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LUNAR SURFACE MINING: A REVIEW OF SOME MAJOR ENVIRONMENTAL CONSTRAINTS

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Selected environmental factors that will influence lunar surface mining operations are reviewed. The moon is at such a distance from earth that all lunar environmental conditions are not determinable and measurements of some others are doubtful or contradictory. However, with the results of the Lunar Orbiter program, the Surveyor program, Apollo 11, and the preliminary results of Apollo 12, there appears to be increasing agreement on the part of investigators as to the magnitude of many factors that would affect a lunar surface mining operation.

The environmental factors and their influence on lunar surface mining that are discussed are: (1) temperature, lunar surface, and lunar subsurface thermal problems; (2) atmosphere and pressure; (3) gravitational force; (4) problems of sun angle, latitude, and shadow; (5) composition and properties of the lunar surface and subsurface; and (6) selenology. The constraints of each environmental factor are summarized. Seven hypothetical ore deposit models are suggested, and calculations are made of the volume and mass of ore overburden that must be removed to supply an assumed annual demand for water on the moon.

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INTRODUCTION

Mining for useful substances on the lunar surface may well be one of the major activities developed from lunar stations along with those of earth weather observation, vacuum and other lunar environment experimentation, lunar exploration and planetary probes, and landing expeditions. It often has been emphasized that lunar mining probably will be a space exploration support activity and not a form of exploitation of lunar resources for earth utilization. Lowman [1] has stated the logistics well when he says, "It appears that we shall ultimately attempt extensive lunar exploration and manned interplanetary flights, although a specific time-table for these projects has not yet been established. The cost of these operations can be considerably reduced if use is made of natural resources existing on the moon and planets; consider the probable state of transoceanic aviation if each plane had to carry all fuel and supplies for a round trip. The use of extraterrestrial resources will not only reduce the cost, but accelerate the rate of manned exploration of the solar system. The moon will, of course, be the real starting point for the exploration of the solar system; correspondingly, the first extraterrestrial material resources used will be lunar resources."

Of these resources, Lowman [1] says, "Lunar raw materials may be conveniently classified on the basis of function in three major categories: life support, structural elements and rocket fuel." In the absence of an atmosphere or hydrosphere on the moon, oxygen and water for life support as well as shelter constructional materials and fuel substances must be obtained from the lunar body. Some constructional materials may lie on the surface, but other constructional materials and the life support and fuel materials will be in the subsurface and therefore will require some kind of mining.

Three general types of mining can be envisaged for the moon. They are: [1] the indirect or Frasch-type mining requiring the minimum disturbance of overburden and the removal of ore as drill cuttings or by getting it into a fluid; (2) surface, strip, or open-cast mining in which overlying material is removed to reach the ore and the ore is broken and loaded in subsequent operations; and (3) underground mining, requiring access shafts, adits, or slopes and breaking of the ore for removal in solid form through one or more openings. In general, either the first or third method must be used for ores at a considerable distance below the surface. Surface mining becomes prohibitive if the mass of overburden material to be broken and handled is large. Indirect mining by drilling yields limited quantities of ore in proportion to effort, and phase changes or solution mining requires materials with properties amenable to these methods and not requiring an inordinate expenditure of energy. As will be seen, postulated selenological conditions make shallow ores possible, and, as on earth, surface mining systems should constitute the simplest, most economical, and most widely applicable way of obtaining the lunar resources now deemed most useful.

Surface mining does have disadvantages. The principal disadvantage is that mining operations will be directly exposed to the very hostile lunar environment. Another disadvantage is that surface mining equipment tends to be heavy and of limited mobility for large units and requires excessive operating personnel for low capacity units.

Four basic problems that must be analyzed for design and implementation of lunar surface mining operations, assuming one or more suitable ore bodies have been discovered and evaluated, are: (1) adaptation to the strange, hostile, and unearth-like environment; (2) minimization of mass and volume requirements of the systems because of the enormous cost of transportation from earth; (3) maximization of dependable automation so as to require the minimum of personnel, also because of enormous cost; and (4) provision of spare equipment units, an adequate spare parts inventory, and a reliable maintenance and supply program.

SELECTED LUNAR ENVIRONMENTAL FACTORS

The lunar environment is more severe than any encountered on earth, including Antarctica. Personnel must be completely isolated from the environment at all times, and installations will be required to withstand severe and rapidly changing conditions. Living quarters will have to approach close simulation of earth conditions and the close quarters, the isolation, the long day-night cycle, and other factors probably will make comparatively rapid rotation of personnel desirable.

The moon is at such a distance from earth that all lunar environmental conditions are not determinable and measurements of some others are doubtful or contradictory. There appears to be, however, increasing agreement on the part of investigators as to the magnitude of many factors and the existence or nonexistence of others. The lunar landings of the Surveyor vehicles and the Apollo manned landings, which returned lunar samples, have provided a wealth of information that allows the lunar environmental conditions to be better assessed and the magnitude of the lunar mining problem to be defined. The most significant of the environmental factors for lunar surface mining operations will be discussed in this section of the paper.

Temperature and Lunar Surface and Subsurface Thermal Problems

HEAT-INDUCED MECHANICAL STRESSES

The surface day-night temperature varies between 410 and 104° K near the equator [2, 3]. Results from lunar eclipse measurements indicate that light-shadow temperature contrasts in lunar daylight can be almost as large, and temperature changes can be extremely rapid. Temperature changes up to 174° K/min have been observed [2], and on metal these rates might exceed 200° K/min.

In daylight, parts of a working machine would alternately be in the sun and in the shadow of other parts so that large and rapid temperature stresses will be induced. These stresses may present more serious problems than insulation from the temperature environment. As an example, a straight aluminum rod, half in sunlight and half in its own shadow, that is 1 m long on the underside will be approximately 1.0075 m long on top. Resulting stresses will tend to warp the rod appreciably. The superior heat conductivity of metals tends to relieve temperature differentials and their resulting stresses quickly. However, as a mining machine maneuvers and turns in the sunlight, shadows from parts of the machine and shadows late and early in the day from topography will place rapidly changing stresses on longitudinal members, panels, welds, bolts, or rivets. Bolts and rivets made of metal having a different coefficient of thermal expansion than that of the bolted or riveted metal may prove impractical. Welds between a shaded and an unshaded member will be heavily stressed.

Night operations, although conducted at temperatures much below any on earth, should be free of this type of stress because of temperature uniformity. If the temperature of lunar soil at about 1-m depth is 233° K, contrasted with surface temperatures of approximately 105° K, bulldozer blades, for example, will be considerably "warmer" than other parts of the machine, but resulting stresses should be relatively low.

Temperature and temperature change factors must be taken into consideration in equipment design and construction.

ADVANTAGES OF NIGHT OPERATIONS

For surface mining operations, there will be certain advantages in addition to temperature uniformity, to night operations. Some of these are: (1) lighting from the earth, as earth-shine; (2) absence of the solar wind; (3) possible absence or reduction of rarified ionized gases of the thin lunar atmosphere; (4) minimum cooling needed for space suits and/or machine cabs or structures; and (5) better heat dissipation from bearings, motors, etc.

Some possible disadvantages of night operations are: (1) the necessity to provide artificial lighting; (2) the high heating load for space suits, cabs, and surface structures; (3) the increase in freezing tendency of working fluids, if they are used; and (4) the suspension of ore production for one-half the time. The latter may not be too objectionable if part of the ore can be stockpiled and the processing for water can be done continuously to insure steady production.

If the ore consists of hydrous minerals requiring large quantities of heat for dehydration, processing plants of sufficient capacity may be designed to process, during the 2 weeks of light, all the ore mined in 2 weeks of lunar darkness. Such a schedule would permit use of solar energy for process heat, and thus the mining and processing can complement each other and the same crew can be used for both operations.

HEAT DISSIPATION AND TRANSFER PROBLEMS

Heat transfer in bearings, motors, cooling systems, etc. will not be quite as easy as on earth. Immersion in a gaseous atmosphere adds convection to radiation as an earth heat transfer mechanism, but only radiation is available on the moon. Any spot on the moon where heat accumulates faster than it can be radiated to space will require additional cooling by circulating fluids and radiators. Large or high speed bearings on mining machines, electric motors, internal combustion engines, etc. may need such cooling systems. Water will not be a suitable closed circuit change-of-state refrigerant because it freezes too readily. However, by proper choice of fluid, it may be possible both to lubricate and cool bearings with the same fluid circulating systems.

INSULATION PROBLEMS

The extreme temperatures encountered and the rapidity of temperature changes on the lunar surface will result in some severe insulation problems. Adequate temperature protection for mining personnel will be essential. At the surface protection can be secured by: (1) permanent or portable environment-controlled structures from which the work will be done by remote control, perhaps requiring continuous television viewing; (2) environment-conditioned cabs mounted on equipment with mechanical, hydraulic, or electronic controls and possibly also requiring some televiewing; or (3) individual, flexible, environment-conditioned space suits.

LOW TEMPERATURE PROBLEMS

The very low lunar nighttime temperatures should not, within themselves, pose great problems unless insufficient energy is available for both heating and motive power. It is true that little is now known of the physical properties of many materials when subjected for long periods to such low temperature levels, but suitable materials probably can be found for this service.

