtained from ice or permafrost. Other gaseous vapors were probably solidified with water in the low temperatures. Thermal cracking procedures could be used in processing to provide local supplies of chemicals.

Deep permafrost and liquid water in the interior will require other techniques of extraction such as underground mining and oil field drilling operations. Underground mining operations for water alone would be too expensive, but drilling operations, with modifications for lunar conditions, could be pursued.

An artificial atmosphere must be created at lunar sites using deep drilling methods. If no air or liquid is present, the heat generated by the force of impact and friction between the bit and material can not be dissipated. The rapid buildup of heat will melt the drill bit shortly after drilling commences.

The supply of drilling fluids causes other problems. If a lunar supply is available to provide the bulk of the drilling fluid, there are no insurmountable problems. Lunar sources of gases, such as those emitted by volcanic vents, could also be adopted for use. If these drilling fluids are to be supplied from earth, there is the question of determining whether the energy cost is feasible. It does not seem that the energy cost would be worthwhile in the case of water. A hole in impervious material 30 centimeters in diameter and 1100 meters deep would hold about 80 metric tons of water. In drilling, a large amount of fluid would leak into the cracks and fissures in the subsurface layers, adding greatly to the amount of fluid required.

The use of light-structured drill rigs will be facilitated by the lunar gravitational attraction. However, the weight of the drill string, which is utilized in drilling by its pressure and impact on the drilled material, would be reduced by this factor. The drill string would be a bulky, heavy item to import from earth. The masses of drilling fluids and the drill string are reasons why other techniques need to be formulated.

Heat in which local vaporization of the subsurface material occurs is a feasible way to blast a hole. The heat would have to be concentrated and applied at high rates for best penetration. Lasers, oxygen and hydrogen lances, or some mode by which the heat of rocket fuels could be applied are means which could produce the high heat rates required.

Heat at lower rates than that required for vaporization could be used. Electrically heated probes, driven into the permafrost, would melt the surrounding areas. The melted material could be jetted with the subsequent advancement of the pipe casing, or caisson methods could be used. If liquids are available, some method using jetting and the principles of the Frasch sulfur process might be applicable (Salisbury, 1963).

After confirmations of a suitable permafrost layer, explorers could detonate a nuclear explosive to shatter the permafrost layer and release water held underneath. The explorers could return to earth, or to other lunar bases, until the level of radioactivity had decreased sufficiently for safe use of the ice and underlying water within the crater area.

Whatever method is used to penetrate the permafrost regions, it would be desirable if the released water would be under sufficient pressure to rise and flow upon the surface. The possibility exists that the trapped volatiles, or the weight of the overburden, would cause the formation of a piezometric surface. A piezometric head would reduce the energy and equipment needed to lift water to the surface.

The temperatures of the permafrost will cause heat losses between the water in the pipe and the surrounding material. Unless the pipe is heated, or allowed to flow continuously, the water will freeze. It would be more desirable to have a heated pipe that could be closed to conserve water and naturally occurring pressure.

The development of the groundwater supplies can be based on terrestrial laws of groundwater and well hydraulics in confined aquifers. The permafrost will form an impermeable barrier to liquids and gases. Piezometric heads could be induced by trapped volatiles, changes in the hydraulic grade lines, and overburden pressure. The equations would be changed primarily by the lower weight density of lunar water. The decrease in fluid density will lower the value of the coefficient of permeability and the value of the hydraulic gradient in the Darcy equation.

Lunar conditions will cause slower rates of flow through the porous media, and thus, lower pumping rates. If flow rates are to be raised, the well diameter should be increased and a larger casing installed. The gain in flow rates from this action probably would not be offset by costs for the extra energy and material required.

The amount of energy needed to extract the water from the hydrates would be greater than with the permafrost due to the higher temperatures necessary to drive the water of hydration off as steam. The value of the by-products from this process lessen worry about costs of water extraction. Hydrates of aluminum, copper, magnesium, and calcium might be more valuable for purposes other than the water of hydration. Electrolysis of the concentrated by-products would produce ample supplies of metals for the lunar colony. Calcium, for example, may be useful as a bearing metal under airless, lunar conditions (Richardson, 1961).

Efforts have been directed to develop mechanisms by which bound water can be extracted from rocks (Salisbury, et al., 1963; Wechsler, et al., 1963; Glaser, et al., 1965; Weber, et al., 1965). The amount of energy required in the process is much larger in proportion to the yield obtained than that demanded by the exploitation of other sources. The rock extraction methods will be operable at any place on the lunar surface. It seems probable that more expenditures on reconnaissance procedures and detection equipment to locate water enriched areas will pay greater dividends over the exploration period than those gained by the development of a low yield, high energy process.

Methods of Lunar Water Transport

Under terrestrial conditions most water is transported through open channels and unpressurized conduits. These types of transport will be unsuitable for lunar application outside the space station. The lunar conditions limit the modes among stations to types where water is carried in solid form, or to those in which contained water is transported under regulated pressures and temperatures.

In transporting water in the liquid state, specific ranges of temperature and pressure must be maintained. It may be carried in separate containers or pumped through a system of pipes. When transported in containers, it can be carried to any site. If the temperature drops below 273°K during conveyance, the water freezes with an attendant change in volume that could rupture the container. When space is allowed for this increase, the positional change in the liquid's center of mass may become disruptive enough to overturn a land vehicle or put a rocketship off course. Leakage of the liquid must be guarded against due to the explosive change of state. Therefore, liquid transport will require expensive storage vessels which will have to be imported from earth.

Great stresses, resulting from the ranges in temperature, would be imposed on pipelines laid on the lunar surface. The expansion and contraction of materials will impose problems. Steel would have an expansion of $\pm$ .1 percent, while aluminum would change by ± .5 percent over the lunar range of temperatures (DiLeonardo and Johnson, 1965). This would amount to 5 meters per kilometer for aluminum pipe. Additional stresses would be placed between the shadowed and exposed portions of the pipe. The use of a non-rigid material would overcome some of this problem, but section joints would still present difficulties. An uninsulated pipe could transport water only during the day. As night approached, the pipe would have to be drained until daybreak.

To counteract variations in temperature the pipes could be buried beneath the surface, or laid across the surface and covered with lunar dust. This would place the pipe in the zone of constant temperature. Pipe networks would require heating stations so that the water in transit could be heated sufficiently to enable it to flow without freezing. These requirements imposed by the temperature and atmospheric conditions would necessitate many loads of bulky, insulated pipe to be sent from earth. This is too impractical to be considered at present, but may become possible with time.

Pipelines could be used without supplemental devices to maintain the heat level within the piped fluids. Water could be separated into oxygen and hydrogen at the extraction facilities. Both gases would be unaffected by the 240°K temperatures of the surface zone. These gases could alternately be piped and recombined at the use point as needed.

Ice particles might be transported pneumatically with those gases, or suspended in liquids unaffected by the ground temperatures.

The laying of pipelines would call for heavy construction equipment and explosives. Even though excavation and burial procedures will be aided by the lower gravitational attraction, considerable power must be available to break and remove blocks of permafrost. Liquid oxygen or water could perform as explosives. The large requirements for construction materials and energy are too much to justify pipelines over the lunar surface. It will be more important to direct heavy construction efforts toward the development of an electric power net for energy transmission.