As an example of some of the problems that may be encountered, consider the problems of distributing power from a central power generator, or large battery pack, to mining machines in case that appears more efficient or effective than mounting batteries or fuel cells on the individual machines. On earth, electric power would be supplied through trailing cables. At lunar nighttime surface temperatures, it is almost certain that earth-designed cables will be too brittle and inflexible. To supply flexibility and provide wear resistance at the same time, it may be necessary to manufacture cables of materials that are suitable at lunar night temperatures but that may require coiling and storing during the lunar day to protect them from disintegration by melting. In short, material that is "liquid" at temperatures appreciably above 105°K may be required. An alternate method might be to use earth-design materials but to interweave heating wires or coils to maintain the cable at temperatures high enough to insure proper flexibility. The latter scheme will increase power consumption [4].

CONSTRAINTS IMPOSED BY THE THERMAL ENVIRONMENT

The most likely constraint on surface mining by temperature factors is that of limiting mining operations to the lunar night or to shadowed locations during any portion of the lunar day.

Personnel protection shelters or space suits must be carefully conditioned by insulation and probably by positive temperature control systems to secure reasonable comfort and as compensation for both heat from exertion and variations in external temperatures. The latter will, of course, be quite steady during night operations.

A third constraint will be placed on equipment design, especially if the equipment is used in daytime or not stored in the shade during the lunar day. Differential temperature stresses are unfavorable to the rigid joining, in any way, of metals with dissimilar coefficients of expansion. Plates and rods may tend to bend or buckle. Materials with unfavorable low temperature properties must be avoided. Equipment design may have to include circulating fluid cooling systems for some bearings and motors.

Atmosphere and Pressure

PRESSURE AND COMPOSITION

The lunar atmosphere is so rare that it probably can be ignored. There will be no atmospheric oxidation or other chemical effects. If the atmosphere consists of a low temperature plasma of charged Ar and Kr ions, the conditions might result in a little electrical charge leakage under some circumstances, but the effect would be small. At earth atmospheric pressure and 273° K, an argon atmosphere would be present at a concentration of 2.2×10^{22} ions/m^3; at lunar atmospheric pressure (maximum possible), there would be only 2.2×10^9 ions/m^3.

In addition to rare gases, the thin lunar atmosphere may contain traces of H_2, H_2O, C_2H_2 or other gases that may be exuded from the lunar surface. They undoubtedly would be fully ionized by solar wind action, on the light side.

The lunar atmosphere is much too rare to provide noticeable shielding from solar radiation or from micrometeoroids.

VACUUM ADHESION EFFECTS

The extent of vacuum adhesion was long one of the great unanswered questions regarding the lunar surface. Virtually all high vacuum experimental work has demonstrated the presence of adhesion among small silicate particles and between these and other surfaces [5,7]. However, none conclusively proved that in the harder lunar vacuum, dust or larger particles will settle on surfaces and coat them or build up on wheels or tractor treads with sufficient strength to render digging of dust or fine rubble difficult. Photographs of the Soil Mechanics Surface Sampler (SMSS) of Surveyors III and VII indicated that some soil clung to the inside of the sampler [8,9]. The cling was not excessive however, nor was there evidence of strong adhesion in those tests or from the vernier engine firing tests on Surveyors V and VI [10,11]. The soil at the Apollo landing sites possessed a small amount of adhesion [12-14]. It possessed the ability to stand as vertical slopes, the holes made by core tubes were left intact upon removal of the tubes, and the fine grains stuck together to make clumps. If vacuum adhesion exists, it is likely to diminish with depth. At depths greater than a few meters, there may be enough water or other condensed volatiles of sufficient vapor pressure for coating nearby or newly created surfaces with vapor so as to prevent any "ultraclean" condition on surfaces, even for very small particles. Certainly, an ore containing even traces of free water should not be stubbornly adherent.

FRICTION AND LUBRICATION

One important problem faced with mining and transportation equipment will be that of lubrication of bearings and other moving parts in the hard lunar vacuum. All lubricated bearings must be sealed, or solid lubricants, such as graphite or molybdenite, must be used. Even solid greases will evaporate. Surveyor observations [8-11,15] as well as the Apollos [12-14] indicate that there may also be a problem with lunar dust around operating machines. If the particles are angular and hard, only sealed bearings can be used.

During the lunar night, the low temperatures should result in an excellent radiation of frictional heat. Heat should also be rapidly conducted away from bearings by metal shafts and housings at these low temperatures. To secure sufficiently rapid total heat transfer to the environment in motors and perhaps in large bearings, it may be necessary to seal these parts and circulate fluids through them to a radiator. Thus, lubrication and heat transfer may be combined in some cases. Certainly, the combination of hard vacuum, extreme and rapidly changing temperatures, and the absence of ambient convective cooling will pose formidable equipment lubrication problems.

The very low temperatures of lunar night and the low pressures suggest potentially very efficient operation of heat engines. With oxygen and fuel both imported from earth and with most of the heat as well as the valuable gases lost out the exhaust, conventional internal combustion engines are not very attractive. Closed circuit condensing engines, operating to ignore the lunar vacuum, or brushless or sealed electric motors seem much more promising.

SUMMARY OF CONSTRAINTS IMPOSED BY ATMOSPHERE

The following constraints are imposed by the lunar atmosphere:

1. Personnel must, at all times, be kept isolated from the lunar atmosphere (or vacuum).

2. All protection against the solar wind or micrometeorites must be provided by shelter, cab, or space suit design.

3. Nonvolatile lubricants or pressure lubrication of bearings must be provided. To protect against dust erosion, bearings probably must be enclosed.

4. Internal combustion engines probably will not be practical because precious fluids will be too difficult to recover. Condensing engines probably will be limited to closed circuit for the same reason.

Gravitational Force

The reduced gravitational attraction at the lunar surface may have little direct effect on mining operations. Adjusting to the reduced gravity apparently was not a problem for the Apollo crews, and operators of mining equipment should have little trouble in adjusting efforts and judgements to it. Power requirements for tramming on the surface, especially up and down slopes, and for lifting loads should, however, be considerably less than on earth. The greatly reduced weights should also permit a larger proportion of the energy required for operations to go into useful work because of the lesser requirements for merely manuevering the machines.

EFFECTS ON LIFTING, DIGGING, TRACTION, AND MASS EQUILIBRIUM

Lifting effort required on the moon should be directly proportional to the lunar gravity. Loads that can be lifted by draglines on earth decrease with boom length. On the moon, with both boom weight and load only about one-sixth of earth values, greater boom lengths and, consequently, greater dragline mining depth and reach may be attained than on earth for equal strength booms. Cranes, power shovels, front-end loaders, and other equipment that involve a lifting operation should all have improved working range in proportion to size if the problem of mass equilibrium is not acute.

A lunar mining machine of given dimensions will be more readily tipped over than the same machine on earth. For a given speed, the turning radius must be greater and curves must be banked more steeply. Considerable ballast or counter-weighting may be required to insure operational stability or adequate traction. As will be seen later, the weight of all equipment must be kept to a minimum for economy in transporting from earth. This restriction may be contrary to use requirements, especially if lunar surface material proves to be hard or tough. Even a hard, rough surface may provide inadequate traction for a bulldozer scraping hard material. If a light power shovel or dragline digs in hard or tough material, the bucket may stand still while the machine moves. A dragline scraping tough material may do the same, unless adequately ballasted.

COUNTERWEIGHTS AND BALLAST

Shipping ballast from earth would be self-defeating, but fortunately the chances are excellent that suitable material is available on, or near, the lunar surface. This material is meteoritic iron-nickel that must have been striking the lunar surface for as long as it has bombarded the earth. With little or none of it burned in an atmosphere, most of it probably is still there. Whether it occurs in large or small descrete masses or as condensed vapor dispersed through the lunar soil is not known. Apparently the individual pieces found in the returned Apollo samples are very small [12-14]. If meteoritic iron proves collectable, it should make ideal material for ballast on construction and mining equipment. The ballast may be collected and added when the equipment is erected on the moon. If it is preferable that it be in monolithic form, "concrete" blocks may be made by embedding small meteoritic iron masses in some medium. Green [16] has suggested either cast basalt or sulphur as a possible concrete substitute. Only if mining operations are conducted at night will sulphur (melting point, 386°K) prove satisfactory. Although lower in density than iron, cast basalt itself (density, approximately 2.92 kg/m^3) should be acceptable for ballast.

CONSTRAINTS IMPOSED BY GRAVITATIONAL FACTORS

A common gravitational constraint probably will be on the design height of centers of gravity above the lunar surface for all working machines. Ballast and counterweights may be required for tough digging, scraping, and possibly for lifting.

The most universal constraint may be on the tempo of operations. Dangers of tipping, different power requirements for various operations, and strange frictional values and vibrational frequencies may slow operations greatly, until operators are instinctively familiar with the magnitude of the forces. After this, the greater "bounciness" of lunar-surface, gravitational-field interactions may keep operations slower than on earth.

Problem of Sun Angle, Latitude, and Shadow

These factors (except latitude) are accepted as constants in earth mining operations. They probably cannot be similarly taken for granted on the moon. On earth, mineral deposits often occur in unusual, out-of-the-way, and inaccessible areas. In the absence of any clear latitude or longitude-dependent arrangement of physical features on the moon's surface, the same thing may be expected to occur on the moon. Deductions have been made with regard to possible association of water deposits with types of lunar surface features [17, 18] but none with one selenographic location over any other, except for areas of greatest concentration of knowledge. Ranger, Surveyor, and Apollo landings, except Surveyor VII, have been near the lunar equator, and the potential landing sites on which Orbiter I through V pictures were concentrated were equatorial ones. There is said to be some fuel economy available by accomplishing equatorial landings as opposed to polar landings [19], therefore early landings and probably early bases established for lunar explorations will be within 10 deg of the lunar equator. Also, it is practically certain that just as the first landings, the first colonies and the first mining operations will be on the earth-facing hemisphere of the moon, where direct communication with the earth is possible. Because of the superior knowledge that will be available of the equatorial areas on the side of the moon facing earth and the likelihood of first finding water deposits there, it appears equally probable that the first mining operations will be at low lunar latitudes in that hemisphere. These locations will have some effect on surface mining operations. The most important of these is that for almost the entire lunar day, the deposit will be subjected to the direct rays of the sun. If any part of the ore, or all of the ore, consists of free water, it will promptly be evaporated upon exposure in the pit at the high temperatures and hard vacuum existing there.