The concept of maximum reuse of water supply will depress the needs for a pipe network. Pipelines are a recent innovation in transport history. Hydrocarbons can only be used once, and this creates the need for a continuous flow of these substances. This factor, combined with a high sale value, makes terrestrial gas and oil pipelines practicable. It is doubtful whether a large pipeline which carries a reusable resource would be profitable, except between the source of the material and a facility for refining and purifying the raw product. A pipeline is most adaptable for use in situations where flow is continuous other than where it serves as a storage facility. If water supplies are maintained in closed systems, perhaps pipelines will not be required. Pipelines laid across expanses of the lunar surface may become profitable if the amounts of make-up water required becomes large, or water is to be processed for use as a rocket fuel. The best solution to this problem, however, is to delay extensive development until sites with adequate local water are discovered.

The transport of water as a solid has the most interesting possibilities of any of the methods during the early phases of exploration and exploitation. Heat is transmitted by radiation or conduction in a vacuum. Light, reflective shielding, in place of elaborate storage containers, would be sufficient to prevent ice from melting during transport to orbiting stockpiles or outlying surface stations. Multi-purpose, mechanical loading devices can be used to load the ice onto the prime movers. The prime movers, whether rocket or surface vehicles, are available for other transport duties with few alterations.

CHAPTER VI

WATER USE

Water usage in space can be largely controlled by adequate planning of the facilities and processes in which water is employed. It will be applied first to domestic uses. With exploitation these applications will be expanded to include commercial and industrial operations.

A water system for the space station could be described basically as follows. A pressurized storage tank receives purified water inputs from the treatment facilities or the water supply point. The latter facility adds water as needed from the stockpile of ice or liquid water. This storage tank then supplies water to the water use facilities via pipe or container. There, the water that fulfills its intended use immediately upon exit from the supply system (i.e. water used by an inhabitant to wash his hands) is collected by means of a vacuum system or gravity. The waste stream is returned to the treatment facilities for processing. Portions of the waste stream could be sent into auxiliary storage. This supply could be used by facilities able to employ water of inferior quality. Finally, the water is returned for treatment.

The remainder that was consumed at the use point eventually returns to the waste water transmission lines or evaporates into the atmosphere. The air conditioning or thermal control system, in stabilizing atmospheric moisture, continuously removes a portion of the water vapor (i.e. 1100 grams per man per day, plus water evaporated from liquid surfaces). The condensate, depending upon the level of atmospheric contaminant, is sent to the storage tank for immediate reuse, or is returned to the treatment facilities for processing.

Some or all of the following considerations should be incorporated into the design of space water systems:

(1) Water use facilities should be grouped together as much as possible so that a minimal amount of fluid transport material will be required.

(2) The use facilities should be designed for staggered or continuous operations rather than to meet peak demand, in order to promote system efficiency and minimize storage requirements.

(3) The system should contain only the amount of water required for the designated uses under normal operating conditions.

(4) Water will be used only for requirements where economy exists in terms of treatment and resupply costs.

The domestic use of water will be discussed in this chapter. The alternatives that can be utilized for each use area will be examined with emphasis on water conserving features. The figures given in Table 1 will serve as the ultimate for domestic planning.

Kitchen Use

Water for use in food preparation and for drinking

There should be no differences between the estimates given for terrestrial use in this category and that for space use. Amounts lower than the 2 gallons per capita cited can be expected in the near future due to complete reliance on prepackaged meals. When kitchens are included in the base design, the water demands will increase. As fruits, vegetables, and poultry are grown locally, water will be required to clean and process those items. However, it is doubtful whether the base will ever be considered self-supporting from a food production standpoint, and continued imports of foods which require station water for preparation will be vital.

The controlled environment of the space base should stabilize the amount of drinking water required for early inhabitants around the 1200 milliliters cited in Chapter I. As base expansion provides facilities for exercise and sports programs, body requirements will increase. This factor should put no strain on the system facilities when compared to the amounts used for other purposes.

Kitchen cleanup operations

If conventional use is made of water during the cleanup phase, a reduction in amounts consumed can best be accomplished by the design of facilities and equipment which display water conserving features. Some features to consider are:

(1) Institutional-type mess facilities which use uniform dishware would enable more dense loading of dish washers.

(2) Steam cleaning apparatus can be adapted for cleaning pots, pans, trays, and dishes.

(3) Adjustable faucets which operate at various rates of pressure and flow are desirable.

(4) Atomized sprays could be employed with great water savings to alleviate inefficient use made of the liquid stream that flows at rates of 4.5 gallons per minute from the sink faucet.

(5) Nozzles or faucets activated by foot, knee, or waist pressure would decrease the amount of water presently wasted with conventional faucets.

(6) Dials could be used to set flow rates from auxiliary tanks at various temperatures, so

that a blended water at the desired temperature is produced immediately upon exit from the faucet.

The method of waste treatment selected for the station will determine whether garbage disposal units or grease traps are required. Pyrolysis or wet oxidation processes would benefit from the use of garbage disposal units, but grease traps would not be required. Other methods would profit from the use of grease traps where garbage would be separated from the water and disposed of separately.

Cleaning of utensils without water is possible. If table and cookware were made from heat-resistant ceramics, heat provided in a laboratory furnace could be used to burn off food scrapes and grease. This would also eliminate the need for further disposal of garbage. Some water or cleansing agent might be required to rinse or remove the residue and stain from the ceramics.

Personal Hygiene Facilities

Baths

Bathing with water is the primary means of cleaning the body. It also serves in a therapeutic role to relax and ease body tensions. Therefore, the actual amounts of water consumed will vary as to the mood and preference of an individual at a given time.

A ten minute shower with a conventional shower head requires from 30 to 50 gallons of water, whereas, a tub will require 15 to 20 gallons. Unless individual facilities are available, groups would probably choose to share showers rather than tubs. Daily cleaning would be sufficient for showers, while cleaning after each use is the accepted mode for tub facilities.

The most desirable means of bathing are showers, sauna with showers, steam bath with showers, and swimming pools with showers. The latter can be disregarded unless adequate, local water is available. Even then, the chemicals, support equipment, and space limitations would act against the inclusion of a pool in the early space stations. Later, the swimming pool-shower combinations would be feasible. The pool would serve in a storage capacity, and at the same time enhance the environment. Sauna and steam baths which produce profusive perspiration under hot, steamy conditions, followed by drenching of cold water, are prescribed for easing tensions. In either case, water savings could result since 1 liter of water will form about .3 cubic meters of steam. Personnel would use the steam facilities and pools for relaxation instead of wasting water through leisurely showers.

Shower facilities can be designed to save water. The primary way will be to reduce water flow. Adjustable shower heads are available which can regulate the amount of flow. Better design could be developed with water conservation in mind.

Another approach uses fogging or atomization instead of the multiple streams of water which are employed by shower heads. This process can be accomplished by pressure, centrifugal action, or gaseous energy, and can obtain infintesimal to normal rates of flow (Blakebrough, 1968). Pressure is the simplest method of atomization from the standpoint of equipment design and maintenance. In this method the water is forced through an orifice. The form of the emerging sheets of liquid depends upon the direction of flow toward the vent. The liquid sheet disintegrates into drops as a result of the instability produced when the surface area of the film increases upon leaving the orifice area.

The most desirable configuration is the full cone. The conical volume is filled with an evenly distributed mass of drops or spray. More efficient use can be made of the applied water than is possible with similar facilities which depend on volumes of water applied in continuous streams. The lower lunar gravity will enable droplets to remain in suspension longer and, therefore, less flow will be required to obtain the desired concentration.

The flow from an orifice can be determined from Equation (6), where "Q" is the flow rate, and "C_q" is the discharge coefficient.

$$Q = C_q A \left(\frac{2P}{\rho}\right)^{1/2} \tag{6}$$

This factor is dependent on the boundary geometry of the spray jet, and is determined by equations of the form given by Equation (7).

$$C_q = \frac{C_c}{\sqrt{1 - C_c{}^2(d_o/D)^4}} \tag{7}$$

The terms are "C_c" for the coefficient of jet contraction, "d_o" for the diameter of the orifice, and "D" for the diameter of the constant diameter section upstream from the orifice.

The flow rate in Equation (6) is seen to vary with the square root of the pressure drop. The flow from a pressure nozzle is, therefore, relatively inflexible. This is a desirable characteristic in many instances. In other applications, such as rinsing the hair after shampooing, this inflexibility would not be appreciated. Pressure nozzles of the swirl spray type have been developed that can vary flow. This variation is produced through design features which bleed or intensify flows and pressures within the nozzle.

The time the drop remains suspended, and thus, able to be captured for use, depends on size of drops and the positioning of nozzles. The drop diameter is a function of the nozzle characteristics, operating pressures, and properties of the gases and liquids involved. Presently, this factor has to be determined experimentally. The nozzle position influences the air movements and drop trajectories within the shower areas. Nozzles placed with their orifices pointing downward (i.e. toward the center of gravity) will impart flows with the least theoretical suspension time. Nozzles with their orifices vertically oriented give the largest theoretical suspension time. Coalescing of drops will occur between the rising and falling streams. This may, under particular conditions, cause undesirable operation when the alternate buildup and collapse of liquid sheets occurs. The placement of nozzles in the floor would also be undesirable for upkeep.

The best results should be obtained by placing the nozzles on the wall with the orifices at some angle between 0 and 90 degrees. Chances of contact with the body surface is increased with side placement. The number and location will depend on the flow rates and spray angles of the nozzles.

The incorporation of sequential operation into the design of water release valves is beneficial. The shower could be operated as follows. Upon entering a dial is set for the desired water temperatures. Next a switch is flipped which initiates a timed fogging cycle. At completion the flow stops and soap is applied. Another alternative adds soap to the water during fogging in predetermined amounts in a fashion similar to car wash operations. After scrubbing sufficiently, the operator resets the dial, and initiates another flow phase in which multiple banks of nozzles apply a quick, heavy spray for rinsing. Additional cycles can be used if needed, but the ritualistic procedure must be repeated to initiate each phase.

Lavatories equipped with shrouds could utilize the spray design and sequential operation. Hand cleansers could be applied before or during the wash cycle. After scrubbing the operator would initiate a timed rinse cycle. To wash other portions individual washcloths would have to be dispensed to capture sufficient spray. To shave and brush teeth would require separate operational cycles in the spray lavatory. Methods of accomplishing both of these tasks can be expected to change. For example, the soap mug and brush have passed from the contemporary shaving scene.

Another device will be needed in the event that a basin or container of water is required for shaving, washing, or soaking. Basins cannot be filled directly from the pressure system because of the accompanying splash effects in the low gravity environment. A vented container of the exact volume can be filled directly from the pressure system initially. This supply container is located so that the wash basin underneath would be filled by water under gravitational influence or by siphoning.

Cleansing creams, promoted for cosmetic use, offer another innovation in water conservation. These are rubbed onto the body and removed with tissues or cloth. The rubbing action during application and removal would provide some therapeutic benefits. The use of these cleansers in combination with deodorants, powders, and perfumes could reduce the frequency of bathing and, therefore, the daily allotment of water required for each inhabitant. The controlled environment of the station should decrease the amount of body perspiration and diminish the need for cleansing. Other variables, such as exercise and emotional strain on the inhabitants, could decrease the effects gained by the controlled environment.

Problems would be presented with the use of chemical cleansers. They would be dispensable and pose a problem of resupply (i.e. to replace a consumption of 4 ounces of cosmetic aids per capita per day would cost $920. per year for transport). The vapors emitted from their use might present atmospheric contamination problems. Wipes, if made from reusable material, would create laundering problems. Acceptance of this type of cleaning might not be satisfactory to the majority of the inhabitants.

Sanitary uses

Several strategies exist for the spatial handling and disposal of human excreta, and for the recovery of water from these products. Burying, composting, and burning are adaptations of age old practices. Others, which neutralize the wastes by chemical or biological means before ejection from the system, are more recent. The idea of regeneration and reuse within the system is the culmination of thought in sanitary practice.

In space a symbiotic relationship in which machines and biological organisms interact to provide a terrestrial type environment can be established. This system will necessarily be large and require ample reserves since biological reactions are slow and inefficient. Considering spatial constraints, the requirements for mechanical procedures to effect this regeneration increase. Thus, the amount and rate of flow of mass through the use and regeneration cycle becomes important. Large storage capacities and ample supplies will allow one of several strategies to be used while the converse will dictate others.

Expulsion from system

The extent and operation of the station's water treatment facility would be simplified if the excrement and urine from inhabitants could be frozen and buried. The use of privies is complicated by the cold of the subsurface layers. Urine which normally seeps into the unfrozen ground on earth would freeze. A storage volume of about .5 cubic meters per man per year would be needed in place of the .05 cubic meters required in unfrozen material. If both urine and feces were wasted from the system, 512 kilograms of water would have to be imported for each man per year to replenish the supplies. When only the feces and the urine associated with the bowel movement (i.e. 100 milliliters of water in feces and .16 of daily urine production) are eliminated, about 115 kilograms of imported water per man per year would be needed. This latter amount would be replaced by the continued imports of foods which contain some water, and the metabolic water produced in the station.

Chemical toilets could be used if wasting from the system is contemplated. Odor can be eliminated by chemical additives, and the bowl is flushed after each use with recycled fluid. The initial charge of water aids in keeping the contents fluid and, therefore, adaptable to hydraulic handling between the toilet and the disposal point.

Burying and composting

Burying provides a way of permanently disposing of wastes. When no further use is required, or desired, of a particular waste material, burying outside of the station is practical. The feces and urine, if frozen and buried below the surface, would not necessarily be wasted from the system. This could be later utilized when a demand for the constituents of the wastes existed. This method can also be used to develop lunar soils.

Eventually, plants will be grown in space stations to provide local sources of food. Hydroponic culture will be practiced initially in which plants are grown with their roots immersed in aqueous solutions containing the essential mineral nutrients. These mineral salts will have to be imported from earth. At some stage it will become more economical to develop lunar soils for use within the space station so that utilization can be made of local mineral salts.

The organic wastes of the space station can be used as an aid in developing the inert inorganics of the moon or other planets into viable soils capable of supporting plant life. Soils are complex admixtures which contain many different forms of living and decomposing biota scattered among inorganic particles. Some of these organisms and their decomposition products are able to extract compounds from the soil minerals. Other living forms synthesize these extracts and compounds from organic decomposition products into forms which higher plants can use. Inputs of organic matter, such as garbage or excrement, aid these lower life forms in developing a soil in the same manner that manure and freshly-turned, green forage crops fortify terrestrial soils. This organic matter conditions the soil by improving its structure and water holding capacity. The end decomposition product of organic matter, humus, exhibits a high cation exchange capacity by which bases are extracted from soil minerals.