If lunar materials in the pit walls stand readily at high angles of repose, there will be a narrow shadow at the foot of the high wall in deeper pits not located right on the equator that will provide protection from evaporation if the active pit wall runs in an east-west direction. If any daytime surface mining of free water ores is contemplated, active strip pits will be advanced toward the south, north of the lunar equator and toward the north, south of the lunar equator. Crater walls, mountainous areas, near mare margins, and even the lee side of domes and serpentine ridges may be used to lengthen the period of lunar shadow. Of course, if the ore consists of hydrous minerals such as serpentine, it will be unaffected by exposure to the sun. However, the samples returned by the Apollo crews did not contain any hydrous minerals [12-14], and if they exist, it must be at a depth of 1 m or more. Other ores such as salt incrustations (for example, $CuSO_4 \cdot 5H_2O$), in which the bound water is in the form of H_2O molecules rather than hydroxol radicals, may be partly dehydrated by the direct sun in the lunar vacuum. The dangers of free water or loosely bound water evaporating can be avoided by confining mining operations to lunar nighttime and leaving little or no exposed ore during the lunar day.

SUMMARY OF CONSTRAINTS IMPOSED BY THESE FACTORS

The following constraints are imposed by the factors discussed above:

1. Since early mining is likely to be near the lunar equator, surface mining of permafrost must be limited to the lunar night.

2. At more that 5 deg from the lunar equator, permafrost surface mines must carry east-west faces and mine toward the equator.

3. Some hydrous salt ores must also be protected from sunlight.

4. The shady side of craters, ridges, mountains, and rills may prove to be favorable mine sites.

Composition and Properties of the Lunar Surface and Subsurface

COMPOSITION

Surveyor V, VI, and VII results indicate that both maria and highland rock are approximately basaltic in character [9-11]. This conclusion may also be supported by the Surveyor magnet experiments [8-11, 15, 20]. The chemical analysis of the lunar rocks returned by the Apollo crews indicates that the major constituents of the samples are Si, Al, Ti, Fe, Ca, and Mg with sodium, Cr, Mn, K, and Zr as minor constituents [12-14]. The lunar rocks contain high concentrations of Ti, Zr, and Y as compared to terrestrial rocks. The lunar rocks are apparently completely devoid of hydrous mineral phases and exhibit numerous differences in detail from terrestrial samples previously available for analysis.

The surface sampled may not, however, be pure "green cheese" but may be a mixture of "original" lunar surface with meteoritic material that has been swept up by the moon for millions of years. This material may or may not have a composition similar to the lunar crust. If it does not and maria and terrae differ greatly in age, there should be a detectable difference in composition of the two areas. In the apparent absence of great differences, stony meteorites and surface lunar rock may have quite similar compositions.

DENSITY

The estimated density of the lunar material as calculated from Surveyor measurements is 1.0 gm/cm^3 for the first few centimeters and 1.6 gm/cm^3 a few centimeters below the surface [11]. The material finer than 1 mm size obtained from the lunar bulk sample of Apollo 11 was found to have a bulk density of 1.36 to 1.80 gm/cm^3 [12, 13]. The densities are somewhat greater than had been estimated previously from lunar photometric properties and possible "fairy castle" structure [9, 11]. While the sundown halo, photographed by Surveyor VI and VII, may have resulted from fine solid particles at or above the surface [9, 11], any "fairy castle" layer must be extremely thin if the first few millimeters have a density of 1.0 to 1.8 gm/cm^3.

The bulk density of maria regolith is estimated as being a little greater than the density at a few centimeters, because there may be increasing proportions of large fragments with depth and solid rock fragments were even denser [12].

TEXTURE

The material of the lunar surface is quite fine and contains rock fragments when in the vicinity of some craters. Surveyor I photographs showed many large blocks (up to 1 m) around craters and smaller ones strewn in intercrater areas in some places [15]. Surveyor III, V, and VI sites apparently reveal fewer and smaller blocks [8,10,11]. The Surveyor VII panorama was quite rocky in places [9]. The Surveyor III and VII Soil Mechanics Surface Samplers turned up few large fragments. The distribution of fragments larger than 1 cm is quite variable. Strangely enough, the apparently "older" Flamsteed crater site of Surveyor I seems to have larger and more numerous large fragments than the "younger" Tranquillitatas site of Surveyor V or the still "older" Sinus Medii site of Surveyor VI [11].

The Apollo 11 landing site in the southwestern part of mare Tranquillitatas was approximately 25 km southeast of the landing site of Surveyor V [12]. The landing site lies between major rays and may contain fragments derived from Theophilus, Alfraganns, Tycho, and other distant craters. Approximately 400 m from the landing site is a crater that is 180 m in diameter and 30 m deep and is surrounded by a blocky ejecta apron that extends out about 250 m from the rim crest. Blocks that are 5 m across occur on the rim of the crater. Rays of blocky ejecta with fragments 0.5 to 2 m across extend beyond the Apollo 11 landing site, which is relatively free of extremely coarse blocks. The lunar surface at the Apollo 11 landing site consists of unsorted fragmental debris that ranges in size from particles too fine to be resolved by the naked eye to blocks 0.8 m across. The lunar regolith formed by this debris grades downward into a similar but more densely packed material consisting of fine particles with many rock fragments. Coarse fragments are scattered in the vicinity of the landing site of Apollo 11 in about the same abundance as at the Surveyor I site. They are more abundant than at the other Surveyor landing sites on the maria. The rock fragments in the Surveyor I and Apollo 11 landing sites were probably caused by the nearby craters which have blocky rims.

There appears to be a clear tendency for the fine particles of the lunar regolith to adhere and form clumps in spite of the rather low cohesive and adhesive forces.

SUBSURFACE

While the Surveyor craft revealed little of the lunar subsurface below a few centimeters depth, the Apollo probes found the surface to be relatively soft. The Apollo 12 astronauts were able to drive the core tubes to the full depth of 70 cm, whereas the Apollo 11 astronauts were able to drive the tubes only about 15 cm [14]. The lunar body mean density of 3.34 gm/cm^3 puts some definite limits on overall composition. Although the moon is small, there is some compression of material in the deep interior. Jefferies [21] has estimated that if lunar material is homogeneous in composition, it has a density of about 3.41 gm/cm^3 at the center and 3.28 gm/cm^3 at the surface. The latter is within the density range for periodotite, pyroxenite, and many stony meteorites. It is a little denser than most basalts, and a little differentation or a small iron core is required to yield surface basalts.

Because of the basaltic nature of the lunar regolith in both the maria and the highlands, it is expected that solid rock underlies both areas at some depth. The astronauts have reported large blocky terrain around some craters. Some blocks have been observed to be hundreds of meters across providing a very rough terrain. These blocks scattered around the rim indicate that solid rock underlies the area.

The common presence of fragmental material, both on and under the surface, suggests that it is doubtful if "solid" rock will be encountered by surface mining. From the fine-grained regolith encountered at all Surveyor and Apollo sites, downward the material probably consists of fine grains, fine grains mixed with fragments, blocky material further down, and finally highly fractured rock.

In the highlands, particularly, aeons of impacts have probably broken the "crust" badly, to hundreds of meters in depth. If shallow masses of lava, intruded or extruded, have been emplaced, these too have been broken in the same way, unless they are very recent in age. On the maria where impacts have apparently been less frequent, presumably because of a younger age, the condition may be somewhat different. Lava beds or intrusions may be less severely broken up, but if surface lavas are slightly distended and brittle or glass-like after extrusion, they are also likely to be badly fractured to a considerably depth. Lava intrusions that cooled under the surface may come the nearest to representing true solid rock of any conceivable lithologic units. Certainly, if the maria are largely flows of fluidized fragments, as has been suggested, the material is, by definition, fragmental in nature. However, it is possible that fragmental material may be partly recemented at depth.

It has been suggested that the observed relative darkness of partially buried material (for example, the underside of fragments) may be a result of the deposition of some strange "varnish", presumably from deeper under the surface [22]. At moderate and great depths, this same material or other material may also produce a cementing effect, so that the nearest analogue on earth to lunar solid rock may be a conglomerate or cemented breccia. Cemented breccias and conglomerates evidently have been rebroken by subsequent high energy impacts, recemented, and again broken through several cycles [12].

All production of very fine particles in the lunar upper layers may not have resulted from direct crushing by micrometeorite impact. High energy shock waves, transmitted through fragmental material, should cause attrition breaking. The effect should be something like "autogenous" grinding of ores from slow tumbling. While high energy impact shock waves should be attenuated rapidly, especially horizontally, and each shock may produce only a small quantity of such attrition, many repetitions could produce considerable amounts of very fine-grained material. This material might even move downward because of "trickle stratification".

In summary, shallow mining probably will encounter only fine to blocky material of quite small grain size. This condition may thwart our ambitions for obtaining pure, unmixed "moon rock" samples, particularly in the highlands, until deep into the post-Apollo era.