Burying processes are slow since decomposition occurs under anaerobic conditions. The water contained in the wastes remain bound in the soil matrix. No control can be exercised over the product or reaction time. Compost processes are mechanically controlled. Unlike burying, the bulk of the wastes is reduced, and most of the water in the wastes is vaporized. An inoffensive end product that is easily handled is produced. This can be stored as a separate, or mixed with inorganics when desired, whereas, the buried refuse becomes a part of the mixture in which it is placed.

Burying may be applicable when sufficient amounts of other organic refuse are not available to provide "body," or to dilute the wastes sufficiently for the biological population. It is also applicable when constraints on time, space, and water are not critical. Composting is fast, and the gaseous by-products can be collected by the atmospheric control system.

Incineration

Water can be separated from sanitary wastes by incineration. The efficiency of the process increases if elimination of any additional water inputs occurs. The water vapor and gases from the incineration of the sanitary wastes can be released to the station atmosphere. If combustion is incomplete, they can be piped directly to the atmospheric control facility for collection. Possible routes to the incinerator are:

(1) The feces and urine are deposited in a disposable container which is removed and burned when full.

(2) The accumulated wastes from chemical toilets are drained and taken to the station incinerator.

(3) The urine and feces are vaporized in the toilet (Macklin, 1966).

The advantage of the vaporization process is that no other materials are required during operation. The feces are deposited on a wire screen. An electric current is impressed onto the screen to incinerate the feces. The ash is blown to a collector by an air stream flowing continuously into the chamber from ports around the toilet seat, and the vapors from the process are released to the station atmosphere. The urine is sprayed back onto the heated screen and vaporized.

Conventional approach

The conventional approach is to transport sanitary wastes via water transport to treatment facilities. Water closets will not be suitable for use in most spatial locations due to low values of gravity and the large amounts of water required in operation. Opportunities which exist for conservation, if water conveyance for sanitary wastes is practiced, are as follows:

(1) Less water will be required on the moon to transport comparable loads.

(2) Water saving features can be incorporated into presently available equipment.

(3) Flush valves can be designed to operate efficiently at shorter flow periods.

(4) Discarded wash water from showers or laundry could be collected in a pressurized auxiliary tank to be used in sanitary transport.

(5) Separate treatment facilities for sanitary wastes could be planned.

The best opportunities for conserving water exist with the last two items listed. Using discarded wash water would eliminate the allotment for water employed separately in sanitary transport. This would cut the daily requirement per person given in Table 1 by 24 gallons. The auxiliary tank would need periodic cleaning to discard the settled materials and scum from the wash water.

The employment of separate facilities for sanitary wastes, for example, could utilize the capabilities of particular treatment processes, and the water conserving features of chemical toilets. The concentrated wastes from these toilets could be initially treated by the wet oxidation processes. The effluent from this process could then be combined with the other liquid wastes for additional treatment in which the remaining organics and inorganics are removed.

Laundry Operations

The habits of dress will be different since neither the extent, nor degrees of clothing required in the variable climates of earth are necessary in the modulated climate of the space station. Variations of dress, ranging from total body coverage in light-weight materials to a complete lack of clothing, are alternatives that can be practiced within the station. The latter would minimize laundry demands, but other factors might tend to discourage its adoption. Some fabric cleaning will be necessary despite the modes of dress so a capability must exist to perform this function, since articles such as napkins and bedding made from paper, or other disposable material, will not be practical from a stores standpoint for long tours of duty in the space stations. Each average hundred pounds of laundry becomes soiled with 1.8 to 4.0 pounds of dirt through normal use (48). This dirt is composed of fatty substances, proteins, dust, and soot. In space stations the latter items should be less than in terrestrial conditions since the atmosphere within will be free of dust.

Dirt is held in clothing by mechanical means, chemical bonds, absorption, and electrical forces. It is normally removed in a washing process which combines the effects of temperature, chemical action, and agitation. Each effect can be varied, but none can be overlooked. Water and chemical compounds are mixed with the soiled clothes. Chemical reactions, which are dependent on temperature, aid water in removing the dirt from the clothes. The agitation disperses the chemicals and dirt from the clothes throughout the mixture.

Chemical solvents, ultrasonics, and physical forces like brushing or suction are other cleaning methods that have been successfully used. Each is geared toward the removal of particular types of soil, and is not generally as suitable as washing.

The use of clothes by the individual will vary. Table 5 gives a sample listing of clothes used in a week by a male inhabitant if conventional practice is followed. If washing facilities are accessible and freedom of choice is allowed in the colors, materials, and kinds of clothes, each individual might wash four or more loads of clothing per week. This would require a minimum 22 gallons per capita per day for laundry.

More control can be gained if the laundry facilities are operated under station supervision. Even if personal freedom of choice is allowed in clothing, more uniform loadings of machines can be obtained. Counter-current flow operation, in which the rinse water from one machine becomes wash water for another, can be initiated to reduce water requirements to one-third in machines which are filled three times per cycle. The laundering process can be geared to the operation rates of the water treatment facilities.

If control is extended as to types of fabrics allowed, other water savings are eminent. Non-wetting fabrics could be used in clothing, and would be comfortable under the controlled conditions of the space station. Laundering would require less water since no absorption occurs. Centrifugal action could remove the water to dry the material. Other textile auxiliaries could be added to fabrics making them

TABLE 5

SAMPLE NUMBERS AND WEIGHTS OF CONVENTIONAL FABRICS USED WEEKLY BY MALES IN A SPACE SITUATION

Item	Number	Approximate Weight in Pounds
Bath Towels	7-10	6.0
Handkerchiefs	7	.5
Napkins (Cloth)	21	2.6
Night Clothes	2	2.0
Pillowcases	1	.3
Sheets	2	3.0
Shirts	7	5.3
Shorts	7	2.2
Socks	7 pairs	1.3
Trousers	7	7.9
Undershirts	7	2.7
Wash Cloths	7	1.0
Total		34.8

dirt, soil, water, and odor repellent. Permanent press materials would further eliminate frequent changes of clothing. The ability to control fabric types enhances the possibilities that fabrics particularly adaptable to cleansing by methods other than washing can be produced.

Station Maintenance

Regular use of water for domestic cleaning within the station will probably be confined to bathroom and kitchen areas. Some infrequent use outside these areas will be made. This limited use is desirable from a water resources standpoint. Factors other than the spatial constraints have caused these reductions.

Acknowledgement of the importance of designing facilities which are easy to maintain has occurred in recent years by industry and the combined hotel and motel interests. The high cost of labor and maintenance supplies coupled with the desire for neat, attractive surroundings have lead to a search for new materials and furnishings. Tile floors and painted walls which prove difficult to keep attractive and clean are being replaced by carpeting and new types of wall paneling. The carpets can be cleaned by daily vacuuming and infrequent shampooing. This is much simpler than the procedure required to keep tile floors presentable. Textured or plain plastic panels, likewise, require little attention to maintain their appearance.

These features can be expected in the space station. The high cost of supporting an individual in space will necessitate his employment in useful work other than household chores. Therefore, labor saving devices and materials must be included in the station design. The absence of combustion engines, the high level of control which is maintained over the station atmosphere, the inaccessibility of the "outside," and the types of work performed by the station inhabitants will tend to maintain the cleanliness of the station's interior.