POSSIBLE CHEMICAL ENVIRONMENT

There is the possibility, supported by no direct data, that corrosive gases, vapors, etc. may be encountered beneath the lunar surface. If the moon was melted early in its history, it might be almost completely devolatilized. If heating without complete melting came later from radioactivity or from tidal friction, the moon should be only partly devolatilized and many condensible vapors such as F_2, Cl_2, HCl, HF, CO_2, SO_2, H_2S, etc. may be entrapped along with water in the cold outer crust. The impact of volatile-containing objects on the lunar surface may have driven much water and non-aqueous volatiles deep into the crust and they may still be there [22]. Thus, either impact or volcanic theories permit the possibility of corrosive volatiles in the crust. Once condensed or reacted, they have not been flushed by circulating groundwater, as on earth, even though they may be water soluble. At a lunar subsurface temperature of about 233°K (-40°C) [23], some of these substances may exist quite close to the surface.

The constancy of the lunar subsurface temperature and its probable range appears to be well established. Any free water below a depth of approximately 1 m should be in solid form.

BEARING STRENGTH

Various estimates based upon Surveyor data [8, 9, 11, 15] yield dynamic bearing strengths of 2.4 N/cm^2 to 7 N/cm^2 (3.5 to 10.2 $lb/in.^2$) and static bearing strengths of <0.1 to 6 N/cm^2 (<0.15 to 8.0 $lb/in.^2$). If the area of an astronaut's shoe is 40 $in.^2$, the lower end of the dynamic range gives support only to a 116-lb force which, on the moon, would be exerted by a 696-lb man. The low static bearing strength refers only to the top 1 or 2 mm. Surveyor VI [11] <0.1 N/cm^2 (<0.15 $lb/in.^2$) for a few millimeters, 2 N/cm^2 (2.9 $lb/in.^2$) at about 2 cm, and 6 N/cm^2 (8.7 $lb/in.^2$) at about 5 cm.

The Lunar Module footpad of Apollo 11 penetrated 2.5 to 7.5 cm, while the astronaut's footprint depths are as much as 5 cm into the lunar surface. These penetrations correspond to average static bearing pressures of 0.41 to 1.03 N/cm^2 [12]. The indications are that the soil bearing capacities at the Apollo 11 and 12 sites are of the same order of magnitude [14]. Neither men or vehicles should expect trouble from sinking into the lunar surface in the areas where the Surveyors and Apollos landed. Lightly inflated tires should readily support fairly heavy machinery, but if there are areas of less bearing strength or if hidden fissures engulf small wheels, tracked vehicles or very large wheeled ones should perform satisfactorily. Tracked vehicles are slower and somewhat awkward but should be most reliable under very adverse conditions.

TOPOGRAPHY

No detailed or extensive study of problems of topographic location of lunar mining operations has been made, although topography may greatly influence the choice. If any of the postulated close associations of mineral deposits with physical features [18] prove correct, only types of topography associated with, or near, the more promising features will need to be specifically considered.

Most of the mineral-deposit, surface-feature association assumed had been with the margin or surface of the maria, preferably near the edges. The so-called walled plains or flooded craters appear to be similar to the maria but on a much smaller scale. The maria are generally quite level and comparatively smooth. A mine located on a mare surface should be surrounded by this sort of surface unless near a crater, rill, or fault. Craters are only about one-fifteenth as frequent on the maria as on upland areas. Large craters that create extensive rough areas are especially scarce on the maria, because all observations indicate a rapid decrease in crater frequency with increase in size on both maria and terrae.

Rills and fissures in some areas may constitute the most formidable topography. If there is a veneer of fine soil and rubble over all mare surfaces, there may be hidden fissures under it that will influence surface mining and mine transportation. Some lunar deposit models imply possible strong control of mineralization by rills, fissures, and shear zones.

The influence of topographic factors on possible lunar resource distribution and on mining problems deserves intensive and detailed study.

SUMMARY OF CONSTRAINTS IMPOSED BY COMPOSITION AND PROPERTIES OF THE LUNAR SURFACE AND SUBSURFACE

Constraints imposed by the factors discussed in this section may prove not as severe as has been supposed in the past. The least known factor, subsurface chemical environment, may prove most severe or it may be of little or no importance.

Except for its possible relation to ore genesis and distribution, rock composition should have little effect on mining. Physical properties of lunar rocks are unlikely to vary more widely than those of earth rocks, and mining techniques are known for handling all the latter. Rock fractured, in place, is likely to prove more difficult to handle than rubble or solid rock. If cemented, it will, of course, handle much like cemented earth breccia or solid rock.

Pit wall support in unconsolidated breccia or rubble may prove to be a problem in excavations of more than a few feet. Trenches and holes dug by the Surveyors and Apollo in the fine lunar outer layer, presumably because of some vacuum adhesion, stood well, but at greater depths, these forces will become much smaller relative to gravity. If volatiles are encountered below the surface, cohesive forces will also be greatly weakened. In the event of "moonquakes", a rather low bank slope may be necessary to prevent slumping.

A particularly dangerous excavation may be one in the slumped walls of a crater or at the toe of slumped masses. Banks in an initially metastable condition require only the slightest disturbance to start sliding and slumping. The famous picture taken by Orbiter II of the slumped inside walls of Copernicus and by Apollo 11 of a similar crater on the far side of the moon illustrate some massive potential slump areas.

As yet, the subsurface chemical environment in terms of possible fugacious substances is entirely unknown. The explanations offered thus far for the lower albedo of lunar subsurface material and the observation of astronaut Aldrin that the material almost appears wet are indications that there may indeed be something more than a merely neutral chemical environment.

If no water or other volatiles are present, or have been present in the past, reactive solids such as metallic carbides (CaC_2, etc.) may be present. If water is present along with such materials as Cl_2, HCl, HF, etc., excavations more than a few feet deep may be quite corrosive of mining and preparation equipment. Of course, evaporation will be very rapid as the material is disturbed.

The Surveyor and Apollo expeditions have proved that bearing strength of the lunar surface is unlikely to be a problem. So far, there has been little evidence of fissures or collapse features that may interfere with surface locomotion.

Selenology

FORMS OF OCCURRENCE OF WATER-BEARING ORES

Water is the substance that will be most sought after on the moon; therefore the "ores" to which most attention will be given are water-bearing ones. Other substances may be recovered in small quantities or as by-products of water-bearing ores.

Water may occur in the form of (1) free water or (2) as water- or hydroxyl-containing minerals. Occurrence of water in the form of free water as pure ice or as massive ice mixed with soluble salts, rock fragments, or condensed vapors would minimize mining costs and the energy required for its recovery. Water physically absorbed into the pores of volcanic tuff, pumice, rubble, etc. probably require the next smallest quantity of energy for economical recovery. Water in the form of molecular water or crystallization as for example in gypsum, $CaSO_4 \cdot 2H_2O$, requires less recovery energy than does hydroxyl-containing minerals such as serpentine, $Mg_6Si_4O_{10}(OH)_8$, or topaz, $Al_2SiO_4(OH,F)_2$. Perhaps the most expensive water, but that with the greatest probability of widespread occurrence, would be that extracted from average lunar rock with no particular water enrichment. Common earth igneous rocks have been shown by Green [16] to average no more than 1 percent water (recoverable at a temperature of approximately 383°K). There was apparently a complete absence of hydrous mineral phases in the samples returned by Apollos 11 and 12.

The ultralow lunar atmospheric pressure and high lunar daytime temperatures preclude the presence of free water in any form on the exposed lunar surface. The principal areas of eternal shadow within which surface ice may be found are (1) certain deep craters near the lunar poles, like the crater Newton near the south pole, and (2) within caves or lava tunnels on the maria.

POSSIBLE OTHER SUBSTANCES

Many other substances may be inferred to be present near the lunar surface. Some of these may be beneficial to lunar technology, even in its primitive stages. Suggested substances are meteoritic iron, diamonds, sulfur, ferrous sulfide (troilite), olivene, basalt, halide salts, sulfates, boric oxide, graphite, many metallic sulfides, carbides, and hydrocarbons [1,16,24]. With the overall lunar composition apparently so different from that of the earth, it is possible that surface chemistry may be different also, and minerals may be present other than those found in meteorites or associated with terrestrial volcanic terrains.

If some useful mineral, or minerals, occur in the material over-lying lunar water deposits, it may prove economic to recover all or part of it. Such recovery probably will have little effect on the mining systems or equipment used, except to divert overburden from direct and immediate disposal to some processing system. Such a system may be simple, such as hand-picking or passage over a magnet with or without prior crushing, or it may be complex as a pressurized, closed system for flotation of diamond. It is obvious that if a large volume of material must be processed for a comparatively small quantity of mineral of low value, the process must be simple and of high capacity. Any recovery of material from overburden at a water deposit, by any method other than occasional hand-picking, would actually amount to a mining operation with two processing plants and with both streams of material from the mine going to processing. Another possible situation would be the immediate disposal of overburden but with a view toward its later recovery by processing for recovery of minerals of secondary value. Our knowledge of lunar surface chemistry is so meager that active investigation of plans for processing lunar surface materials, other than water, probably will be limited to meteoritic iron, ferromagnesian' rock (olivene and pyroxene), and, possibly, troilite and sulfur. Metallic carbides may also be included.

DEPOSIT MODELS

Just as fundamental as lunar surface and environmental problems are those of the kind, grade, extent, structure, and location of the deposits that may contain water or other useful minerals. At this point, of course, there is no direct evidence of the presence of mineral deposits at all. The presence of water or any other mineral deposit can only be inferred, and inferences must, in turn, rest upon assumptions regarding lunar origin, thermal history, chemical composition, the extent of near-surface chemical differentiation, and the water concentration processes operating [25]. No attempt will be made here to explore the many possibilities that have been suggested.

At the present time, when considering mining problems and techniques, it is necessary to cover the entire range of possible chemical differentation of the lunar crust. In a previous report [17], one of the authors examined twelve deposit models. They ranged from strictly impact origin to both intrusive and extrusive volcanic models. Nine of the twelve models were associated with the lunar maria. Of the nine, four imply the maria consist of bedded tuff layers, three imply that they are filled with successive lava flows, and two could be interpreted as a filling from one thick lava outpouring. One lunar upland model consists of a single rubble blanket over granodiorite; a second consists of interbedded, lenticular rubble layers over granodiorite; and the third is a rubble layer alone, with imbedded serpentine boulders.

If lunar mineral deposits occur in the form of local mineral enrichments, as do earth deposits, a program for their discovery, evaluation, and exploitation will be necessary. If they can be associated early with surface features (maria edges, crater bottoms, crater rims, lunar domes) or with visible or hidden structural features (fracture systems, fluid vents, etc.), or if they are found to occur in groups or geographic districts, as on earth, the problem of discovery and evaluation will be greatly simplified. Unless concentration does occur to some extent, drilling or other exploration to evaluate the deposit will be useless, and mining will become merely the random removal of country rock.

Water occurring in free form as massive ice deposits should be more economical to mine and process than chemically combined water. If free water occupies pores, shear zones, or small fractures in hard or tough rock, mining it will be almost as difficult as for hydrous minerals in similar rock. Permafrost zones in tuff, pumice, or similar rocks should be much less difficult to mine.

Seven hypothetical models selected for quantitative description are shown in Figures 1 through 7 [17,18]. Two of these are different from any of the twelve models previously mentioned. Deposit geometry and dimensions have been somewhat arbitrarily assigned. Calculations have been made of the volume and mass of ore and overburden that must be removed to supply an assumed annual demand for water on the moon. The results of the calculations are shown in Table 1 and illustrate the wide size range and diversity that must be expected for lunar water deposits. Earth mining systems should be adaptable to exploitation of these hypothetical deposits [26].

A deposit model and its quantitative evaluation serve merely as a basis on which to compare alternate mining systems and equipment. However, an attempt has been made to make the assumptions as realistic and consistent as possible with the present state of our knowledge and/or speculative extrapolation to the moon.

ORE GRADE AND QUANTITIES OF MATERIALS TO BE MINED

The "grade" of the lunar water deposits may vary from 100 percent for pure massive ice down to 1 percent or less. As on earth, an ore grade of 100 percent is most unlikely, and in view of the common occurrence of hydrogen and oxygen on and in the earth's crust and in the universe, a complete absence of water at moderate depths below the lunar surface appears almost equally unlikely. Even a moon of cold accretion origin, with no melting or surface volcanic activity, would be expected to carry some water in view of its presence in carbonaceous chondrite meteorites [27].

The quantities shown in Table 1 have been calculated on the assumption of an ore grade of 2 percent water, by weight [28]. This figure appears reasonable and quite conservative.

Some assumed dimensions have been attached to serve as examples of the seven model deposits with the results shown in Table 1. Quantities of material to be moved vary widely. Model 1 presupposes overburden of 10 m (32.8 ft) over 3 m (9.8 ft) of ore. In model 2, the same ore body is

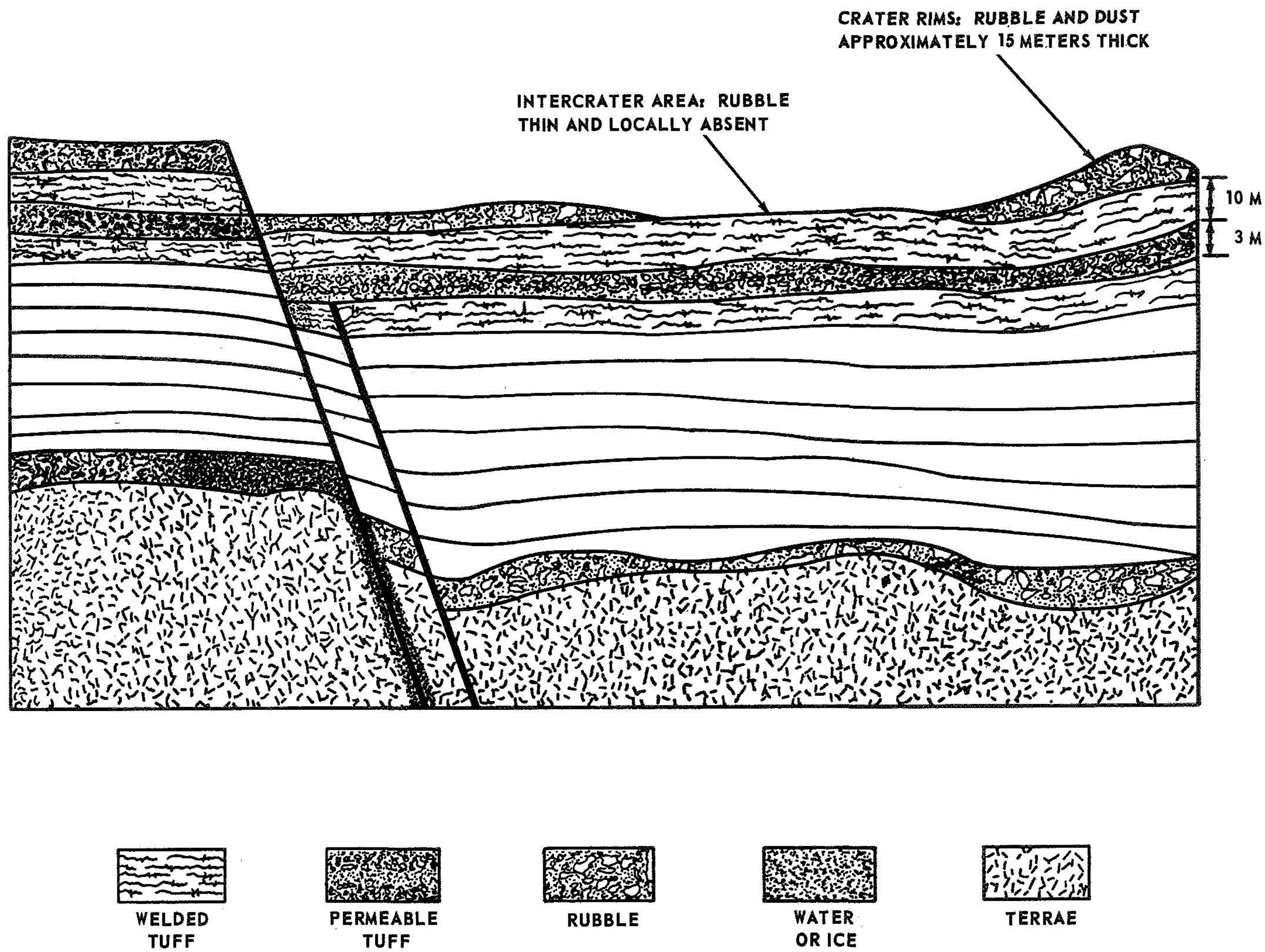

Figure 1. Section across hypothetical deposit number 1, a permafrost zone with shallow cover.