Mission Use

Water required in conjunction with mission objectives becomes subject to different values from those by which the life support functions have been discussed. The supply, employment, and treatment of water for purposes other than life support will depend upon the feasibility of conducting the enterprise in space. The requirements for water will have to be judged in similar manner as the other materials, or chemicals required in the operations. The feasibility of cooperative use with the station's life support system will have to be determined during the planning stages of the station facilities, or as the situations later arise.

CHAPTER VII

WATER TREATMENT

The control of the environment will require expertise in balancing the operations of the many diverse subsystems within the space station. The by-products produced by one system will interact, and possibly complicate, the operation of other components. Terrestrial procedures and techniques will not be adaptable, in all instances, due to the low level of interaction allowed. Terrestrial systems for water supply and waste water disposal will be analyzed as to their suitability of employment in space stations.

General Considerations of Waste Treatment

Waste treatment in extraterrestrial situations will be concerned with the separation of the components in the waste streams, and preparation of the separates for primary and secondary use or for final disposal. All mixtures can be separated by one or a combination of these basic procedures:

(1) The addition or removal of heat energy

(2) The replacement or destruction of the product of interest by electro-chemical processes

(3) Exploitation of the differences in force among the mixture components

There are options available in design of facilities for treating all types of solid, liquid, or gaseous wastes using these procedures. Each type of waste could be treated individually. This would result in undesirable duplication of facilities. The most likely approach will be one similar to that in practice here in which compatible wastes are mixed for treatment, and incompatible wastes are treated separately. With control exercised over material entering the space environment, this should be effective.

The ideal facility would be one that could treat all wastes generated at the particular location. A uniform mixture of solid and liquid wastes is batch loaded into one of a series of furnaces. Heat energy is applied to the mixture. As the temperatures are raised, the different constituents are drawn off at their various critical heats. When the process is in the high temperature range, air from the station atmosphere is pulled into the furnace. The product gases driven from the mixture, and the heated gases of the station atmosphere, are sent through various combinations of thermal and cryogenic cracking units to break the gaseous compounds into the desired components. Metals and metallic alloys are refined during the process. The separates from the various stages in the process are stored for future use, prepared for immediate reuse, or discarded.

The ideal system would operate continuously with a uniform loading of wastes. Departures from this could come during the early stages of colonization as a result of the inability of obtaining a uniform waste, and the lack of an energy source which could maintain uninterrupted operation at high temperatures. Metallic wastes, and others which require high energy input, will have to be stockpiled for periodic treatment. Uniform loadings will not occur until the personnel and equipment reach such proportions that statistical procedures can be used to compute the amount, kind, and nature of wastes arriving at the facility.

It is doubtful if every station should have a complete treatment capability. The compatible wastes of a station could be partially treated so that a portion is ready for reuse in the facility. The remaining concentrate, and the other incompatible wastes, are then sent to a major facility for complete processing. Such a scheme can be illustrated as follows.

Heat is used to evaporate a portion of the water from the liquid wastes. The vapor drawn off is condensed, purified, and returned to the water system for reuse. The concentrated wastes from the partial treatment are pumped into molds that contain solid wastes in the station. This mixture is frozen. The blocks are taken from the molds and shipped to a waste treatment facility. The wastes could be stored for years in frozen form. After treatment facilities are available, the chemicals and materials contained in the wastes can be regenerated for use.

Treatment processes and facilities will be modified with advances in technology. These advances can be adopted into the individual designs of each base. Another alternative is that base equipment be manufactured and used over a specific period with only minor modifications planned until a model change is contemplated.

The model concept offers alternatives. The treatment facilities can be built as a complete unit in modular form to be plugged into the station, or it could be assembled from modular subsystems. Greater flexibility is possible, in the latter case, since interchangeability of units between bases can occur. Sizing of facilities can vary since groups of the sub-units can be transposed when necessary.

Properties of Terrestrial Facilities

The objectives of most terrestrial water treatment facilities is to produce a potable water. Public health considerations, coupled with the low cost of producing a quality product, have favored the employment of this standard even though the majority of this water is subsequently employed in uses in which an inferior product would suffice. The water treatment processes have been designed to benefit from free air, the free energy of gravity, and the low cost of surface space and water. The processes of sedimentation and filtration utilize gravity to affect separation of suspended solids from water, and to provide the impetus for flow. Use of chemicals in the treatment processes is based upon the ease of application, and the availability of the chemical supplies. The venting of by-product gases and the disposal of the sedimentation products from chemical use have posed no problems in the majority of cases. In specific locations the need for water has caused the employment of more costly treatment techniques which require high inputs of energy or more elaborate chemical processing.

Municipal water supply and waste water disposal systems have been treated as two processes separated physically by distance and organization. This is logical since the most common practice has been to allow water to flow only once through the same municipal system. Both systems take a feed of varying composition, and produce a product that meets certain specifications. The differences between the two have been primarily those concerned with types of treatment, and the quality of the effluent. This difference and separation is nullified once water reuse is practiced, and the waste stream produced by the system again becomes the water supply.

The objective of municipal waste water disposal systems is to break down or nullify liquid wastes into substances whose presence in the effluent stream meet the quality standards of the receiving environment. The development of treatment processes has been focused primarily in the biological area. Since most liquid wastes from human activities are organic, they are amendable to biological methods. Organisms can profitably be employed to decompose the wastes in situ using the "free" energy supplied by the waste products, or that provided by the sun. The organisms become the basis for the design criteria in this type of process. Their environmental requirements determine the operational characteristics since for their continued well being, only specified types and amounts of material can be introduced into the system. The protracted reactions which occur during the biological decomposition of liquid wastes make this a slow process. Therefore, large volumes of water are held in the treatment chambers. This is an advantage in that the wastes are diluted, and it is easier to maintain a non-toxic climate for the organisms. Some types of industrial wastes, however, are not well suited to biological breakdown. Other processes, such as those used at particular locations for water treatment, have been employed in these cases.

Environmental Constraints on Lunar Facilities

The individual elements comprising the conventional processes of treatment could be adopted with modifications for lunar use. Constraints imposed by other factors will require deviation from terrestrial procedures. Contrary to the artists' concepts in which buildings and vegetation are arranged in familiar patterns under translucent domes, the amount of available space within the base will be limited far into the future. The expected number of inhabitants will determine the planned volume of the base. Until lunar capabilities exist for the manufacturing of construction items, the material and parts which will partition and surround the planned volume will have to be pre-formed on earth and shipped to the moon for assembly. The planned volume per man for periods of 300 to 400 days will range from absolute minimal values of 5.6 to 7.0 cubic meters to the value of 56.5 cubic meters which was used as the basis of design for the Arctic expeditions (Frazier, 1968).

The atmospheric pressure maintained in the station will affect the volume and requirements for materials to be imported. A pressure of 760 millimeters of Hg requires about 1.5 times as much cabin wall weight as an atmosphere in the 260 to 560 millimeters of Hg range (Roth, 1967). Diffusion losses of the atmosphere increase directly with increases in station volume, and with increases of the pressure differential between the base interior and the lunar atmosphere.

The bulk and mass of items to be used in space must be minimized. These two properties will have more influence upon the selection and design of system components than will the requirements for energy. The cost of providing sufficient energy to continuously operate treatment processes appears to be less than that required for the storage and water necessary in periodic treatment which takes place only during the lunar day.