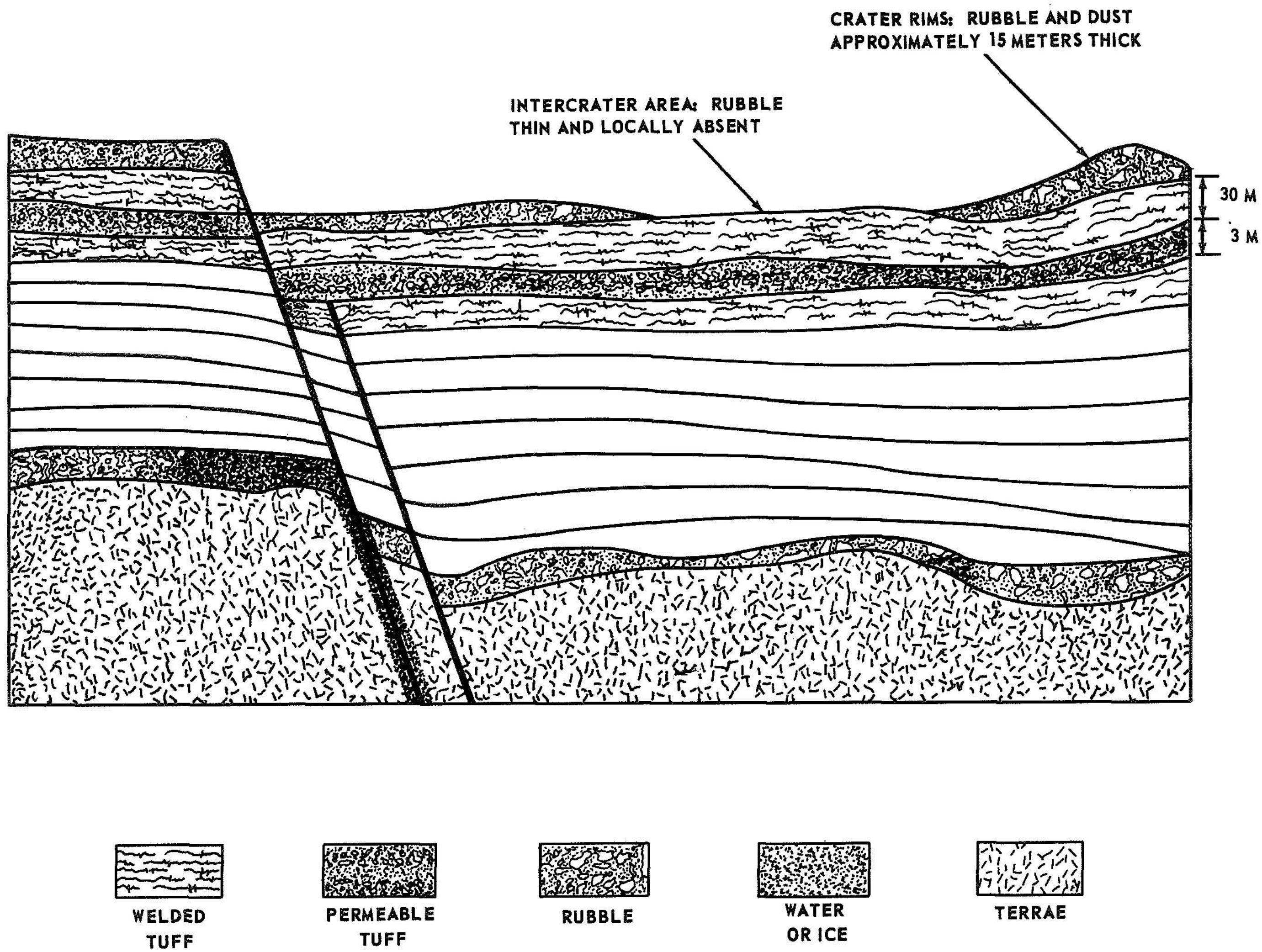

Figure 2. Section across hypothetical deposit number 2, a permafrost zone with deep cover.

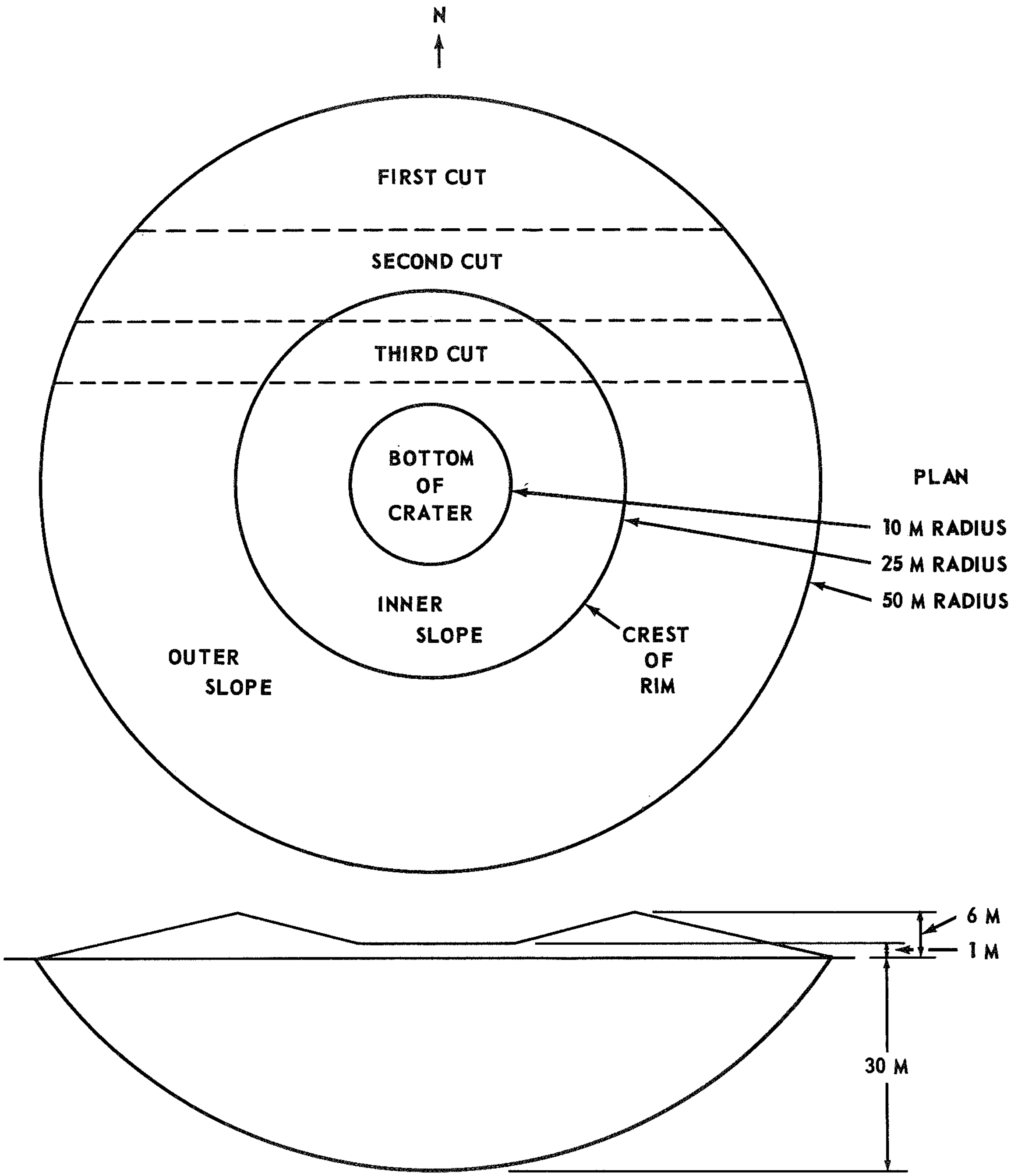

Figure 3. Section across hypothetical deposit number 3, a fractured and mineralized zone under an upland crater.

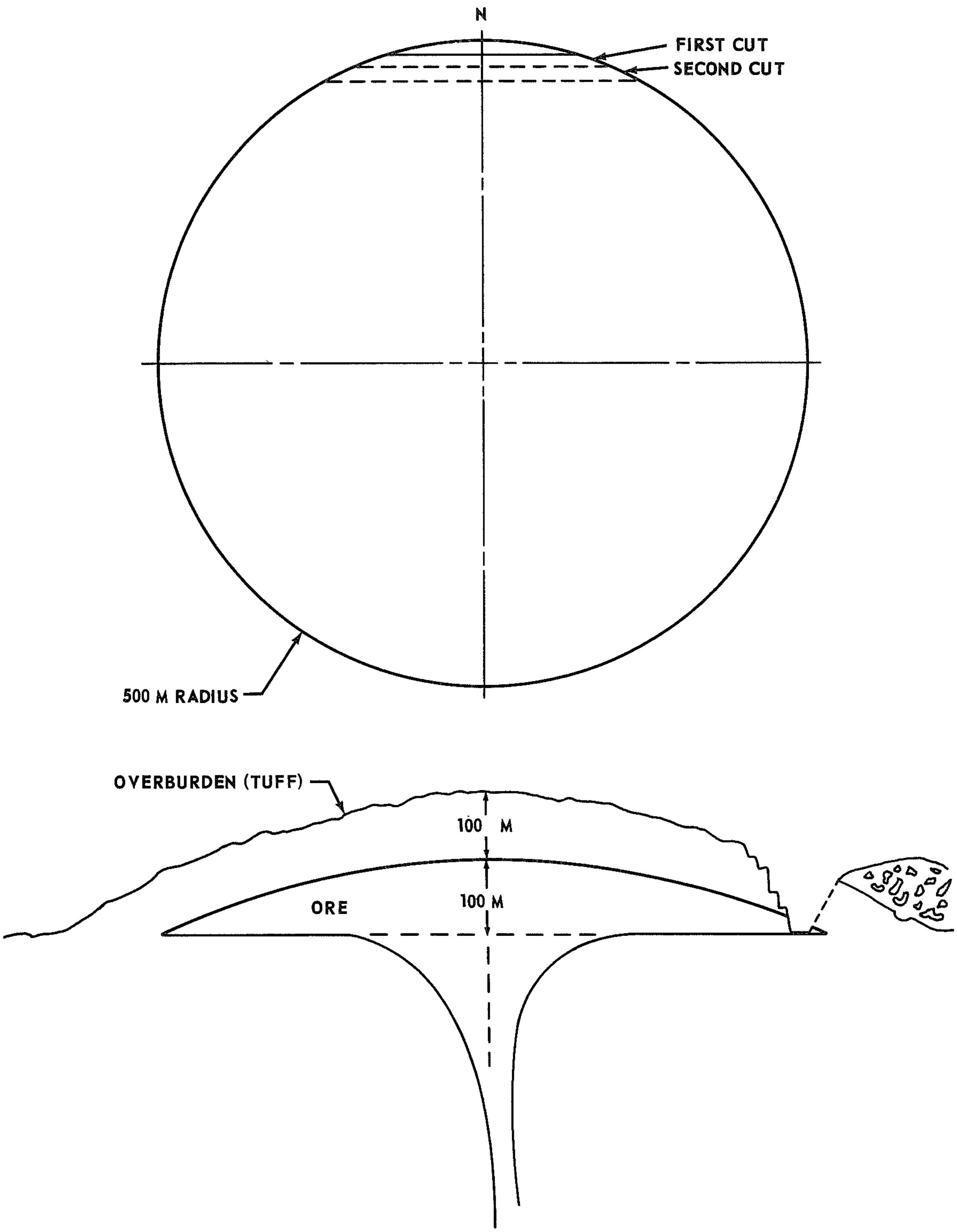

Figure 4. Section across hypothetical deposit number 6, a serpentine laccolith on a mare dome.

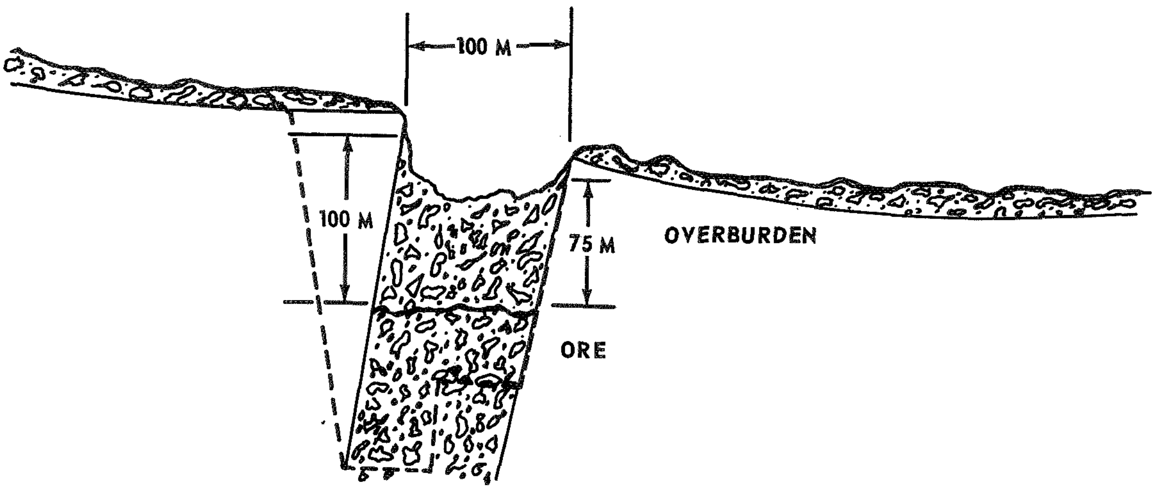

Figure 5. Section across hypothetical deposit number 5, a rubble-filled rill on a mare surface.

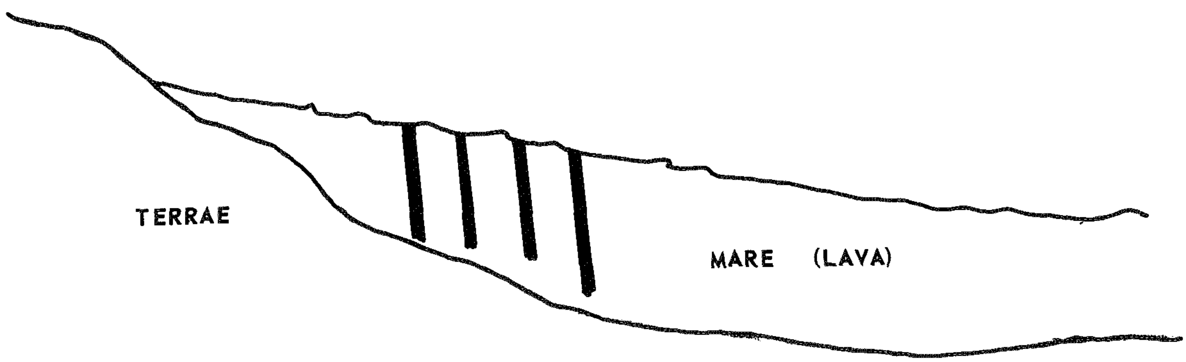

Figure 6. Section across hypothetical deposit number 7, a parallel, narrow, mineralized fracture near the edge of a mare.

assumed, but the overburden is 30 m (98.4 ft). An overburden of 10 m is less than the average of 15.3 m (50.1 ft) removed in strip coal mining in the United States in 1965 [29], and 30 m is considerably more than the average and close to the maximum mined with small or average sized equipment.

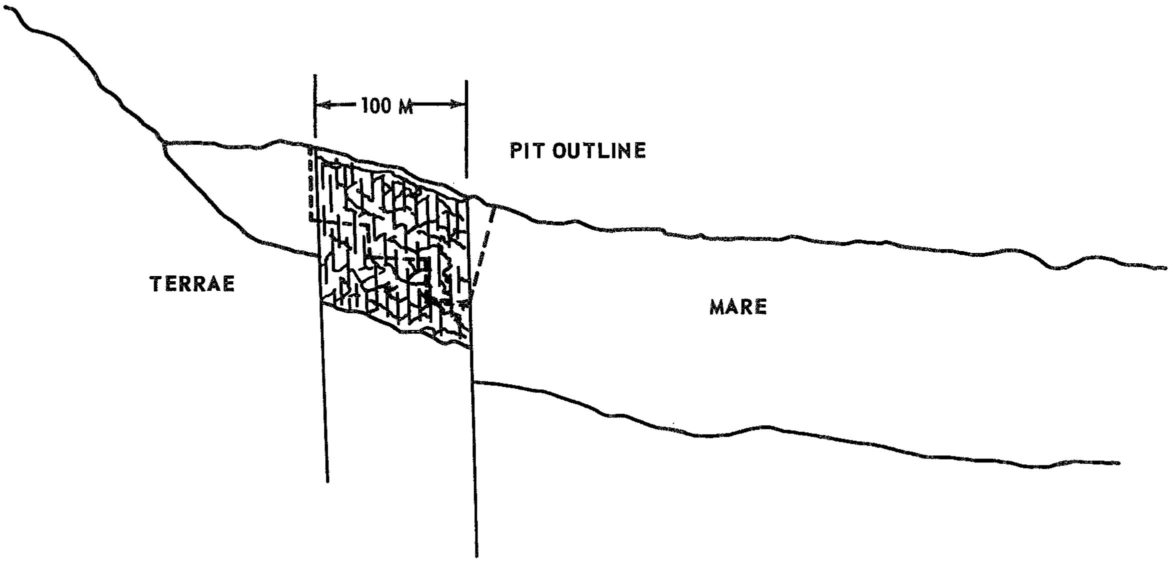

Figure 7. Section across hypothetical deposit number 4, a mineralized fracture or shear zone near the margin of a mare.

Model 3 presents a lenticular ore zone under a small crater with an overburden thickness of 6 m at the highest part of the rim and zero at the edges. The ore requirements per shift are the same, by weight, as for all the other models, but the thickness of overburden removed will be highly variable; the value shown in Table 1 is the average. The crater chosen for model 3 is a very small one, but the low overburden to ore ratio shown, about 0.16, should be near the average for all crater sizes.

Model 4 is a very large deposit. Although deposit depth can be very great, mining depth is arbitrarily limited to a 103-m (100 m ore) depth for calculation of quantities of ore available. Length of the deposit is assumed to be 300 m. Some wall rock probably must be removed, especially on the hanging wall side, as shown in Figure 7 and Table 1.

Model 5 is similar in dimensions to model 4, but an average of 75 m of barren rubble must be removed to reach ore. Much more wall rock must be excavated in model 5 because the country rock is assumed to be friable tuff rather than basaltic lava.

Model 6 is very large and the average overburden that must be removed to reach ore is large. The overburden-to-ore ratio is variable. Its average value is 1.97:1.

TABLE 1. TYPE, GRADE, SIZE, REQUIREMENTS PER SHIFT, AND EXPECTED LIFE AT A WATER DEMAND OF 122 470 KILOGRAM/YEAR FOR SEVEN HYPOTHETICAL LUNAR WATER ORE DEPOSITS

Model No.	Description	Ore		Ore Thickness		Overburden Thickness		Density (kg/m^3)		Requirements/Shift				Size of Entire Deposit				Wall Rock		Deposit Life (years)
										Ore		Overburden		Ore		Overburden				
		H_2O Percent	Density (kg/m^3)	Maximum (m)	Minimum (m)	Maximum (m)	Minimum (m)	Over-burden	Wall Rock	m^3	kg	m^3	kg	Volume (m^3)	Mass (kg)	Volume (m^3)	Mass (kg)	m^3	kg	
1	Permafrost zone in volcanic tuff, thin overburden	2.0	1200	3	3	10	10	1250	—	31.57	37879	105.23	131 538	large		large		none		indefinite
2	Permafrost zone in volcanic tuff, thick overburden	2.0	1200	3	3	30	30	1250	—	31.57	37879	315.7	394 625	large		large		none		indefinite
3	Mineralized zone under an upland crater	2.0	2400	30	0	6	1	2000	—	15.80	37879	2.46	4 920	134 232	3.22×10^8	20 923	0.42×10^8	none		47.2
4	Mineralized shear zone near edge of a mare	2.0	2500	100[a]	100	3	3	2000	2500	15.15	37879	17.12[b]	34 240[b]	3.0×10^6	75×10^8	3.0×10^8	60×10^8	0.39×10^6	9.75×10^8	1100.0
5	Rubble-filled rill near edge of a mare	2.0	1200	100[a]	100	75	75	1250	2500	31.57	37879	52.1[b]	75 125[b]	3.0×10^8	36×10^8	2.25×10^6	28.3×10^8	2.70×10^6	67.5×10^8	528.0
6	Serpentine laccolith (dome) on mare surface	2.0	3000	100	0	100	100	1250	—	12.63	37879	24.92[c]	31 150	39.6×10^6	1188×10^8	78.5×10^6	98.1×10^8	none		17 500
7	Parallel faults near edge of mare, incrusted salts minerali-zation	2.0	1200	10[a]	10	2	2	1250	2500	31.57	37879	6.31	7 888	4500	5.40×10^6	900	1.13×10^6	c		0.8

a. Deposit may extend much deeper. Mining is arbitrarily assumed to this depth.
b. Average for entire deposit. Actual removal rate per shift is highly variable.
c. Some wall rock must be removed if mined deeper than 12 m.