Treatment processes that require a continuous supply of expendable material should be eliminated. When possible, substitutions of processes utilizing regenerative materials should be included in the design. For example, the use of chlorine in water purification imposes a supply problem, and creates difficulties when introduced to the station atmosphere. The use of ozone, ultraviolet radiation, or nuclear radiation could be substituted since energy for their use will be available. The supply demand from these latter processes will be limited primarily to equipment parts.

There is no standard process available which is optimally suited to the destruction of all types of waste. Those in use are suitable for removing, or negating only portions of the waste streams. Treatment in extraterrestrial situations will depend upon a grouping of processes into a suitable system that satisfies the station requirements.

The preceding discussion initiates the advancement of ideas that will influence the design and selection of processes for water treatment facilities within the station. These factors are:

(1) Energy will be available for continuous operation of water treatment facilities.

(2) Water reuse will be commonly practiced, therefore, one treatment facility will suffice.

(3) Water must be moved under pressure.

(4) The treatment processes must be rapid since space for water storage will be limited.

(5) The processes should be confined in a minimal space.

(6) The processes should utilize a minimum of expendable supplies.

(7) The end products should be in an innocuous form for final disposal, or in a form suitable for reuse.

The normal treatment procedure here has been to remove the suspended, settleable organics and mineral solids from the waste stream as the first step. In the secondary stage the non-settleable organics and mineral solids are removed, and the levels of dissolved organics are lowered. At the completion of this stage, the effluent, with its load of dissolved minerals, is released from the system. If reuse is planned, the effluent, instead of being released, is sent to tertiary treatment processes. The levels of dissolved minerals are lowered, and thorough removal of dissolved organics occurs. The processes employed for these stages will be analyzed as to their relevance for lunar use.

Settleable Solids

The process of sedimentation is used to remove settleable organics and minerals from waste streams. This process will not be as rapid or efficient on the moon. The terminal velocities of suspended solids will be but .408 that for similar sized particles on earth. In addition, the energy required to support small particles is directly proportional to the square of gravitational attraction (Rubey, 1933). The load carrying capacity at any flow velocity on the moon would be 36 times greater than here. Longer detention times and smaller surface loadings will be needed for continuous flow tanks. Consequently, huge volumes of water will have to be maintained in the system.

Suspended Solids

Biological

Much action has been directed toward adapting biological methods for spatial waste treatment since these methods can produce oxygen and growths of organic materials as by-products. The production of organic matter has been one of the main reasons this method has received so much attention. The material produced could be used as a food source for man, or as a food for other life forms.

The length of treatment time, and the accompanying demands for increased water and storage, make this process undesirable for use in the early space stations. This method could prove feasible if adequate local water supplies are available and energy stores are limited.

It is doubtful whether a food chain, based upon the conversion of untreated human wastes into usable food, will ever be as satisfactory as food chains developed to utilize the growth potential of organisms that perpetuate the chain.

The former can be accomplished, but it seems much more logical to expend effort in developing methods which synthesize foods from stockpiles of carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus obtained from the breakdown of wastes. These foods could be developed directly for use by man, or for animals which serve as food for man.

Until means of effecting food synthesis are developed, water will be required as an aid in producing food energy resources. Water will be used as a habitat for lower life forms. It will function as the transport media in which nutrients are carried to the organism and wastes are removed. It will serve as an essential compound within higher life forms. Therefore, the most efficient use of water by organisms will occur if the water is purified, and the necessary attributes added, in order that the resulting solution can be applied in the desired role.

Filtration

In the lunar environment this process can be performed by gravity, capillarity, pressure, vacuum, or centrifugal forces. Available equipment could be adapted for employment and use of the latter two forces. If flocculation is required, it could be used most effectively in conjunction with vacuum or centrifugal filtration equipment. Space and supply support requirements are favorable for use of these two types of filtration.

Filtration caused by flow through porous beds of unconsolidated materials has been powered primarily by gravity. The effects of lunar gravity on patterns and rates of flow are not favorable. Capillarity and pressure, however, can be used to promote flow. The availability of filter media is an advantage for utilization of this form of filtration. The material handling equipment and space requirements will be substantial. The chemical composition of the local material may place restraints on use. The need for soils that are suitable for plant growth may dictate the use of this method to leach excess salts from lunar surface materials.

Flocculation

Chemical and biological means have been employed to coalesce the suspended, non-settleable organics and minerals. The greater load carrying capacity of lunar waste streams would promote the rapid growth of large flocs. This advantage would be offset by the following factors. Sedimentation processes are normally employed to remove the floc particles. The chemicals used for flocculation are expendable. The precipitates from the process present a disposal problem.

Dissolved Organics

Adsorption

Some form of adsorption process will be required to remove the refractory organics from the portion of the effluent which will be used for potable supplies in the station. Since the adsorption material must be regenerated or replaced after removing a particular amount of contaminant from the waste stream, other processes can be more profitably employed in the initial removal of suspended and dissolved organics. Results from using materials other than activated carbon has been discouraging. A local supply of make-up carbon could be obtained by pyrolysis of the stations organic wastes, or through the stripping of oxygen from carbon dioxide.

Foam separation

Bubbles will rise through water at slower rates on the moon. Since lunar flows are able to carry large amounts of particles in suspension, this will result in an increased chance for contact. This process could utilize the normal frothiness of the waste stress and float out a sizeable portion of the suspended and settleable material.

Hydrolysis-absorption

This is a two step method called the Z-M process. The influent wastes are mixed in a chamber with predetermined amounts of a combination of calcium hydroxide and other chemicals. Hydrolysis takes place within the chamber, and the larger organic molecules are reduced to smaller sizes more amenable to absorption. The stream then enters activated carbon columns for final purification. Claims are made that a higher quality water is produced at two-thirds the cost of water from conventional tertiary treatment (Chemical Engineering, 1969). The disadvantages of using the process in space would be those associated with the absorption process, and the use and resupply of the chemicals needed in the hydrolysis phase.

Oxidation

Several types of oxidation processes offer benefits in that regenerative materials already in the life support system are utilized. Their use will not produce secondary pollutants or necessarily add to the inorganic salt load in the treated water. HEW studies have identified these types as:

(1) oxidation by oxidants containing active oxygen
(2) accelerated molecular oxygen oxidation
(3) catalytic oxidation of absorbed organics by oxygen
(4) electrochemical oxidation

The first process utilizes ozone, hydrogen peroxide, and hydroxyl radicals as sources of active oxygen. The facilities for producing ozone and hydrogen peroxide will affect their selection and use as oxidant sources. Corona discharges in water vapor, and ultraviolet, ultrasonic, or nuclear radiation directed through water can produce quantities of hydroxyl radicals for use. The second process requires molecular oxygen and an initiator of hydroxyl radicals to work. Other factors influencing the efficiency of this process have not been completely identified. The third process relies on molecular oxygen as the oxidant. A catalyst, such as palladium or nickle, is used to lower the activation energies and speed the reaction rate. The last process, electrochemical oxidation, can be used in a dual role to break down the organics in waste water, and to provide oxygen supplies to the station.

Solvent extraction

Separation of the waste stream into portions which contain high or low concentrations of dissolved organics is possible with this method. The solvent must be regenerated periodically. The contaminants which are stripped from it require further treatment or disposal. The low-concentrate effluents need additional treatment before reuse is possible. These factors discourage wide-scale applications of this method in extraterrestrial situations during the early phase of lunar development.

Wet oxidation

This process and equipment presently in use can break down suspended and dissolved organics. No pre-treatment is necessary. Oxygen and high pressures must be supplied to support the reactions. A fixed ratio of organics to inorganics exists that must be maintained for effective process reaction. The high load carrying capacity of lunar flows will be an asset. The energy to run the process can be obtained from the reaction. The product gases, other than steam, can be treated or disposed of through air conditioning system, but the residual brines will require further treatment before ultimate disposal or regeneration.

Dissolved Inorganics

Electrodialysis, reverse osmosis, ion exchange

These processes are each suitable for removing particular types of dissolved inorganics. Their employment on a limited scale during the early stages is probable since package systems are available. As the base size increases, other methods appear more favorable unless technological advances are made in these methods. All are subject to fouling so the organics must be removed prior to treatment. Electrodialysis and reverse osmosis require quantities of acid for pH control. The ion exchange process requires an acid and a base to regenerate the reactor column. The supporting supplies must be imported since their production in space cannot be foreseen. The brines from the processes must undergo additional processing before final disposal.

Eutectic freezing

The concentrated brines from other processes are placed in a cooling tank, and the temperature is lowered. Since the water contains solutes, ice formation commences at some particular temperature below 0°C. This mark is dependent upon the type of solute and its concentration. As ice forms, and is separated from the mixture, the solute concentration increases to further lower the freezing point of the solution. By continuing this process through steps at successively lower temperatures, a place is reached where the liquid attains a specific composition called the eutectic. However, at some level it will be more economical to eject the concentrate from the system, or to recover the water for use through incineration or freeze drying instead of attempting to reach the eutectic.

Comprehensive Treatment Processes

Atomized suspension technique

This method could be adapted for lunar operation. It is a "complete" process in that the waste stream is separated into gaseous and solid residuals. The solids in the stream must be finely divided before entrance is made into the reaction chamber. The droplets containing the waste liquids and solids are mixed with gaseous reactants in the presence of heat. The solids are separated from the resulting gas stream. Heat from the effluent gas stream is used to maintain the reaction chamber temperatures. Space requirements for the process are favorable.

Distillation

High efficiency removal of organics and inorganics from the lunar waste stream is possible with distillation.

The lunar vacuum could be used to depress the boiling point. Present technology could be employed, but operating problems can be expected. Inorganics will be present that could cause surface scaling or corrosion. Polishing methods will be needed to remove the volatile organics that pass with the distillate. The large amount of organic material carried in suspension could cause fouling. Partial removal of this load must be made before distillation. The discharged concentrates will require additional processing to effect final separation in conventional units.

Forms of distillation which make use of the air recirculation within the station are possible. The unit could be located between the air intake and the atmospherical control system. Several techniques could be used that would increase the efficiency of the evaporator, such as heating the entering air stream, pumping the air through the waste, and spraying the water through the air stream.

One possible system is structured as follows. A triangular tank is partitioned by a wall which is lowered to a point just above the vertex of the bottom angle. The halves of the tank are, thus, connected at the bottom. The waste water enters at one side. The other side is filled with porous material. Woven wire pipes are laid through this material above the water line. An outlet below the water line in this side removes clarified water for inferior uses. Air returning to the atmospheric control system is forced through the woven wire pipes where it evaporates water raised through capillary action. An auger at the bottom of the tank continuously removes the porous material and its load of strained solids. This material is emptied into the incinerator where the granular particles are cleaned. These particles are then returned, unloaded into the top of the tank, and once again allowed to sink and filter a load of settleable solids.

Freezing

The cold temperatures on the moon make this process attractive. Separation of pure water from the waste stream, rather than treatment per se, occurs through freezing. The amounts of energy involved are much less than those required to vaporize the liquid. Heat pumps, heat pipes, or the circulation of brine solutions through the constant temperature zone of the lunar surface could provide the cold necessary for freezing.

Studies have shown that up to 85 percent of the organic contaminants and 90 percent of the inorganics could be removed from secondary liquid wastes (AWTR-14, 1965). A portion of the product water will be required to wash the ice after the concentrated waste has been drained. If reuse is practiced, it is unknown what yield of pure water could be attained from the process under steady state conditions. The effectiveness of the separation depends upon the concentration of salts in the solution that is to be frozen. A normal buildup of salts from human wastes should occur with reuse. The excess concentrate from the process will require further attention.

Freeze drying

Another method utilizing the low temperature regime is that of freeze drying. This method could be used to treat the entire liquid waste stream, or the concentrated brines from other processes. The wastes can be frozen in the presence of liquid nitrogen, or where vaporization of liquid nitrogen occurs. Conventional means, using the cold of the shadowed lunar surface, can also be used to freeze the solution.

The resulting bulk ice is ground into small particles which are injected into a controlled gas stream to sublime. The vapor is condensed and removed.

The liquid wastes are mixed with a granular agent to the saturation point. This mixture is frozen, and the resulting slabs placed in an evacuated chamber. Heat is applied to the sides of the slabs, and the ice crystals therein sublime, leaving the organics and inorganic wastes trapped.

The granular agent used in the mixture could be local inorganics, or a granular metal selected for its heat transfer properties. The granular metal could be purged by heat before reuse. If lunar inorganics are used, this mixture could be combined with other material that is innoculated with micro-organisms to form soils for use within the station.

Incineration

There are several forms of this process by which all wastes can be treated. The most favorable for treating liquid wastes has been the flash dryer and multiple-hearth furnace. Air and heat must be supplied to operate this process.

The best results with liquid have been obtained when concentrated, rather than diluted, wastes were treated. Pre-evaporation by distillation has been found more efficient than evaporation in the incinerator. The stack gases can be used to help in furnishing heat for the distillation process. The water vapor in this gas can be condensed during this step. The other product gases can be stripped from the station atmosphere at the atmospheric control facility.

Irrigation

Disposal of the waste stream is made by periodic surface applications to one of a series of soil-filled tanks. Though the soil serves as a biological filter, essential differences exist between this and the terrestrial trickling filter. Innoculation of the soil with terrestrial flora and fauna would be necessary to aid in decomposing the organics and to fix the inorganics. Broad leaf plants selected for their high rates of water use and utility as food are planted on the surface. The atmosphere above the plant could be maintained so maximum rates of evapotranspiration occur. This water vapor that is evaporated could be condensed and polished to form potable water supplies. Clarified seepage water could be collected through drains in the bottom of the tank. This could be recirculated to serve in sanitary use, or could be refined for higher use.

The disadvantages of such a system is that a large volume of water would necessarily be in storage in the soil tank. Odor control would be a problem unless the exiting air stream went directly to the atmospheric control system, or the liquid wastes were incorporated into the surface layers.

Another possibility would be underground irrigation. Instead of pumping or spraying directly onto the surface, the waste could be pumped into tanks underneath floating platforms of soil. Gas and odors could be sealed in hydraulically. The platform would rise or sink in response to the liquid level. Capillarity would bring the water upward through the soil to the plants at the surface. Anaerobic bacteria could be used in the liquid. The remaining concentrated wastes could then be treated further by any of the suitable methods. The water vapor from the surface could be collected and used as mentioned.