Model 7 consists of narrow, parallel, ore-filled fissures of the dimensions shown in Table 1. Mining to a depth of only 12 m (10 m ore) and along only a 300-m length makes this a small deposit. If the deposit was to be mined deeper than 12 m (39.4 ft) and with something other than a hoe, small dragline, or ditching machine, some country rock must be removed. If the rills are 25 m or more apart, much country rock will have to be excavated. To complete the range of possible water-bearing ores, the cracks in this deposit can be filled with rubble, lava, or incrusted porous salts (partly hydrous), sulfur, mercury, etc.

The last column in Table 1 shows the life expectancy of each of the seven deposits at an anticipated water demand for 1982 [30]. The life of models 1 and 2 is limited only by their area of occurrence. The dimensions assigned to models 4, 5, and 6 result in an almost infinite deposite lifespan from the short range view. Model 3 has a finite life, but a crater with a diameter exceeding 1 km — and they are relatively common on the moon — will belong in the infinite life class. Model 7 is large for miles of length or for mining at much more than a 12-m depth.

SUMMARY OF CONSTRAINTS IMPOSED BY SELENOLOGICAL FACTORS

At this time, of course, less is actually known about the selenological aspects of the lunar environment than of any others. The major conflict regarding the roles played in the formation of lunar surface features (and possibly of lunar mineral deposits) by impact and volcanic activity processes is not yet resolved. There is convergence [31], however, and proponents of each process now freely admit some considerable effects of the less favored process. Constraints outlined now are likely to be expressed as broad limits depending rather importantly on the magnitude of the role played by each of the major processes and the distribution of those roles in lunar history. The following constraints are imposed by selenological factors:

1. Water appears more likely to be abundant, of widespread occurrence, and in free form in areas in which volcanic processes have been more important or of more recent date, rather than in areas where impact processes may be predominant.

2. Hydrated minerals are more likely to be present in areas subjected to thermal metamorphism from the heat and gaseous products of high velocity impacts.

3. The more nearly selenology and selenologic forces prove to resemble those operative on the earth, the more likely it is that water deposits will be associated with a wide variety of lunar features.

4. Free water appears to be most likely in the form of subsurface permafrost filling fractures or interstices in rubble. This is the most desirable form of occurrence of water from the economic and technological standpoint, but it may preclude any lengthy surface storage of ore or daytime surface mining.

5. More costly and elaborate processing will be required for water occurring as hydroxyl ion in minerals such as serpentine, but such ores should be storable and surface mineable during the day.

6. Large deposits, especially if low grade, will require more preplanning and will permit larger and more permanent installations. Small, scattered deposits will require more mobile mining and haulage units and little or no permanent, on-site installations [26].

7. Minerals other than water may be recovered, possibly as byproducts of water mining, but to be economic, they must be usable by lunar colonies or in space exploration and simple to recover and process. Constructional materials appear most likely to meet these requirements.

8. Lean, free water deposits are likely to be more usable than rich hydrous mineral deposits, if both are found.

9. Among published deposit models, potentially large ones seem to have been favored.

REFERENCES

1. Lowman, P. D., Jr.: Lunar Resources: Their Value in Lunar and Planetary Exploration. Astronautica Acta, vol. 12, nos. 5-6, 1966, pp. 384-393.

2. Sinton, W. M.: Temperatures on the Lunar Surface. Physics and Astronomy of the Moon, Z. Kopal, Ed., Academic Press, New York, Chapter 11, 1962, pp. 407-428.

3. Salisbury, J. E.; Eckhard, D. H.; and Hunt, H. S.: The Lunar Environment. Handbook of Geophysics and Space Environments, S. L. Valley, Sc. Ed., U. S. Air Force, Chapter 19, 1965.

4. Shotts, Reynold Q.; and Cox, Robert M., Jr.: Lunar Resources: A Study of Surface Mining. Final Report, Contract NAS8-20134, Bureau of Engineering Research, University, Alabama, January 31, 1967.

5. Fields, S. A.: Behavior of Simulated Lunar Material in an Ultra High Vacuum Environment. Journal, Alabama Academy of Science, vol. 38, 1967, pp. 114-130.

6. Halajian, John D.: Laboratory Investigation of "Moon-Soils." Report No. ADK 04-04-621, Engineering Department, Adv. Dev. Program, Grumman Aircraft Engineering Corp, 1962.

7. Ryan, J. A.: Experimental Investigation of Ultra-High Vacuum Adhesion as Related to the Lunar Surface. Fourth Quarter Program Report and First Year Summary, Report SM-47914, Missile & Space Systems Division, Douglas Aircraft Co., Inc., Santa Monica, Calif., 1965.

8. Surveyor III Mission Report, Part II: Scientific Results. Technical Report 32-1177, Jet Propulsion Laboratory, Pasadena, California, June 1, 1967.

9. Surveyor VII Mission Report, Part II: Science Results. Technical Report 32-1264, Jet Propulsion Laboratory, Pasadena, California, March 15, 1968.

10. Surveyor V Mission Report, Part II: Science Results. Technical Report 32-1246, Jet Propulsion Laboratory, Pasadena, California, November 1, 1967.

11. Surveyor VI Mission Report, Part II: Science Results. Technical Report 32-1262, Jet Propulsion Laboratory, Pasadena, California, January 10, 1968.

12. Anderson, D. H., et al.: Preliminary Examination of Lunar Samples from Apollo 11. Science, vol 165, no. 3899, 1969, pp. 1211-1227.

13. Costes, N. C.; Carrier, W. D.; Mitchell, J. K.; and Scott, R. F.: Apollo 11 Soil Mechanics Investigation. Science, vol. 167, no. 3918, 1970, pp. 739-741.

14. Anderson, D. H., et al.: Preliminary Examination of Lunar Samples from Apollo 12. Science, vol. 167, no. 3923, 1970, pp. 1325-1339.

15. Surveyor I Mission Report, Part II: Scientific Data and Results. Technical Report 32-1023, Jet Propulsion Laboratory, Pasadena, California, September 10, 1966.

16. Green, J.: Geophysics as Applied to Lunar Exploration. Final Report, AFCRC Document No. AFCRL-TR-60-409, U. S. Department of Commerce, Office of Tech. Service, Washington, D. C., 1960.

17. Shotts, Reynold Q.; Cox, R. M.; Grubbs, David M.; and Ahrenholz, H. Wm.: A Study of Lunar Resources: A Preliminary Report on Surface and Some Other Mining Systems. Bureau of Engineering Research, University, Alabama, 1966, also NASA-CR-77720.

18. Westhusing, J. K.; and Crowe, C.: Techniques for Lunar Water Exploration. Final Report, Contract No. AF 19(628)-3287, Air Force Cambridge Research Laboratories, September 30, 1965.

19. Green, Jack: The Geology of the Lunar Base. Report SID 61-58, Space and Information Systems Division, N. Amer. Aviation, Downey, California, 1961.

REFERENCES (Continued)

20. De Wys, J. H.: Surveyor V: Magnet Experiment. Science, vol. 158, no. 3801, 1967, pp. 632-635.

21. Jefferies, H. C.: The Earth. Cambridge University Press, 4th Ed., 1959.

22. Shotts, Reynold Q.: Pseudo-Volcanism and Lunar Impact Craters. American Geophysical Union Transactions, vol. 49, 1968, pp. 457-461.

23. Salisbury, J. W.; Eckerd, D. H.; and Hunt, M. S.: The Lunar Environment. Handbook of Geophysics and Space Environments, U. S. Air Force, L. S. Valley, Science Ed., Chap. 19, 1965.

24. Shotts, R. Q.; Grubbs, D. M.; and Ahrenholz, H. W.: Three Lunar Geochemical Models for a Study of Possible Systems for the Generation and Synthesis of Fuel on Extraterrestrial Launch Sites. Summary Report of MSFC, NASA, and Bureau of Engineering Research, University of Alabama, University, Alabama, Contract NAS8-5043, 1963.

25. Shotts, R. Q.: Processes Which May Result in the Concentration of Mineral Species on the Moon. Alabama Academy of Science, Mobile, Alabama, April 11, 1969, In Press.

26. Shotts, R. Q.: Early Water Mining on the Moon. Seventh Annual Meeting, Working Group on Extraterrestrial Resources, Denver, Colorado, June 18, 1969.

27. Mason, Brian: The Minerals of Meteorites. Researches on Meteorites, C. Moore, Ed. John Wiley, New York, 1962, pp. 145-163.

28. Shotts, R. Q.; and Cox, R. M.: Lunar Resources: A Study of Surface Mining. Final Report, Contract No. NAS8-20134, Bureau of Engineering Research, University, Alabama, January 31, 1967.

29. Young, W. H.: Thickness of Bituminous Coal and Lignite Seams Mines in 1965. Inf. Circ. 8345, U. S. Bureau of Mines, August 1967.

30. Paul, D.: 3rd. Economic Analysis of Extraterrestrial Propellant Manufacture in Support of Lunar Exploration. Proceedings, Fourth Annual Meeting, Working Group for Extraterrestrial Resources, Air Force Academy, Colorado Springs, Colorado, Nov. 30-Dec. 2, 1965, pp. 341-376.

REFERENCES (Concluded)

31. Walter, L. S.; French, B. M.; and Lowman, P. D.: Planetology. Space Science, NASA Sp-167, 1967, pp. 305-437.

APPROVAL

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LUNAR SURFACE MINING: A REVIEW OF SOME MAJOR ENVIRONMENTAL CONSTRAINTS

By

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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