This would not be as effective as surface irrigation since there would be larger quantities of waste water in

CHAPTER VIII

SUMMARY AND RECOMMENDATIONS

Summary

The purpose of this study was to examine the space environment and determine what problems would be encountered in providing the inhabitants of space bases or stations with water. This artificial environment enables water to be transported, handled, and used with modified terrestrial techniques. The major problem confronting planners is the high cost of transporting materials into space. This constraint is reflected in limitations placed upon the size of facilities comprising the space station, and the masses of material and equipment that can be contained within the station. The amounts of water, like other materials, will require justification as to the benefits obtained. Water will be needed to meet the physiological needs of man. Its employment in other roles which have developed in conjunction with the copious supplies here will be abolished or modified. Recycling of any water which is taken into space will be the accepted practice since transport costs make it too valuable to allow consumptive usage.

The study was oriented toward the specific problems posed by the lunar environment on water resources systems for moon bases. The low temperatures and the length of the lunar night dictate the provision of energy to insure the survival of the inhabitants through the operation of equipment dealing with life support functions. The power level maintained during the night will influence the design of the water system. Meager amounts of water can provide large daily per capita use rates if energy is available to provide continuous treatment and recycling. Low rates of energy will necessitate periodic treatments. If this procedure is practiced, a large water supply will have to be maintained, or the daily water allotment will have to be lowered to minimal levels during the night. The subject areas of water supply and transport, water use, and water treatment were investigated, and alternating schemes of action were developed for a moon base.

The probability that lunar water sources exist for development is accepted in this study. A description of the possible sources, and the problems associated with their utilization, are discussed in Chapter V. The most fortunate source, from the standpoint of exploitation, would be surface ice. The least desirable store would be the water of crystallization in lunar rock.

Unless station sites can be located at, or near, lunar water sources, some method of transport will be fundamental.

Pipelines can be employed within the confines of the station, or in the immediate vicinity. Their use in transporting water across broad expanses is not foreseen at the present. The most advantageous means of transport over substantial distances are to convey water as ice on the flat beds of wheeled vehicles. Ice is a suitable form of storage also. When protected by shade, ice lasts for long periods of time in the lunar environment. This would eliminate the need for costly facilities to store liquid water.

In Chapter VI, the domestic usage of water within the space station is examined. The daily amounts of water can be reduced, or eliminated by appropriate planning and design of the facilities. A comparison of the domestic requirements per capita which were developed from the discussion in that chapter, and those portrayed in Table 1, are shown on Table 6.

The treatment of water is discussed in Chapter VII. Recycling of the station water supplies enables the waste treatment and water purification functions to be combined into one facility. The processes used in terrestrial operations are examined as to their suitability in space applications.

Those processes which are expedient for removing similar wastes are rated from 1 to 3 according to their requirements for support materials, reaction time, and equipment size. When the process can be used to treat several

TABLE 6

A COMPARISON OF WATER TREATMENT PROCESSES FOR USE ON THE MOON

Domestic Use	Consumptive Rates in gpd			
	Earth	Space		
		Water in conventional role		Alternate method with resulting water need
		Maximum	Minimum	
Drinking and water used in preparation of food	2.00	2.99 Normal food preparation	.60 Prepacked food	.60 Prepacked food
Dishwasher	3.75	3.75 Terrestrial equipment	2.00 Atomization and steam cleaning	0 Disposable containers or heat cleaning
Bathing	20.00	20.00 Terrestrial device @ 120 gal/hr	3.00 Atomization @ 9 gal/hr	0 Skin cleansers
Sanitary	24.00	0 Electric toilet	0 Electric toilet	0 Electric toilet
Laundering	8.50	23.00 4 loads/wk with free access to machines	4.00 2 loads/wk using counter current flow	0 Dry clean
Totals	58.25	48.75	9.60	.60

waste forms, a second digit, if other than zero, compares the apparent differences in effectiveness. The processes are grouped according to energy requirements. Those which consume large amounts of energy during treatment are first. The processes requiring periodic inputs of energy at high rates for regeneration of material are second. The last group is comprised of those processes which utilize low rates of energy during all phases of operation. The results are shown in Table 7. Water reuse systems assembled for operation in space will require process coverage in at least the first three categories of Table 7. Unless the brines or concentrates can be wasted, provision must be made for the reduction of the brines.

Some systems might consist of only one process such as pyrolysis. Other systems for single or multiple streams of waste could conceivably consist of four or more different processes. The selection of the processes for the treatment system will also depend upon the types and levels of wastes in the waste water streams. For example, if the sanitary wastes are excluded from treatment, the lower levels of suspended and dissolved organics will permit employment of methods not suitable for higher loadings.

Recommendations

We may assume that man will continue his travels and feats in outer space. Being the creature he is, man will persist in demands for water on these trips to salve his

TABLE 7

A COMPARISON OF WATER TREATMENT PROCESSES FOR USE ON THE MOON

Process	Suspended Solids	Dissolved Organics	Dissolved Inorganics	Brine Separation
<u>Continuous High Energy Inputs</u>				
Atomized Suspension	12	12	12	12
Distillation		12	11	
Electro-dialysis			30	
Incineration	21	22	21	21
Oxidation		20		
Pyrolysis Aeration	12	12	12	12
Reverse Osmosis			30	
Wet Oxidation	12	12		
<u>Periodic High Energy Inputs</u>				
Adsorption		30		
Freeze Drying	11	12	11	11
Hydrolysis-Absorption	31	32		
Ion Exchange			30	
Solvent Extraction		30		
<u>Continuous Low Energy Inputs</u>				
Biological	32	31		
Eutectic Freezing			20	
Filtration	20			
Foam Separation	21	22		
Freezing		22	21	
Irrigation	31	32		33

Note: The first digit shows rank of process among the processes which are capable of removing similar types of waste. The second digit, when different from zero, compares the apparent differences if a process can be used to treat several waste forms.

physiological needs. The subject of spatial water resources gains increased significance as the number of space projects grow. President Nixon's announced program to effect a landing on Mars in the 1980's is a case in point. The performance of water recycling systems in the present family of space vehicles has been disappointing, but the length of a mission to Mars will dictate the need for the development of a satisfactory recycling system.

Lunar bases and orbiting space stations will be developed in the future as ideas and schemes for exploitation evolve. Space tourism, rather than scientific goals, could easily provide this impetus for development. The larger demands on water systems for such enterprises will be just as complicated as that designed for the spacecraft which is to land on Mars.

The minimal water requirements for man have been established, but the level of absolute needs have yet to be determined. The amount required by a small group of highly trained astronauts might not be accurately extrapolated to serve as the basis for design of a system serving an admixture of scientists, technicians, and administrators of both sexes within a lunar base. Fruitful studies could be developed toward answering questions in this area.

The exactness required to fit the diversified operations and subassemblies of the station together, so that a minimum of negative interaction occurs, demands a high degree of co-ordination and communication between designers of the various components. A combined effort in which members of different disciplines work together to develop the relationships between the water system and other component systems within the space station would seem beneficial.

Numerous questions have arisen during the preparation of this work and, some have been posed in the study. Many ideas have been discussed without understanding the complete relationships between the water system and the other components of the station. At this point, it appears most important that a study, or a group of studies, be directed toward making comparisons between designs which incorporate the basic ideas of water and waste treatment into configurations suitable for use in the spatial environment. Comparisons should be made on the basis of shipping weight, power use, amount of supplemental materials required for operation, and production of by-products. As design criteria evolves for the base or the spacecraft, this information will serve as a basis for the selection of a treatment process around which the water systems will be built.

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